More info

UTM Library

UTM UNIVERSITI TEKNOLOGI MALAYSIA

SDi@JPUTM

SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my | InformationExcellence

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
1) Innovation in higher education institutions towards sustainability using LED technology (2024)	INTERNATIONAL JOURNAL OF INNOVATION SCIENCE (Article From : EMERALD)
2) Transforming document management for environmental sustainability: the mediating effect of pro-environmental culture and service satisfaction in higher education institutions (2025)	SUSTAINABILITY (Article From : FRONTIERS)
3) An Overview of Advancing Green Energy Solutions and Environmental Protection Toward Green Universities (2024)	ES ENERGY & ENVIRONMENT (Article From : ENGINEERED SCIENCE PUBLISHER)
4) Building Sustainability in Higher Education through Green Management and Innovation: A Case Study of Private Universities in Jakarta (2024)	JOURNAL OF ECOHUMANISM (Article From : Creative Publishing House)

27th FEBRUARY 2025

SOURCE: PERPUSTAKAAN UTM

More info

UTM
UNIVERSITI TEKNOLOGI MALAYSIA
UTM Library

SDi@JPUTM
SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my | InformationExcellence

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
5) Collaborative Green Initiatives: Integrating Human Resources, Intellectual Capital, and Innovation for Environmental Performance (2024)	SUSTAINABILITY (Article From : MDPI)
6) Fostering Education for Sustainable Development in Higher Education: A Case Study on Sustainability Competences in Research, Development and Innovation (RDI) (2024)	SUSTAINABILITY (Article From : MDPI)
7) Integrated sustainability assessment framework for geothermal energy technologies: A literature review and a new proposal of sustainability indicators for Mexico (2024)	RENEWABLE & SUSTAINABLE ENERGY REVIEWS (Article From : ELSEVIER)
8) The Sustainable Integration of AI in Higher Education: Analyzing ChatGPT Acceptance Factors Through an Extended UTAUT2 Framework in Peruvian Universities (2024)	SUSTAINABILITY (Article From : MDPI)

27th FEBRUARY 2025

SOURCE: PERPUSTAKAAN UTM

More info

UTM
UTM Library
UNIVERSITI TEKNOLOGI MALAYSIA

SDi@JPUTM
SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my | InformationExcellence

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
9) The influence of using smart technologies for sustainable development in higher education institutions (2024)	INTERNATIONAL JOURNAL OF DATA & NETWORK SCIENCE (Article From : GROWING SCIENCE)
10) Transformative Approaches to Sustainable Education: Technology, Leadership and SDGs in Higher Education Institutions (2024)	INTERNATIONAL JOURNAL OF LEARNING, TEACHING & EDUCATIONAL RESEARCH (Article From : Society for Research and Knowledge Mgt)

27th FEBRUARY 2025
SOURCE : PERPUSTAKAAN UTM

More info

UTM
UNIVERSITI TEKNOLOGI MALAYSIA
UTM Library

SDi@JPUTM

SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
1) Innovation in higher education institutions towards sustainability using LED technology (2024)	INTERNATIONAL JOURNAL OF INNOVATION SCIENCE (Article From : EMERALD)

27th FEBRUARY 2025
SOURCE: PERPUSTAKAAN UTM

Innovation in higher education institutions towards sustainability using LED technology

José Carlos Pereira de Morais, Nelson Castro Neves,
Luís Abranches Soveral and João Lima
ISPGAYA, Vila Nova de Gaia, Portugal

Received 15 August 2022
Revised 9 February 2023
17 July 2023
4 October 2023
17 November 2023
Accepted 5 January 2024

Abstract

Purpose – There is a growing urgent concern in involving higher education institutions (HEIs) towards an international effort in implementing a more suitable role as conductors of sustainable development. This paper/study aims to present the application of light emiting diode (LED) technology in an HEI assuming technology innovation as part of a larger institutional innovation management strategy addressing multiple dimensions in sustainability.

Design/methodology/approach – Investments in LED technology are analyzed for their impact on consumption results and quantitative comparisons between 2008 and 2022 are impaired with detailed information on the types of luminaires and the amount of installed energy.

Findings – The collected data shows a clear economic advantage of using LED technology, and the results subsidize institutional planning, considering not only ongoing technological innovation, but also educational components and community involvement in the organization sustainability strategy.

Research limitations/implications – The study is limited to a specific HEI and further comparative research should be carried out.

Practical implications – A holistic approach on sustainability objectives encourages further investment in environmental-friendly technology, example to other HEIs.

Social implications – The strategic vision of innovation is confirmed with the involvement of the community, at various levels, such as the academic community, local community, scientific international community.

Originality/value – This study addresses the lack of examples in the literature of structural planning and management systems that see sustainability as a strategy built in HEIs. The elaboration of an environmental sustainability plan places environmental sustainability at the confluence of themes such as education, investigation, use of natural resources, waste separation. For each topic are listed measures, actions, environment improvements, institution improvements and their results.

Keywords Innovation, Multidimensional sustainability, Higher education institution management, LED illumination

Paper type Research paper

Introduction

As the planet faces climate change, there are increasingly striking examples of the impacts of human activity, such as the deterioration of the quality of drinking water due to pollution and the effects of global warming (Alimba and Faggio, 2019; Harvey, 2018; Kasperson, 2022). Although the education sector is not considered a polluting sector, it includes the consumption of natural resources and the production of waste, which raises sustainability concerns for all higher education institutions (HEIs) (Hill, 2020; de Matos, 2020; Manisalidis, 2020). In the literature, HEIs are often associated with the set of transformations called digital transition and the using of clean technology in all dimensions of the institutions' management, in the path of their

International Journal of Innovation Science
Vol. 16 No. 2, 2024
pp. 296-319

1757-2223
DOI 10.1108/IJIS-08-2022-0153

sustainable management (Abad-Segura *et al.*, 2020). In recent years, it is getting broader assumption that HEIs have the vision, the knowledge and the power to lead the achievement of a societal new paradigm positioning humanity in a sustainable development model inducing the changes needed to achieve it (Ramísio *et al.*, 2019).

The theme "sustainability" begins with the need to reconcile environmental biases (Randers *et al.*, 2019) and often combines the concepts of development and innovation (Barska *et al.*, 2020; Wyrwa *et al.*, 2021; Wyrwa *et al.*, 2021; Shi *et al.*, 2019) and energy efficiency (Almeida, 2019a; Almeida, 2019b; Almeida, 2021; Gökgöz and Güvercin, 2018; Kolosok *et al.*, 2020; Weaver, 2017; Sun *et al.*, 2019).

The approach we favor in this study seeks to highlight the effort of a Portuguese HEI, in the sense of introducing innovation in the way it produces and manages electricity consumption through light emitting diode (LED), an innovative technology that impacts energy consumption and the associated costs, as well as the gains it represents in terms of luminosity in the building rooms. We assume that the introduced technological innovation is an example of a public demonstration of the involvement of this institution to influence society to adopt technological innovations. Besides economic gains, they contribute to the sustainability of the institution and the planet through economic and environmental resources savings, together with a planning and execution component of environmental education and dissemination of environmentally friendly practices.

The study aims to contribute to the research gap that links sustainability, innovation and higher education since sustainability is part of the declared objectives by HEIs for their "systems." However, regarding the integration of sustainability in education – curriculum and pedagogy – there is still the challenge of integrating sustainability both in teaching and in research and development, simultaneously with the management (operations) of these organizations (Menon and Suresh, 2020). Redesigning HEI systems is not easy (Menon and Suresh, 2020; Thürer *et al.*, 2018). We assume that the path of structural implementation of a sustainable development model with a direct reference to management planning and practices, which can be addressed as the institutionalization of sustainability policies embodying a committed to sustainability organizational culture, is a difficult path to concretize (Ramísio *et al.*, 2019). This path toward sustainability can be made addressing interconnected focuses, embodying a strategy. Pedagogical components associating teaching research must be reinforced by activities such as campus planning, design, construction and rehabilitation of buildings and infrastructures (Leal Filho, 2015).

Energy efficiency, along with technology innovations, does have favorable impact on environmental quality of countries (Wenlong *et al.*, 2022). These topics direct to LED lighting and its undeniable benefits, which are increasingly addressed by research, exposing financial benefits of this technology, associated with productivity gains and energy saving (Adhvaryu *et al.*, 2020). In effect, according to authors (Zhang *et al.*, 2021), LED is an energy-saving and environment-friendly lighting technology ten times more energy efficient than conventional incandescent lights.

Although nowadays HEIs favor a "greening" discourse related to Sustainable Development Goals (SDGs) (Ruiz-Mallén and Heras, 2020), the studies on energy efficiency prevail on facilities related to other areas of human activity, and studies in HEIs about energy management and energy efficiency focus on energy consumption or general investment in energy efficiency, pointing also the weight on institutions budgets of locally produced energy based on renewable sources (Ribeiro *et al.*, 2022). Besides pointing an optimistic scenario on greener energy use, reports on institutions sustainability lack detailed information on gains obtained specifically by implementing LED technology on the facilities.

Innovation can reside in the way innovation is implemented, shared by the community, implemented in a holistic approach to curricular content and management practices of institutions. This is the addressed challenge here, presenting data on the implementation and benefits of LED technology, and proposing a holistic approach to the IES Environmental Sustainability Plan, which includes lifelong learning about sustainability issues and community involvement – local national and international. Figure 1 shows our theoretical analysis model.

A driving force of this research is implementing ISO 14001 environmental certification within institutions in line with the understanding of sustainable development (Alnavis *et al.*, 2021; Fonseca and Domingues, 2018) and increasing mutual benefits by resorting to greener practices and adoption of greener technologies (Bravi *et al.*, 2020). It shows the institution investment in technology and innovative solutions to simplify and optimize energy use, including replacing conventional light bulbs with energy-saving light bulbs. This organizational record history (data record) dates to 2008 and continues through 2022. It presents data demonstrating the significant economic benefits of adopting environmentally friendly practices, data underlying the integration of HEI ESP.

The research question states:

RQ1. What are the economic and environmental benefits of using innovative LED technology in the HEI building?

Note: Environmental sustainability
Source: Authors

Figure 1.
Theoretical model of analysis: innovation on the HEI management system toward sustainability

Literature review: construction of an environmental management system

The theoretical construction presented aims to demonstrate the set of measures taken within the studied institution, comprising the replacement of traditional lamps by lamps that use LED technology in a framework of technological innovation using technology that allows the reduction of consumption and energy costs, but also understanding the use of technology as innovation in the organization's management processes. This comes in line with the integration of a development model of human societies in which technological innovation is associated with innovation in management processes, which are increasingly efficient and rational.

In terms of the institution's management, the used technology and the elaboration of an ESP contribute to sustainability in the environmental aspect. It also foresees a permanent innovation associated with social sustainability involving the institution employees, namely, in terms of education and training. The reference to the objective of certification according to the ISO 14001 standard is justified because it is an international reference that can be followed, assuming that it is aligned with the UN SGDs. It facilitates the achievement of environmental sustainability objectives, and it presents some guarantees of this implemented innovation to overcome the so-called energy efficiency gap (EEG).

Sustainability consists in the integration of a set of actions based on three pillars: environmental, social and economical. It is a multidimensional concept, such as the concept of sustainable development, which proposes a rupture in the regular patterns of development by linking it to issues such as quality of life (De Guimarães *et al.*, 2020; Oláh *et al.*, 2018; Oliveira Neves *et al.*, 2017). This concept of development is explicit in the 17 SDGs that guide the 2030 agenda (United Nations, n.d.), seen as the guarantee of the planet itself and the basis of a "smarter development model" (Randers *et al.*, 2019). Recent research relating SDGs with energy efficiency does find a positive relation between sustainable economic development and energy efficiency, suggesting that sustainable economic development is associated with increased energy efficiency (Zakari *et al.*, 2022).

ISO 14001, published in September 1996, last edition dated 2015 (International Organization for Standardization, 1996; International Organization for Standardization, 2014; Fonseca and Domingues, 2018), is widely considered the most important environmental certification (Kuhre, 2018; Sartor *et al.*, 2019), and corresponds to the content of the SGDs, paving the way for a common vision for humanity in a more executive/practical approach. This international standard is based on budgeting the best environmental performance that can be achieved through the systematic identification and management of environmental aspects, considering issues such as yield prevention, improvement of environmental performance and satisfactory compliance with embodied laws in management systems of each institution, which must be subject to certification granted by agencies. ISO 14001 contains the requirements for the environmental management system (EMS), making it a useful tool in facilitating environmentally friendly and confident practices for institutional sustainability, together with the dominant ideology about a viable planet: organizational structure and responsibilities; activity planning; definition of practices, processes and procedures; allocation of resources to plan, implement, verify and improve the environmental policy (Bravi *et al.*, 2020; Fonseca and Domingues, 2018).

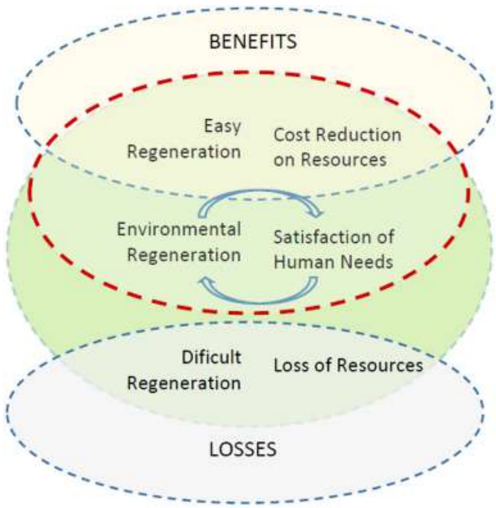
The norm is not new, but there is an urgent and growing concern to involve HEIs in an international effort to fulfill a more adequate role as drivers of sustainable development, implementing specific national regulations that go beyond globally signed declarations on sustainability in higher education (Grindsted, 2011). Sustainability must be present in education management, in all dimensions, covering both practices and curricular contents and key competences in terms of sustainability must be developed in universities

(Blanco-Portela *et al.*, 2017; Brundiers *et al.*, 2021). The Institutional Assessment Manual of the Portuguese higher education assessment agency A3ES (A3ES, 2022), establishes this national internal standard that will ensure the executive procedure of this role that drives higher education toward sustainability and commitment to the SDGs that direct the 2030 agenda. This Agency intends to mandate evidence demonstration in the adoption of a strategy and governance in HEIs that place sustainability in their educational, scientific and cultural project. This study fulfills the objective of highlighting sustainability as a key factor in an HEI, helping to outline its EMS, accessible to the institution's internal and external public.

With the presentation of data from this study, we expect to evolve toward overcoming the difficulties of measuring efficiency and other factors that are implicit in the implementation of the HEI EMS, such as bureaucratic issues, high costs, lack of available advice or the generic character requirements of this ISO (Fonseca and Domingues, 2018).

In addition to solidifying the institution's EMS, we intend to contribute to overcome what is known in literature as the EEG. EEG occurs when energy-efficient technologies, which offer considerable promise for reducing the financial costs and environmental damage associated with energy use, cannot be adopted by individuals and businesses to a level that can be justified on an environmental and/or financial (Gerarden *et al.*, 2017). Overcoming the EEG is the reason and inspiration for all the work and planning dedicated to the institution general management model, taking another step toward financial rationality and environmentally friendly approaches.

In Figure 2, we can see that, in contrast to the satisfaction of human needs, there is the need to regenerate the environment. Depending on man's will and the technological state of the art, it is possible for man to use resources with no or low impact on nature, without compromising financial gains. Figure 1 exposes the possibility of financial and environmental benefits, according to a "double/multiple benefit"



Note: Environmental sustainability
Source: Authors

Figure 2.
A model for environmental sustainability analysis

approach (Helepciuc *et al.*, 2018). In contrast to the satisfaction of human needs, there is the need to regenerate the environment.

The environmental sustainability model presented above is part of the HEI adopted approach. According to the model, environmental sustainability is a strong argument for gains with the implementation of ecologically correct technologies, with simultaneous reduction of costs and minimization of adverse impacts in the environment.

Methodology

By collecting data from the history of energy consumption related to replacing traditional light bulbs with low-consumption light bulbs, a perspective is offered on the financial gains achieved, presenting numerical data that demonstrate the advantages of adopting ecologically correct practices. This numerical and descriptive presentation allows quantitative comparisons associated with periods of time, enabling evaluations and estimates with qualitative and strategic components, referring to items and variables such as: types of lighting fixtures in the building and also installed power in lighting on each floor and throughout the entire building.

The followed method keeps itself to quantitative approach on data gathering and interpretation. Data shown refers to items and variables such as: types of lighting units existing in the building and also installed power in lighting on each floor and in the whole building from 2008 to 2022, the actual panorama of LED technology used, distinguishing between LED downlight units and LED tubular units.

The characterization of the main types of lighting at the beginning of the operations of the IES building in 2008 is made, and the data referring to the use of LED lamps in the building in 2022 allows the comparison of data regarding the use and distribution of energy, distinguishing the LED Tube Technology or LED Downlight. The preferential use of LED Downlight is conditioned to the structural height of the floors. In addition to the distinction between the used LED technology, reference is made to the introduction in the first year of analysis of LED technology by more efficient LEDs, both the Tube and the LED Downlight.

A description of lighting technology and its distribution on the building was made, presenting the distribution of electrical power installed in the HEI building. The year 2017 is presented as the starting point for the evolution on conversion from discharge lighting to LED technology, mentioning the change according to year, semester and floor intervened.

Evaluation of energy saving (gain) can be stated comparing its consumption previous to the changes in lighting and after the changes. Reliability and durability of technology used was taken into account directing changes toward the option for a specific LED technology – LED tubes.

The study was developed using two forms of data collection to extrapolate the evolution of energy consumption in the lighting component, analyzing data since the conversion to lighting with LED technology. A network analyzer [1] was used on two spaces chosen after the typification of classroom or work spaces in the building (downlights and tubulars), Room 6.1 and Laboratory 1.7. The consumption of the lighting circuit was collected by comparing the energy consumed by the discharge technology luminaires existing at the beginning and the LED technology luminaires. Although the equipment can provide data via communication network [2], the data was collected by consulting the liquid crystal display incorporated in the network analyzer.

By accessing the portal that is responsible for energy distribution and charging tariffs at the platform e-Redes Portugal [3], it was possible to monitor consumption data for the period from 2017 to July of 2022, allowing also conclusions about consumption according to tariff periods. Analysis of the building’s consumption was performed by consulting the consumption maps platform using the institution’s credentials to access information relating to the consumption point [4]. Data for 2017, 2018, 2019, 2020, 2021 and 2022 were collected from this platform. We give the example of two pairs of months, February and July, considering the years 2017 and 2020. Below are the graphs obtained on the e-Redes platform (Figures 3, 4, 5 and 6):

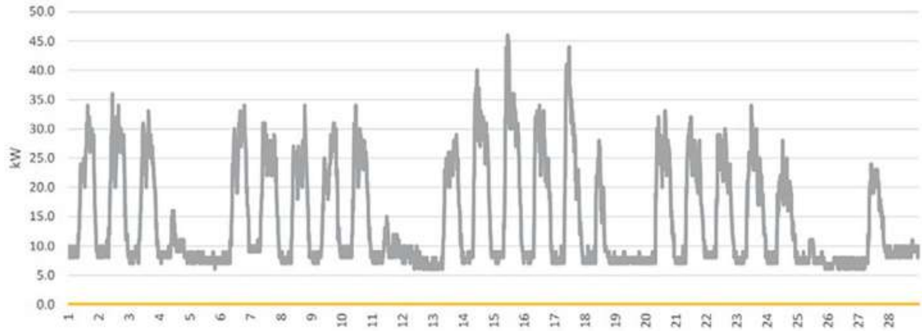


Figure 3. Building consumption in February 2017

Source: e-Redes, consumption point

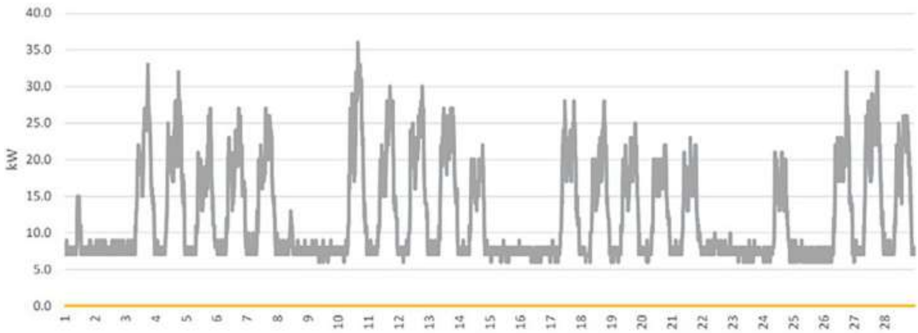


Figure 4. Building consumption in February 2020

Source: e-Redes, consumption point

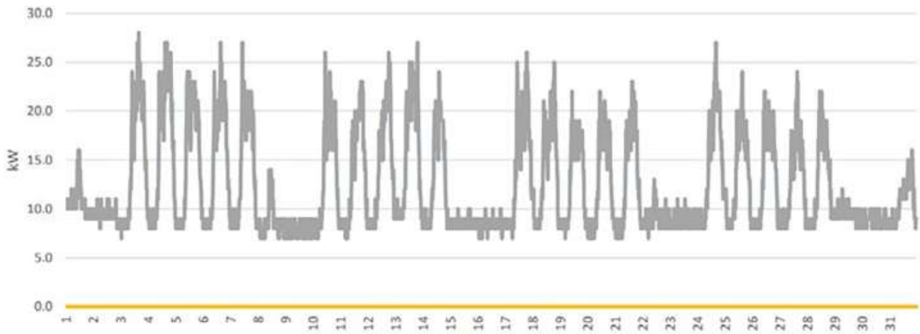


Figure 5. Building consumption in July 2017

Source: e-Redes, consumption point

Comparing consumption between the two years in both months, it is possible to see the reduction obtained with the contribution of the reduction in consumption in the lighting circuits.

It should be referred the participation on collecting data on energy of a student of the HEI on Renewable Energy degree during 2022, collection of data that was supervised by one of the authors of the manuscript presented [5].

Data collection was authorized by the institution's management upon request made by the researchers involved, making possible to access data related to: illumination gain – LUX gain – collected by an external auditor on health and safety on work of the studied HEI recurring to lux meters; energy consumption; LED units in the building; installed power in lighting on each floor and in the overall building.

Overall, hypotheses to be tested typical of quantitative research (Bell *et al.*, 2022), were not proposed, rather relying on a methodological approach as an exploratory one, presenting data to answer our research question (Almeida, 2021).

Results

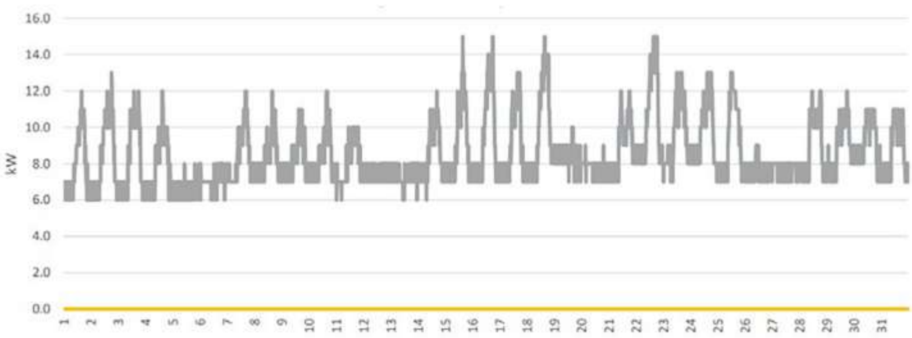
When the studied HEI started operating in the current building in March 2008, the building had two main types of lighting, which were dual-discharge downlights and fluorescent discharge lamps. The former illuminated the spaces directly, while the latter illuminated the spaces indirectly through the ceilings. The distribution of the two types of lighting was also not uniform as the downlights were installed on the third, fourth and fifth floors, while the drainpipes were installed on the first and second floors, whose ceiling height is lower than normal as a result of the suitability of the building for the regular HEI activities.

Thus, Table 1 quantifies the characterization of lighting through downlights with two discharge lamps and presents the installed power in the lighting circuits per floor.

While, Table 2 quantifies the characterization of lighting through the installed power in the different floors and in the overall building using fluorescent discharge lamps.

Figure 7 presents the distribution of electrical power installed in the building for lighting circuits for both types of lighting.

Despite the distribution of types of lighting leaning toward flush downlights, HEI management decided to start by replacing the tubular flush lighting with LED technology. This process began in 2012, and the first replacement point was the 24-h elevator cabins. This option was taken as a test of the same technology considered not reliable at the time (Meneghini, 2010). In 2014, a discharge technology was tested but with electronic ballasts. In this solution, the T8 tubulars were replaced by T5 tubulars whose adapter included an



Source: e-Redes, consumption point

Figure 6. Building consumption in July 2020

electronic ballast. This solution was implemented on a trial basis in the computer lab and on the second floor computer center for two reasons: first, because it is cheaper than solutions at the time for LED tubes, and second, because they are intensely busy and are interiors without natural light, but with an occupancy of 8 h a day. This solution lasted until the second half of 2020, when it started to break down and replacement was very expensive.

However, in 2017, the replacement of discharge downlights with LED downlights began, and the replacement of discharge tubes with LED tubes became general throughout the building, with the main impact on the lighting of the first and second floors.

This process was completed at the end of the first half of 2022.

Thus, the evolution of the conversion from discharge lighting to LED technology from the first floor to the sixth floor was as follows:

- 2017 (first semester) – classrooms of sixth floor not including the library or hallways;
- 2017 (second semester) – classrooms of fifth floor with corridors and sixth floor corridor;
- 2018 (first semester) – service, secretariat and third floor in general, except the office corridor;
- 2018 (second semester) – LED tubes on Floor 2, except computer lab and computer center;
- 2019 (first semester) – LED tubes on the ground floor;
- 2020 (second semester) – LED tubes in the computer lab on the second floor;

Table 1. Discharge downlight units in the building in 2008 and installed power in lighting on each floor and the whole building

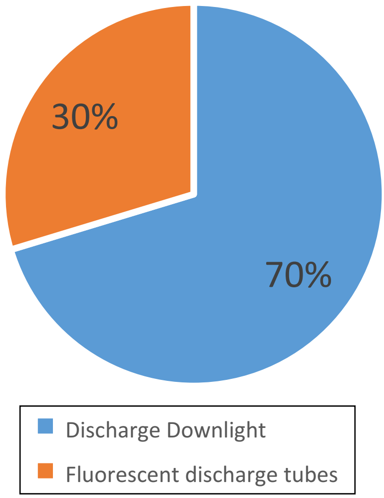
Floor	170 mm 26 watts	200 mm 52 watts	220 mm 52 watts	Total power
1	5	15	28	2,366 W
2	36	26	0	2,288 W
3	6	109	0	5,824 W
4	11	102	0	5,590 W
5	0	99	0	5,148 W
6	0	59	17	3,952 W
7	1	0	0	26 W
			Total power	*25,194 W*

Source: Authors

Table 2. Fluorescent discharge lamps units in the building in 2008 and installed power in lighting on each floor and the whole building

Floor	60 mm 18 watts	120 mm 36 watts	150 mm 58 watts	Total power
1	2	41	64	5,224 W
2	25	33	59	5,060 W
3	0	0	0	0 W
4	0	0	0	0 W
5	0	0	0	0 W
6	0	0	0	0 W
7	0	0	6	348 W
			Total power	*10,632 W*

Source: Authors



Source: Authors

Figure 7. Distribution of electrical power installed in the building for lighting circuits for both types of discharge lighting

- 2021 (second semester) – library; and
- 2022 (first semester) – classrooms and corridor of fourth floor and office corridor on the third floor.

After the process ended, it was possible to begin to quantify the obtained gains in terms of installed power in the same lighting circuits, noting that only the lighting technology was changed without changing the quantities.

Thus, Table 3 quantifies the installed power on the different floors and in the overall building using LED downlight.

While, Table 4 quantifies the installed power on the different floors and in the overall building using LED tubes.

Figure 8 presents the new distribution of electrical power installed in the building for lighting circuits for both types of LED lighting.

Floor	170 mm 20 watts	200 mm 40 watts	220 mm 40 watts	Power by floor
1	5	15	28	1,820 W
2	36	26	0	1,760 W
3	6	109	0	4,480 W
4	11	102	0	4,300 W
5	0	99	0	3,960 W
6	0	59	17	3,040 W
7	1	0	0	20 W
			Total power	*19,380 W*

Source: Authors

Table 3. LED Downlight units' existence in the building and installed power in lighting on each floor and in the overall building in 2022

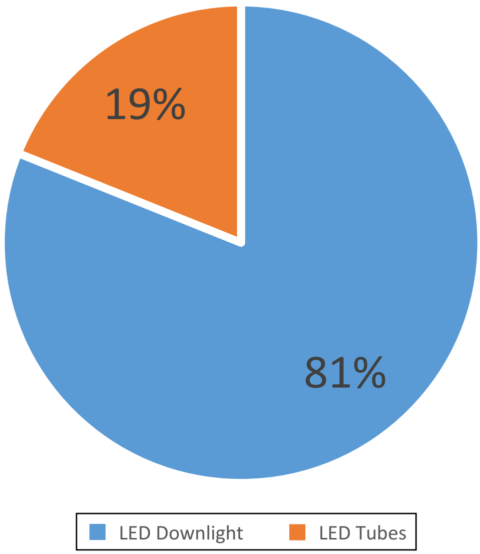
Comparing the two implemented solutions, which are summarized in the previous tables, a gain of more than 53% is concluded, as it can be seen in Figure 9, in terms of installed power in the lighting circuit, thus translating into energy savings, making the building more sustainable in terms of lighting.

An important aspect is the reliability of the used equipment. It is common knowledge that technology has evolved ensuring greater reliability. However, this reliability depends a lot on the installation points, specifically their ventilation (Richter, 2019). This observation is made when realizing that there are several AC/DC converters that must exist in LED lighting, in which if the lighting point is not ventilated, the AC/DC converters tend to fail early. Thus, in the installation of the HEI, it was rare to have to replace the LED tubes, while the frequency of failure of the AC/DC drives of the LED downlight is much higher because they are placed in a false ceiling where there is no ventilation of the space.

Table 4. LED Tubes units' existence in the building and also installed power in lighting on each floor and in the overall building in 2022

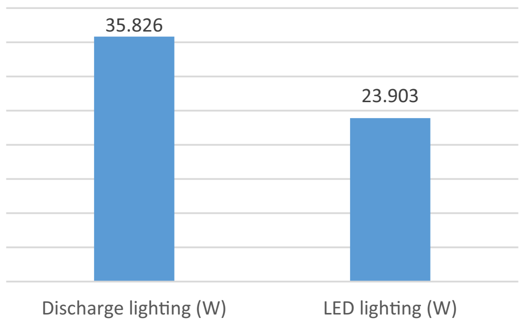
Floor	60 cm 9 watts	120 cm 16 watts	150 cm 24 watts	Power by floor
1	2	41	64	2,210 W
2	25	33	59	2,169 W
3	0	0	0	0 W
4	0	0	0	0 W
5	0	0	0	0 W
6	0	0	0	0 W
7	0	0	6	144 W
			Total power	*4,523 W*

Source: Authors



Source: Authors

Figure 8. Distribution of electrical power installed in the building for lighting circuits for both types of LED lighting



Source: Authors

Figure 9. Summary of installed power gain between both solutions

This issue forced the installed downlights more recently, despite having the same electrical characteristics and light color to be of the second generation where AC/DC drives provide more guarantees, having even begun to replace the first generation downlights.

Impact of light emitting diode lighting on real consumption

E-Redes is the company in Portugal that distributes electricity [6] independently from the supplier. Through its internet portal (https://balcaodigital.e-redes.pt/login), it is possible to collect the energy consumption history of a point of an electricity consumer in Portugal.

Table 5 shows the tariff applied to the HEI consumer, which is called the "daily cycle."

Applying this tariff to the energy consumption in the lighting circuits, and comparing them with the opening hours of the teaching sessions, it is clear that it is important to analyze the evolution of consumption in the Peak (iii), Partial Peak (ii) and Valley (iii) tariffs corresponding to the timetable from 6:00 p.m. to 12:00 a.m. of each day of classes from Monday to Friday, when most classrooms, laboratories and other spaces are functioning with the lights on. However, this is not possible because the data collection on the E-Redes portal does not separate the sub-periods of (i), (ii) and (iii) in the Peak and Valley periods, nor the sub-periods (i) and (ii) in the Partial Peak period. Thus, the analysis will have to incorporate an error of quantification and approximation to the real scenario.

Tariff period	Sub-period	Winter time	Summer time
Peak	(i)	08h00 to 09h00	08h00 to 10h30
	(ii)	10h30 to 18h00	13h00 to 19h30
	(iii)	20h30 to 22h00	21h00 to 22h00
Partial Peak	(i)	09h00 to 10h30	10h30 to 13h00
	(ii)	18h00 to 20h30	19h30 to 21h00
Valley	(i)	00h00 to 02h00	00h00 to 02h00
	(ii)	06h00 to 08h00	06h00 to 08h00
	(iii)	22h00 to 00h00	22h00 to 00h00
Super Valley		02h00 to 06h00	02h00 to 06h00

Source: Authors

Table 5. E-Redes "daily cycle" tariff

Thus, with the HEI access credentials, it was possible to obtain data for the period from 2017 (the first year made available) to July of 2022, recording the consumption shown in Table 6 and Figure 10.
It is concluded that there is a decrease in energy consumption that follows the adoption of LED technology lighting. This fact is supported by the increase in the weight of consumed energy in the period of the super empty tariff, while in the other tariffs. there is a constant relative decrease.

LUX gain
In addition to the improvements felt in terms of energy sustainability, the conversion of lighting from discharge technology to LED technology brought improvements in terms of LUX measured at the level of the work plan, which are classroom tables (see Figure 11 referring to the geometrical model of the building).

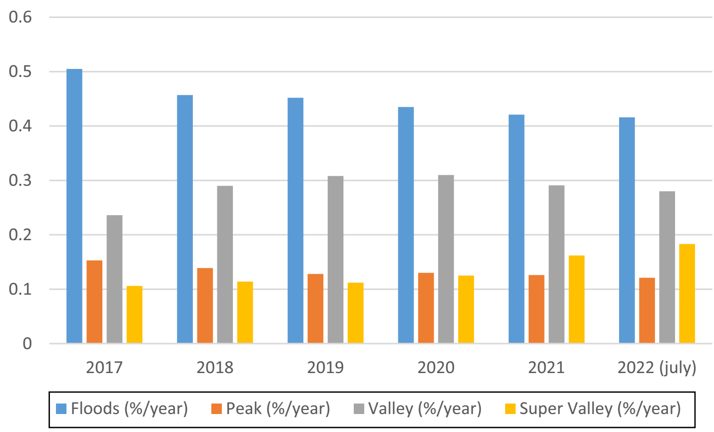
Comparing the measurements carried out in 2012 and in 2022, there is a substantial increase in LUX. According to the external auditor procedure, measurements are made twice a year in each room recurring to a lux meter, corresponding to winter or summer period [7]. The variations are not uniform as there are aspects that contribute to potentiate these variations felt with recent measurements.

Thus, there are several factors that influence a non-uniform variation:

Table 6. Total energy consumed per year and percentage weights of each energy tariff

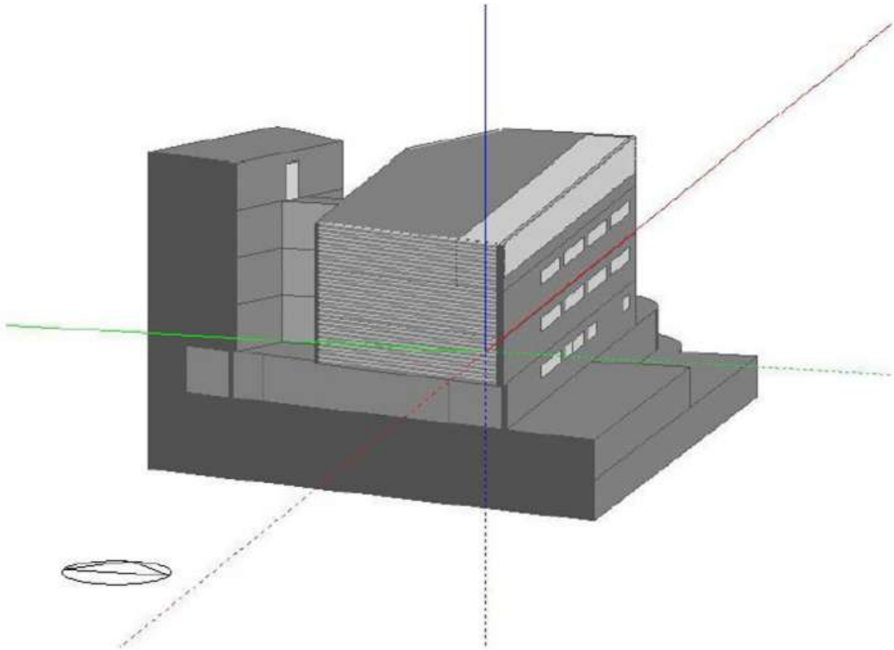
Year	Power provider (Rates): EDP	Peak (%/year)	Partial peak (%/year)	Valley (%/year)	Super valley (%/year)
2017	132,55 MWh/year	0.505	0.153	0.236	0.106
2018	120,14 MWh/year	0.457	0.139	0.29	0.114
2019	113,92 MWh/year	0.452	0.128	0.308	0.112
2020	89,72 MWh/year	0.435	0.13	0.31	0.125
2021	94,96 MWh/year	0.421	0.126	0.291	0.162
2022 (July)	42,73 MWh/year	0.416	0.121	0.28	0.183

Source: Authors



Source: Authors

Figure 10. Evolution of the percentage weights of each energy tariff between 2017 and the end of the first half of 2022 at the HEI



Source: Authors

Figure 11. Geometrical model of the HEI building, south view

- The color of the walls – The rooms on the fourth, fifth and sixth floors were repainted and the walls, instead of light cream, were changed to a semi-gloss white. The ceilings were also repainted.
- Indirect light – The classrooms on the first and second floors do not have direct light, but crown moldings whereas the room is illuminated by reflection on the classroom ceilings.
- Measurements with natural light component – Measurements made at 6:00 pm showed variations in the orientation and size of the classroom windows. Thus, we have different gains if the room is inner compared to rooms facing east, south or west.
- Furniture change – The furniture of the classrooms on Floors 4, 5 and 6 was changed from having tables and chairs in light and dark brown to white tables and chairs in white or light gray.
- On the first and second floors, the laboratories and inner rooms kept the cream color on the walls, only the ceilings were painted, so there was not such a sharp increase in LUX.

As the analyzed spaces are many, around 35 spaces of classrooms, laboratories, offices, library, study room, snack bar, etc., an aggregation by typology and orientation was chosen. The results of this aggregation are summarized in Table 7.

The results show economic gains that demonstrate, from a financial point of view, the advantages of making investments in environmental issues.

Theoretical contributions and practical implications

This study offers both theoretical and practical contributions on giving to HEIs their central role as innovators on sustainability, enhancing profound changes on human societies. Besides presenting data on adoption of LED technology by an HEI, contributions are made to resolving the situation of lack of sustainability models "built in" regarding HEIs. Example of an integrated sustainability plan is presented at the end of the manuscript, on Appendix Table A1 – The environmental sustainability plan (ESP) for the HEI. The dimensions of intervention toward sustainability are listed, along with ways of evaluating these dimensions, actions, along with improvements for both the environment and the institution and expected results concerning: lifelong education and formative offer; organization of scientific events with international impact; conducting scientific production/associated with scientific events; education |awareness/internal stakeholders; residue and plastics separation and treatment; energy sources and energy use.

A journey was carried out to include the presentation of data on the adoption of LED technology by the studied institution and its planned and phased application over the years, confirming through the presentation of consumption data and gains in luminosity the advantages of adopting environmentally friendly technology and the development of greener and more sustainable consumption scenarios in the long term.

More than presenting numerical data on consumption, a task of demonstrating the viability of the technology from the perspective of double benefit to the HEI and to the environment was carried out, exposing the savings on expenses in energy costs and inherently on any negative impacts that the technology used will have on the environment.

More than a merely economic option, technological innovation in the area of building lighting was framed within a social innovation approach, including these technological changes in a medium and long-term plan aimed at the theme of sustainability that involves training dimensions, that is, it involves all the dimensions of HEI management.

We show the possibility of finding a strategy that aims to be increasingly built-in into the HEI and that is not made up of scattered sectoral changes that are not brought together in comprehensive planning. In this way, we contribute to scientific production from a theoretical perspective and address the research gap that is now beginning to be overcome. Concrete data on the application of LED technology in buildings in the education sector was shown, while data on industrial and commercial facilities is what normally presented and addressed in scientific research.

Conclusions

A case of adoption of more environmental-friendly technology related to illumination – LED – on an HEI is presented. Obtained data on the period 2008–2022 goes toward a confirmation of

Orientation of classrooms in the building	Medium with discharge lighting (lumens per square meter)	Medium with LED lighting (lumens per square meter)	Improvement (%)
Classrooms facing east	291.7	2975.3	491
Classrooms facing west	400.7	1483.8	370
Classrooms facing south	557.9	2413.7	432
Inner rooms	267.1	692.6	259
Laboratories	489.8	1368.2	279

Source: Authors

Table 7.
Lighting improvements by space typology and orientation

the option for new illumination technology. Our aim was to context this technology innovation on a broader view about addressing sustainability in HEIs explaining an innovative approach on the institutional overall management system, planning and procedures.

Presenting descriptive data obtained within the context of one HEI about exemplifying mutual benefits for the institution and to the environment by recurring to LED technology reinforces the need of case comparison. Other institutional cases must be explored and presented, comparing data and also sharing results. The specific data obtained and presented must be associated only with the HEI studied, although some results can enhance followers of innovation not only centered in the use of LED technology but in all dimensions that are gathered in the organization management.

The analysis proceeded must be continued in the institution in following years, and control of some variables should be attended, such as those regarding to lux gain, or those related to the lighting circuits.

In future research of the case we present, there should be a demonstration of the clear details of environmental gains, in addition to the exploration of financial benefits of LED technology. Energy consumption can also be related to building occupancy, accurately considering the people inside the building. Specific data on the use of the building, floors details, rooms and number of people in the rooms must be related to variables such as external luminosity according to days and months of the year. As Motuzienė *et al.* (2022) point out, the impact of the confinements due to the Covid-19 pandemic should be considered in future developments in the presented study. The shown data is the possible data, for now.

The study made it possible to understand that the HEI should change the energy contract weekly, as it uses energy at the end of the week as if it were a working day when activities are only from 09:00 a.m. to 6:00 p.m., and there is almost no use of the facilities after dinner.

Although we must be cautious in generalization of results, the theoretical and practical contributions achieved can be referred to by other studies or cases in study. The obtained results allow the consolidation of the institution's ESP (Annex 1), in a short, medium, and long-term planning give to future researches and institutional managerial planning a perspective of the set of measures and actions that may result in environmental and sustainability improvements. The innovation that this study brings gives an integrated view on planned and implemented sustainability in the analyzed institution, setting an example to other institutions, namely, HEIs. The study presented solidifies a multidimensional approach of sustainability by the HEI, which connects the planning of permanent offered education to the closest stakeholders and the community in a broader approach.

The research question raised in the introduction to the manuscript was answered, demonstrating the financial benefits of applying environmentally friendly technology. More difficult to prove is the dual benefit concept, where benefits to the environment are only deducted.

Future research must relate to the longevity of the approaches suggested on the environmental sustainability plan, and provide a methodology of assessment of benefits, specifying also the impacts on the environment, not forgetting the pedagogical approach, and the social impacts of the overall activity of the institution. Basically, we can recommend a more and more built-in approach of sustainability in the HEI. Perhaps, we could name it: the sustainability of the sustainability approach by the HEI.

Notes

1. CIRCUTOR network analyzer CVM MINI-MC-ITF-RS485-C2.
2. EIA485 communication network.
3. Company that manages the energy distribution network in mainland Portugal. available at: https://balcaodigital.e-redes.pt/home
4. Consumption point: PT0002000110451972PH.
5. This student was working on his end project, entitled: energy audit and definition of the improvement plan.
6. www.e-redes.pt
7. Measurements are made using two models of lux meters allowing comparison of data obtained: BEHA 93408 Digital Lux Meter UNI-T UT 383 Mini Light Meter.

References

Abad-Segura, E., González-Zamar, M.-D., Infante-Moro, J. C. and Ruipérez García, G. (2020), "Sustainable management of digital transformation in higher education: global research trends", *Sustainability*, Vol. 12 No. 5, p. 2107, doi: 10.3390/su12052107.

Adhvaryu, A., Kala, N.E. and Nyshadham, A. (2020), "The light and the heat: productivity co-benefits of energy-saving technology", *The Review of Economics and Statistics*, Vol. 102 No. 4, pp. 779-792. doi: 10.1162/rest_a_00886.

Alimba, C.G.E. and Faggio, C. (2019), "Microplastics in the marine environment: current trends in environmental pollution and mechanisms of toxicological profile", *Environmental Toxicology and Pharmacology*, Vol. 68, pp. 61-74, doi: 10.1016/j.etap.2019.03.001.

Almeida, F. (2019a), "the contribution of the internet of things to the emergence of sustainable innovative cities»", *em Managing Sustainable Innovation*, Routledge, pp. 87-103.

Almeida, F., *et al.* (2019b), "Measuring innovation through a crowd source initiative", *International Journal of Innovation Science*, Vol. 11 No. 3, pp. 471-488, doi: 10.1108/ijis-04-2019-0046.

Almeida, F. (2021), "Open-innovation practices: diversity in Portuguese SMEs", *Journal of Open Innovation Technology Market and Complexity*, Vol. 7 No. 3, p. 169, doi: 10.3390/joitmc7030169.

Alnavis, N.B., Martono, D.N.E. and Hamzah, U.S. (2021), "Recommendations for improving the ISO 14001 certification based on the company's perception analysis of the certification obstacles and benefits", *Jurnal Kesehatan Lingkungan*, Vol. 13 No. 3, p. 132, doi: 10.20473/jkl.v13i3.2021.132-141.

Barska, A., Jędrzejczak-Gas, J., Wyrwa, J. and Kononowicz, K. (2020), "Multidimensional assessment of the social development of EU countries in the context of implementing the concept of sustainable development", *Sustainability*, Vol. 12 No. 18, p. 7821, doi: 10.3390/su12187821.

Bell, E., Harley, B. e. and Bryman, A. (2022), *Business Research Methods*, 6.a ed Oxford University Press, Londres.

Blanco-Portela, N., Benayas, J., Pertierra, L. R. and Lozano, R. (2017), "Towards the integration of sustainability in higher education institutions: a review of drivers of and barriers to organisational change and their comparison against those found of companies", *Journal of Cleaner Production*, Vol. 166, pp. 563-578, doi: 10.1016/j.jclepro.2017.07.252.

Bravi, L., Santos, G., Pagano, A. and Murmura, F. (2020), "Environmental management system according to ISO 14001:2015 as a driver to sustainable development", *Corporate Social Responsibility and Environmental Management*, Vol. 27 No. 6, pp. 2599-2614, doi: 10.1002/csr.1985.

Brundiers, K., Barth, M., Cebrián, G., Cohen, M., Diaz, L., Doucette-Remington, S., Dripps, W., Habron, G., Harré, N., Jarchow, M., Losch, K., Michel, J., Mochizuki, Y., Rieckmann, M., Parnell, R., Walker, P. and Zint, M. (2021), "Key competencies in sustainability in higher education—toward an agreed-upon reference framework", *Sustainability Science*, Vol. 16 No. 1, pp. 13-29, doi: 10.1007/s11625-020-00838-2.

De Guimarães, J.C.F., Severo, E.A., Felix Júnior, L.A., Da Costa, W.P.L.B. and Salmoria, F.T. (2020), "Governance and quality of life in smart cities: towards sustainable development goals", *Journal of Cleaner Production*, Vol. 253, p. 119926, doi: 10.1016/j.jclepro.2019.119926.

de Matos, A.T. (2020), *Poluição Ambiental: Impactos No Meio Físico*, Editora UFV, Viçosa, Brazil.

Fonseca, L.E. and Domingues, J. (2018), "Exploratory research of ISO 14001:2015 transition among Portuguese organizations", *Sustainability*, Vol. 10 No. 3, p. 781, doi: 10.3390/su10030781.

Gerarden, T.D., Newell, R.G.E. and Stavins, R.N. (2017), "Assessing the energy-efficiency gap", *Journal of Economic Literature*, Vol. 55 No. 4, pp. 1486-1525, doi: 10.1257/jel.20161360.

Gökgöz, F.E. and Güvercin, M.T. (2018), "Energy security and renewable energy efficiency in EU", *Renewable and Sustainable Energy Reviews*, Vol. 96, pp. 226-239, doi: 10.1016/j.rser.2018.07.046.

Grindsted, T.S. (2011), "Sustainable universities from declarations on sustainability in higher education to national law", *SSRN Electronic Journal*, doi: 10.2139/ssrn.2697465.

Harvey, L.D.D. (2018), *Global Warming*, Routledge, London.

Helepciuc, C.M., Serbanoiu, A.A.E. and Serbanoiu, B.V. (2018), "Concrete with thermal insulating properties-a double benefit in terms of money and environmental protection", *Advances in Environmental Sciences*, Vol. 10 No. 1, pp. 55-61.

Hill, M.K. (2020), *Understanding Environmental Pollution*, 4.a ed Cambridge University Press, Cambridge.

International Organization for Standardization (1996), *Environmental Management Systems-Specification with Guidance for Use*,

International Organization for Standardization (2014), *Environmental Management System: Requirements with Guidance for Use*.

Kasperson, J.X., *et al.* (2022), "Vulnerability to global environmental change», em the social contours of risk", pp. 245-285.

Kolosok, S., Pimonenko, T., Yevdokymova, A., Hajiyev, N. O., Palienko, M. and Prasol, L. (2020), "Energy efficiency policy: impact of green innovations", *Marketing and Management of Innovations*, No. 4, pp. 50-60, doi: 10.21272/mmi.2020.4-04.

Kuhre, W.L. (2018), *ISO 14001 Certification: Environmental Management System*, Prentice Hall, Hoboken, New Jersey, U.S.

Leal Filho, W., *et al.* (2015), *Putting Sustainable Development in Practice», em Sustainability in Higher Education*, Chandos publishing, Elsevier, pp. 1-19.

Manisalidis, I., *et al.* (2020), "Environmental and health impacts of air pollution: a review", *Frontiers in Public Health*, Vol. 8, doi: 10.3389/fpubh.2020.00014.

Meneghini, M., Tazzoli, A., Mura, G., Meneghesso, G. and Zanoni, E. (2010), "A review on the physical mechanisms that limit the reliability of GaN-based LEDs", *IEEE Transactions on Electron Devices*, Vol. 57 No. 1, pp. 108-118, doi: 10.1109/ted.2009.2033649.

Menon, S. and Suresh, M. (2020) "Synergizing education, research, campus operations, and community engagements towards sustainability in higher education: a literature review", *International Journal of Sustainability in Higher Education*, Vol. 21 No. 5, pp. 1015-1051. doi: 10.1108/ijshe-03-2020-0089.

Motuzienė, V., Bielskus, J., Lapinskienė, V., Rynkun, G. and Bernatavičienė, J. (2022), "Office buildings occupancy analysis and prediction associated with the impact of the COVID-19 pandemic", *Sustainable Cities and Society*, Vol. 77 No. 103557, p. 103557, doi: 10.1016/j.scs.2021.103557.

Neves, F. D O., Salgado, E.G.E. and Beijo, L.A. (2017), "Analysis of the environmental management system based on ISO 14001 on the American continent", *Journal of Environmental Management*, Vol. 199, pp. 251-262, doi: 10.1016/j.jenvman.2017.05.049.

Oláh, J., Kitukutha, N., Haddad, H., Pakurár, M., Máté, D. and Popp, J. (2018), "Achieving sustainable E-commerce in environmental, social and economic dimensions by taking possible trade-offs", *Sustainability*, Vol. 11 No. 1, p. 89, doi: 10.3390/su11010089.

Ramísio, P.J., Pinto, L.M.C., Gouveia, N., Costa, H. and Arezes, D. (2019), "Sustainability strategy in higher education institutions: lessons learned from a nine-year case study", *Journal of Cleaner Production*, Vol. 222, pp. 300-309, doi: 10.1016/j.jclepro.2019.02.257.

Randers, J., Rockström, J., Stoknes, P.E., Goluke, U., Collste, D., Cornell, S.E. and Donges, J. (2019), "Achieving the 17 sustainable development goals within 9 planetary boundaries", *Global Sustainability*, Vol. 2.

Ribeiro, A., Silva, C., Pinho, H. and Tchepel, O.(2022), "Análise da secção G. Mobilidade sustentável realizada pelo grupo de trabalho mobilidade sustentável, em", Madeira, A. C. (eds) *Primeiro Diagnóstico Sobre a Implementação da Sustentabilidade No Ensino Superior em Portugal. Resiultados de um Inquérito*, a Rede de Campus Sustentável, Porto Portgal, pp. 77-84, available at: https://repositorio-aberto.up.pt/bitstream/10216/148980/2/619773.pdf

Richter, J.L., Van Buskirk, R., Dalhammar, C. and Bennich, P. (2019), "Optimal durability in least life cycle cost methods: the case of LED lamps", *Energy Efficiency*, Vol. 12 No. 1, pp. 107-121, doi: 10.1007/s12053-018-9662-4.

Ruiz-Mallén, I.E. and Heras, M. (2020), "What sustainability? Higher education institutions' pathways to reach the agenda 2030 goals", *Sustainability*, Vol. 12 No. 4, p. 1290, doi: 10.3390/su12041290.

Sartor, M., Orzes, G., Touboulic, A., Culot, G., and Nassimbeni, G. (2019), "ISO 14001 standard: literature review and theory-based research agenda", *Quality Management Journal*, Vol. 26 No. 1, pp. 32-64, doi: 10.1080/10686967.2018.1542288.

Shi, L., Han, L., Yang, F. and Gao, L. (2019), "The evolution of sustainable development theory: types, goals, and research prospects", *Sustainability*, Vol. 11 No. 24, p. 7158, doi: 10.3390/su11247158.

Sun, H., Edziah, B.K., Sun, C. and Kporsu, A.K.(2019), "Institutional quality, green innovation and energy efficiency", *Energy Policy*, Vol. 135, p. 111002, doi: 10.1016/j.enpol.2019.111002.

Thürer, M., *et al.* (2018), "A systematic review of the literature on integrating sustainability into engineering curricula", *Journal of Cleaner Production*, Vol. 181, pp. 608-617, doi: 10.1016/j.jclepro.2017.12.130.

Weaver, P., Jansen, L., van Grootveld, G., van Spiegel, E. and Vergragt, P. (2017), *Sustainable Technology Development*, Routledge, London.

Wenlong, Z., *et al.* (2022),"Impact of energy efficiency, technology innovation, institutional quality, and trade openness on greenhouse gas emissions in ten Asian economies", *Environmental Science and Pollution Research*, Vol. 30 No. 15, pp. 43024-43039, doi: 10.1007/s11356-022-20079-3.

Wyrwa, J., Barska, A.E. and Jedrzejczak-Gas, J. (2021), "An indicator analysis for the development of EU countries in relation to sustainable development", *European Research Studies Journal*, Vol. 24 No. 3, pp. 918-933.

Zakari, A., *et al.* (2022), "Energy efficiency and sustainable development goals (SDGs)", *Energy (Oxford, England)*, Vol. 239, p. 122365, doi: 10.1016/j.energy.2021.122365.

Zhang, X., *et al.* (2020), "A review on the effects of light-emitting diode (LED) light on the nutrients of sprouts and microgreens", *Trends in food Science & Technology*, Vol. 99, pp. 203-216, doi: 10.1016/j.tifs.2020.02.031.

Further reading

Acharya, N.E. and Mukherjee, A. (2017), "The human factor in cyber security: issues, challenges and way forward", *International Journal of Advanced Computer Science and Applications*, Vol. 8 No. 1, pp. 389-396.

De Guadalupe Arras-Vota, A.-M. (2017), "Perceptions of ICT competencies among e-postgraduate students and faculty»", *Revista Latina De Comunicacion Social*, Vol. 72, pp. 1186-1204.

Integrated System for Physical Security in Food Industry (sem data) (2024), "Procedia engineering", 182, pp. 674-681.

Ji, S., Chen, J.E. and Ji, L. (2019), "Implementation of active directory based on Zentyal®", *Journal of Physics: Conference Series*, Vol. 1259 No. 1.

Kamata, K., Koide, T.E. and Kawanishi, K. (2017), "An approach to security enhanced OpenVPN implementation for remote access VPN", pp. 546-551.

Lourenço, J., *et al.* (2023), *Cybersecurity Concerns under COVID-19: Representations on Increasing Digital Literacy in Higher Education», em Perspectives and Trends in Education and Technology*, Springer Nature Singapore, Singapore, pp. 739-748.

Madeira, A.C., *et al.* (2022), "Primeiro diagnóstico sobre implementação da sustentabilidade nas instituições de ensino superior: análise dos resultados de um inquérito", Disponível em, available at: https://repositorioaberto.uab.pt/bitstream/10400.2/12971/1/InqIES_analise2022_VFinal%20copy.pdf

Mansouri, H.E. and Ajalloeian, R. (2018), "Mechanical behavior of salt rock under uniaxial compression and creep tests", *International Journal of Rock Mechanics and Mining Sciences (Oxford, England: 1997)*, Vol. 110, pp. 19-27, doi: 10.1016/j.ijrmms.2018.07.006.

Thakur, R.E. and Shukla, S.K. (2020), "implementation of virtualization technology in food processing unit: a case study", *Journal of Food Science and Technology*, Vol. 57 No. 3, pp. 915-921, doi: 10.1007/s13197-019-04087-2.

University of Melbourne (2023), "Melbourne university sustainability report 2022", University of Melbourne, available at: https://about.unimelb.edu.au/__data/assets/pdf_file/0019/391114/Sustainability-Report-2022.pdf (Acedido: 2 de outubro de 2023).

Corresponding author
José Carlos Pereira de Morais can be contacted at: jcpmorais@gmail.com

Appendix

Table A1.
The ESP for the HEI

ESP
According to the HEI's integrated management system integrating ISO on education organizations management, quality management and environmental management

Theme	Measure	Action	Improvements for the environment	Improvements for the institution	Results
Lifelong education/ Formative offer	Creation of a graduation courses related to the topic of "sustainability"	Implementation of the course "Tourism and sustainable business"	Integrated ecological approach on business	Education offer on innovating approaches on sustainability Visibility of the institution Enhancement of I&D on sustainability/innovation	Degree on tourism/ management on a broad approach considering sustainability Impact on/accordance to the labor market demands Offer of know-how on sustainability
	Creation of post-graduation courses related to the topic "sustainability"	Implementation of the post-graduate course "Management, Innovation and Digital Technology"	Integrated ecological approach on business	Education offer on innovating approaches on sustainability Visibility of the institution Enhancement of I&D on sustainability/ innovation	Offering formation on multidimensional sustainability
Organization of scientific events with international impact	Creation of a sustainability culture associated with the institution's internal and external image (sustainability present on internal and external communication)	Creation of a sustainability culture associated with the institution's internal and external image (sustainability present on internal and external communication)	Creation of a sustainability culture associated with the institution's internal and external image (sustainability present on internal and external communication)	Creation of a sustainability culture associated with the institution's internal and external image (sustainability present on internal and external communication)	Creation of a sustainability culture associated with the institution's internal and external image (sustainability present on internal and external communication)
Conducting scientific production/ associated with scientific events	Edition of books and scientific articles associated with the theme of sustainability/ innovation	Consistently increase the number of scientific publications associated in some way with the institution and its professors and researchers	Engage world-class publishers in the publication of books with manuscripts submitted to the events	Scientific visibility of the institution and its faculty, students and researchers	Publication of scientific articles in scientific journals such as *IJINS*, *Journal of Cleaner Production*; *EDAPECI*; etc. Publication of conference proceedings by Sprature, etc.

(*continued*)

Table A1.

ESP
According to the HEI's integrated management system integrating ISO on education organizations management, quality management and environmental management

Theme	Measure	Action	Improvements for the environment	Improvements for the institution	Results
		Associating research centers with the events	Involving scientific journals of high international impact with thematic and dedicated issues and reservation of a minimum number of articles to be published		
Education awareness/ internal stakeholders	Awareness-raising actions for students, teachers and staff	Invite institutions to hold annual lectures on environmental sustainability (QUERCUS, ZERO, etc.)	Increase awareness and behavior with potential changes in habits with gains for the environment, in reducing consumption of natural resources, waste reduction, etc.	Sense of mission of an educational institution, with potential gains in the reduction of plastics, paper and other environmentally harmful products	Perceptible, but not possible to measurable
	Lecturing sessions on sustainability (planning and practices) for students, teachers and staff	Invite specialists sustainability planning and practice to lecture according to planned sessions	Increase awareness and behavior with potential changes in habits with gains for the environment, in reducing consumption of natural resources, waste reduction, etc.	Sense of mission of an educational institution, with potential gains in the reduction of plastics, paper and other environmentally harmful products Compliance with sustainability ISO certification	Perceptible, but not possible to measurable
Water	Flow reducers	Adoption of efficient water management practices	Increase awareness and behavior with potential changes in habits with gains for the environment, in reducing consumption	Substantial reduction on water bills	Decrease in cubic meters consumption

(*continued*)

Table A1.

ESP
According to the HEI's integrated management system integrating ISO on education organizations management, quality management and environmental management

Theme	Measure	Action	Improvements for the environment	Improvements for the institution	Results
	Automatic faucets	Responsible use of this resource	Increase awareness and behavior with potential changes in habits with gains for the environment, in reducing consumption	Substantial reduction on water bills	Decrease in cubic meters water consumption
Paper	Digitalization of processes Digitalization of documents	Use of IT in document processing	Decrease in paper/tree consumption	Substantial reduction on paper bills and paper residues	Decrease on paper bills and amount of residue
Fossil fuel	Minimization of vehicle use	Minimization of vehicle use	Decrease in fossil fuel consumption	Substantial reduction on fuel use	Decrease in diesel/fuel consumption (liters)
Residue	Reduction, recycling and treatment of solid waste (plastics, electronics, hazardous waste) and others Specific containers for collection of light bulbs, batteries, etc. Partnerships with recycling waste companies	Containers/selective collection of waste Dispatch of obsolete electrical and electronic equipment for recycling	Minimize the impact on the environment by promoting the circular economy	Proper waste management and contribution to the circular economy	Decrease residue production Increase residue collection and recycling
Plastics	Reduction of use of single-use plastics	Increase collection and recycling of plastics Increase use of recycled plastic	Minimization of plastic waste	Use of recycle plastic and use of recycled plastic	Decrease of plastic waste

(continued)

Table A1.

ESP
According to the HEI's integrated management system integrating ISO on education organizations management, quality management and environmental management

Theme	Measure	Action	Improvements for the environment	Improvements for the institution	Results
Energy	LED lamps	Substitution of normal lamps by led lamps	More efficient and sustainable lighting	Substantial reduction on energy bills	Reduction of consumption by indirect evaluation because there is no measurement in the various lighting circuits
	Solar thermic panels	thermosiphon thermal solar panel and forced circulation thermal solar panel	Sanitary hot water without electricity consumption	Reduction in the cost of electricity consumption	100% gain in reducing energy bill
	Photovoltaic solar panels	24 photovoltaic panels for a total of 4,800 watt peak	Electricity production without oil, nuclear, gas or coal components	Reduction in the cost of electricity consumption	Placed at 75% Gains of xx per month on electricity bill Investment paid back in x years
	Luminosity sensors	Implementation of automatic on/off control in bathroom lighting without external light	Reduction of consumption waste	Reduction in energy consumption costs	Residual compared to the global power of the lighting circuits

Source: Authors

More info

UTM
UNIVERSITI TEKNOLOGI MALAYSIA
UTM Library

SDi@JPUTM
SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
2) Transforming document management for environmental sustainability: the mediating effect of pro-environmental culture and service satisfaction in higher education institutions (2025)	SUSTAINABILITY (Article From : FRONTIERS)

27th FEBRUARY 2025
SOURCE: PERPUSTAKAAN UTM

frontiers | Frontiers in Sustainability

TYPE Original Research
PUBLISHED 08 January 2025
DOI 10.3389/frsus.2024.1479927

OPEN ACCESS

EDITED BY
Zeeshan Ahmad,
Chinese Academy of Sciences (CAS), China

REVIEWED BY
Hamad Raza,
Government College University, Faisalabad, Pakistan
Teresa Nogueiro,
University of Evora, Portugal

*CORRESPONDENCE
Jessie Bravo
jbravo@unprg.edu.pe

RECEIVED 13 August 2024
ACCEPTED 26 December 2024
PUBLISHED 08 January 2025

CITATION
Bravo J, Valdivia C, Alarcón R, Germán N, Serquén O, Aquino J, Arbulú Ballesteros MA and Guevara L (2025) Transforming document management for environmental sustainability: the mediating effect of pro-environmental culture and service satisfaction in higher education institutions.
Front. Sustain. 5:1479927.
doi: 10.3389/frsus.2024.1479927

Transforming document management for environmental sustainability: the mediating effect of pro-environmental culture and service satisfaction in higher education institutions

Jessie Bravo[1]*, Carlos Valdivia[1], Roger Alarcón[1], Nilton Germán[1], Oscar Serquén[1], Janet Aquino[1], Marco Agustín Arbulú Ballesteros[2] and Laurita Guevara[3]

[1]Digital Transformation Research Group, Pedro Ruiz Gallo National University, Lambayeque, Peru, [2]Institute for Research in Science and Technology, Cesar Vallejo University, Trujillo, Peru, [3]Academic Program of Computer Engineering and Informatics, Pedro Ruiz Gallo National University, Lambayeque, Peru

This research investigates the factors influencing environmental sustainability in a Peruvian higher education institution (HEI), using Structural Equation Modeling (SEM) with SmartPLS. The methodology included data collection through questionnaires administered to students, alumni, and professors, followed by SEM analysis to assess the relationships between technological support (TS), document management (DM), open government (OG), pro-environmental organizational culture (POC), service satisfaction (SS), and environmental sustainability (ES). The findings emphasize that technological infrastructure significantly enhances document management, which in turn boosts service satisfaction and promotes a pro-environmental organizational culture. The pro-environmental organizational culture emerges as the most powerful mediator, significantly impacting environmental sustainability. Although service satisfaction also contributes positively, its effect is less pronounced. Furthermore, transparency and open access to information improve document management, albeit with a lesser impact. Sociodemographic variables such as gender and academic program within the institution influence the relationship between the examined variables, suggesting that these characteristics can affect the perception and effectiveness of sustainability practices. This study provides a robust foundation for designing effective strategies to promote environmental sustainability in higher education institutions and would contribute to the fulfillment of the SDGs.

KEYWORDS

document management, environmental sustainability, pro-environmental organizational culture, higher education institution, service satisfaction, SEM

1 Introduction

Documents are the most crucial assets of any organization; therefore, understanding how to properly maintain a paper trail can significantly impact the efficiency of its management (Reyes et al., 2023), conversely, document management represents a major issue for higher education institutions. According to Regla and Marquez (2020) extensive storage spaces, filing cabinets, and necessary security measures are required, Sheela Rani et al. (2023) indicate that records, time, and energy are lost, and resources are squandered, with the main challenge being the upkeep of records and the failure to meet deadlines for obtaining information. In most higher education institutions (HEIs), there are no academic document management systems (DMS) nor are the necessary technologies for their development identified (Hüller et al., 2022). Added to this, other issues of document management (DM) include the quality of managerial staff, the significance of the work, the funding, and the information, which directly affect the administration of archives and documents overall (Sun, 2022).

Moreover, the continuous enhancement of education with various approaches and reforms has led to a substantial number of educational policies, programs, and research reports, which also increases the processing and information load for HEIs, also, traditional methods of classification and manual filing are ineffective and vulnerable to the loss of documentation and inefficiency in DM processes (Zhang et al., 2024), Additionally, many offices use a hierarchy of folders on computers to organize documents and the use of labels to sort them, which is currently not an efficient process due to the vast amount of documentation generated (Watanabe et al., 2024). Similarly, when it comes to collecting information managed traditionally, it becomes an isolated process due to the lack of communication between different types of stored data and even incomplete documentation (Korro et al., 2024). HEIs also face the maintenance of their documents and records, where records, time, and resources are lost, not meeting the search for documents (Sheela Rani et al., 2023).

Industrial advancement has led to economic progress and societal well-being, but the impact of industrial complexes has altered the environment, causing environmental effects and climate changes (Barragán-Ocaña et al., 2024). The growing awareness of environmental challenges, resource scarcity, and the urgent need to address climate change necessitate paradigm shifts in product and service design (Lyu et al., 2024). Increasingly, companies are seeking to enhance their operational performance and paying more attention to sustainability issues, leading to practices that improve sustainability performance and, specifically, environmental impacts (Fiorello et al., 2023). Companies are even beginning to discuss a "green paradigm," seeking the integration of Industry 4.0 technologies and management model principles that enhance precision, customization, competitiveness, and environmental sustainability (Costa et al., 2024), This fosters green product innovation as a key strategic issue in companies.

In universities, energy usage is a critical issue, as the aim is to balance growing operational demands with ES (Laporte et al., 2024). Additionally, it must be considered that HEIs have a significant impact on the society and environment in which they operate, influencing various fields of development, including ES, and contributing with their social role in the education of future generations (Usta et al., 2024). However, many HEIs place significant emphasis on integrating ES at a strategic level, but generally lack policies that incorporate it into operational aspects (Christou et al., 2024).

Nevertheless, the environmental implications remain relatively unknown, and there is no substantial literature addressing the elements of this research. Therefore, this article offers an analysis of DM in HEIs, evaluating the level of organizational culture and service satisfaction present as a mediating effect on environmental sustainability. This will identify the needs for "paperless" management, the use of digital environments, and enhancing operational efficiency by adopting new digital practices framed in Digital Transformation (DT), understood as the process by which HEIs integrate digital technology to all its areas, which will allow cultural and operational changes that are better adapted to the changing needs of users, thus improving the perception of its benefits by users.

The aim of this research is to use Structural Equation Modeling (SEM) to assess the mediation of organizational culture and service satisfaction between document management and environmental sustainability, whose findings will define environmental strategies and policies in HEIs.

The significance of this study lies in its potential to generate valuable knowledge that enables HEIs to foster a cultural change that promotes the commitment and active involvement of various stakeholders, raising awareness of ES, developing pro-environmental policies, and incorporating them into curricular experiences. This is supported by efficient DM based on effective strategies that reduce the environmental footprint, aligned with sustainability principles, under a "paperless" approach, using digital environments and optimizing operational processes. This will lead to tangible benefits such as reduced paper usage, savings in natural resources, and contributing to the education of professionals and citizens aware of the importance of environmental preservation.

2 Theoretical framework

2.1 Document management in organizations

DM and archiving are critical responsibilities in any organization, as they must ensure the access, upkeep, preservation, and oversight of pertinent information. The ISO 30300 standard offers a framework that sets forth guidelines for the enhancement of DMS in organizations (Manzanelli, 2023). Similarly, in DM, best practices need to be established for the creation and maintenance of information and documentation, which enables decision-making, activities, and operations within the organization, easing its use in business procedures and at every level of the organization (Alonso, 2020).

In the context of HEIs, Hüller et al. (2022) observe that these institutions retain vital academic and administrative data that must be safeguarded. However, many of them still lack the required technology to implement effective DM. According to Mulchan and Wang (2024) digital transformation is progressing rapidly, with the widespread presence of digital technologies and technology-driven innovations transforming organizational processes, where one of the principal initiatives is to enhance record and document management to boost productivity.

In a study by Simwaka et al. (2023) at universities in Malawi, a survey uncovered the presence of document records such as minutes, grades, theses, political documents, and reports, but there was an absence of management of such documentation due to, among other factors, a lack of management policies, limited financing, and information technology infrastructure. On the other hand, Henriksen (2023) examined the impact of user-focused digitalization on record management in the public sector in Norway. Through interviews, it was discovered that municipalities lack resources and technologies and do not engage their users, despite their professionals attempts to assist them. Likewise, according to Mosweu and Bwalya (2023), government entities frequently implement automated record management systems without a clear governance structure to support automation.

2.2 The role of technological support in document management efficiency

Over the past decades, the role of technological support (TS) has been a significant concern in research. The acceptance and application of innovations in information systems (IS) and information technology (IT) have been evaluated through theoretical frameworks examining their acceptance (Dwivedi et al., 2019). Among these frameworks, the Unified Theory of Acceptance and Use of Technology (UTAUT) stands out, proposing that actual technology utilization is driven by behavioral intention. This theory suggests that technology adoption hinges on performance expectations, effort expectations, social influence, and facilitating conditions, with individual perceptions of technology being crucial for enhancing job performance (Marikyan and Papagiannidis, 2023).

Recent advancements in technologies are affecting document and record management worldwide. Key elements of the Fourth Industrial Revolution, such as blockchain technology and artificial intelligence (AI), are shaping how digital records are administered within organizations (Ngoepe et al., 2024). In Tsabedze (2024) study, viewpoints and readiness of professionals for records and archives management were assessed through a survey, revealing insufficient experience and budget constraints for acquiring technology. Therefore, improved funding and AI integration into DM are suggested.

In the context of HEIs, this swift technological progress has introduced innovative methods for safeguarding crucial student data (Dongre et al., 2024). Similarly, Reyes et al. (2023) identify documents as the most valuable assets in a university, so maintaining paper trails greatly impacts DM efficiency. Consequently, technological platforms and IT systems have been developed to organize and centralize their files.

Various studies, such as those by Ayaz and Yanartaş (2020), have examined UTAUT, concluding that technological support is essential for the acceptance and effective use of systems, positively affecting document management. Additionally, Alghobiri et al. (2022) demonstrated that advanced technologies in HEIs, such as optimization with graph-based document clustering algorithms and distance functions, enhance document retrieval. Sidhimantra et al. (2024) indicate that repository system development improves academic document management and supports accreditation processes in HEIs. Karpenko et al. (2020) note that these systems also contribute to the effectiveness of academic workload distribution, and (Chen et al., 2022) assert that the adoption of technologies like blockchain enhances the security and efficiency of the entire DM process.

The reviewed studies provide consistent evidence of the positive effect of technological support on DM. Although various approaches and technologies are utilized, all studies conclude that technological support is fundamental for the automation, security, and accessibility of DM, directly impacting efficiency in HEIs.

Finally, the role of technological support represents an opportunity to boost the efficiency of DM processes. Therefore, the following hypothesis is proposed:

> *Hypothesis* 1: Technological support has a significant impact on effective document management in HEIs.

2.3 Impact of efficient document management on user satisfaction in HEIs

As Alonso (2020) highlights, DM establishes best practices for the generation and maintenance of information and records, facilitating appropriate decision-making. According to Gamido et al. (2023), the procedure of an electronic DMS starts with the transformation of paper documents into digital files with standardized formats, enabling effective document organization and encouraging the reduction of paper waste in document reproduction. It also enhances user access to essential documents distributed in real-time, with simple searches and retrieval of necessary records.

According to Alade (2023), one sector that has seen rapid expansion in recent years is document management, regarded as essential in the organizational work environment. For this reason, a web-based electronic DMS was developed, which, when utilized, achieved a 96.60% satisfaction rate among participants, concluding that it enhances user satisfaction, boosts productivity, and ensures data efficiency in a timely manner.

In Peru, according to Ramirez et al. (2023), public institutions have a substandard service in DM. To tackle this, robotic process automation (RPA) technology was implemented, reducing the processing time of procedures, preventing citizen dissatisfaction, and improving their experience.

DT is acknowledged as a phenomenon that has drastically changed how organizations function. The emergence of digital technologies in the public sector presents multiple possibilities, where user satisfaction is deemed one of the most critical conditions for effective DT implementation (Kitsios and Ioannou, 2024). DMS are a necessity in the organizational work environment and specifically in HEIs because they facilitate access to documents in shortened times (Alade, 2023) and must have secure and interoperable management of crucial and legal documents (Siva Rama Rao et al., 2023), both for university faculty with documentation related to their academic duties (educational, methodological, scientific, and organizational) (Pleskach et al., 2023), and for general document procedures. Therefore, this service satisfaction regarding digital document management could generate positive user attitudes toward sustainable practices, facilitating their adoption and maintenance.

Based on the reviewed literature, the following hypothesis is proposed:

> *Hypothesis* 2: Efficient document management positively influences service satisfaction in HEIs.

2.4 User satisfaction as a driving factor for environmental sustainability in HEIs

User satisfaction as a driving force for environmental sustainability in HEIs is based on the notion that when the services provided meet user expectations, users develop affirmative behaviors and attitudes toward the institution, which results in greater commitments to sustainable practices.

In the study by Mansoor and Hussain (2024) on the impact of knowledge-based leadership on service quality in HEIs, it was shown that effective and user-centered management can significantly influence service quality, which in turn promotes a more sustainable environment conducive to pro-environmental practices. Similarly, Rolo et al. (2024), concerning service quality in HEIs in Portugal and Angola, emphasize the importance of adjusting service quality strategies to local needs and expectations. In the context of environmental sustainability, this suggests that HEIs should consider user specifics to implement sustainable practices perceived positively. Likewise, Kidido et al. (2024), on the management and sustainability of event facilities in HEIs in Ghana, also discovered that user perception of facility management can affect their satisfaction and, consequently, their support for sustainable resource practices.

The research by Bao et al. (2024) on the assessment of sustainable service quality in HEIs emphasizes the importance of considering the varied opinions and expectations of users in the decision-making process. HEIs can design and adjust their services to better meet user needs, incorporating sustainable practices that are valued by the educational community. On the other hand, Alshamsi et al. (2024) examine the factors driving the sustainability of blockchain technology in higher education, underscoring that its implementation largely depends on user acceptance and satisfaction, concluding that well-received technology can contribute to more sustainable practices in HEIs.

As stated by Ozdemir et al. (2020), measuring sustainable service quality on university campuses includes dimensions such as waste management, energy efficiency, and community participation, highlighting a holistic approach to campus sustainability. Santos et al. (2020) explore the influence of social responsibility on service quality and student satisfaction in higher education, concluding that when universities implement socially responsible practices, such as volunteer programs and environmental sustainability, they tend to have more satisfied and committed students.

These studies underscore that service satisfaction in HEIs is closely linked to environmental sustainability. By focusing on user satisfaction, positive cycles are created where satisfaction and sustainability reinforce each other. Therefore, the following hypothesis is proposed:

> *Hypothesis* 3: Service satisfaction has a positive impact on environmental sustainability in HEIs.

2.5 Promoting a pro-environmental organizational culture through efficient document management

According to Nanayakkara and Wilkinson (2021), organizational culture (OC) theory is one of the most influential in the workplace because if an organization does not maintain a suitable culture to support its activities, it could adversely impact its procedures and overall performance. Additionally, Sindakis et al. (2024), the adoption and transfer of culture are achieved through the sharing of knowledge within and between areas, departments, and units of large organizations. Additionally, as Schlegel et al. (2023) emphasize in the context of DT, having a data-based OC is a crucial factor in data analysis capabilities, innovation, and competitive advantages for companies.

Based on the study by Souza and Aganette (2022), digital preservation and efficient DM are closely associated with POC, arguing that implementing efficient document management practices can positively impact organizational culture, promoting sustainable and pro-environmental practices. Similarly, Netshakhuma (2022) demonstrated that using the SharePoint platform as a DMS in a university not only enhances administrative efficiency but also supports the development of a sustainability-oriented OC.

The reviewed studies provide evidence that efficient DM can be a key driver in fostering an organizational culture dedicated to environmental sustainability in HEIs, therefore proposing the following hypothesis:

> *Hypothesis* 4: Efficient document management promotes a pro-environmental organizational culture in HEIs.

2.6 Influence of pro-environmental organizational culture on achieving sustainability in HEIs

Various studies have indicated that an organizational culture that fosters pro-environmental values and behaviors can significantly affect the environmental sustainability of HEIs. Kalsoom and Hasan (2022) stress that a POC can transform educational and administrative practices in HEIs. Additionally, Dieguez (2023) underscores the importance of leadership as part of the organizational culture in the sustainability of higher education, promoting educational transformation and enhancing the entrepreneurial and innovative spirit necessary to implement sustainable practices in HEIs.

As proposed by Khan and Terason (2022) fostering pro-environmental behaviors through a green organizational culture can encourage sustainable attitudes among the employees of an institution. Barros et al. (2020) illustrate in a Brazilian university that an organizational culture centered on sustainability leads to the development of sustainable practices and greater environmental awareness. Moreover, Žalėnienė and Pereira (2021) suggest that global integration allows universities with this pro-environmental culture to serve as global models that incorporate sustainability into all facets of university life.

According to Fuchs et al. (2023), an organizational culture dedicated to sustainability is crucial for the success of Sustainable Development Goals (SDG) initiatives in Latin American universities. Marques et al. (2023) contend that an organizational culture that values sustainability can facilitate cooperation between universities and businesses, promoting a positive impact on environmental sustainability.

These theories and studies provide insights into organizational culture and its role in advancing environmental sustainability in HEIs; therefore, the following hypothesis is proposed:

> *Hypothesis* 5: A pro-environmental organizational culture positively influences environmental sustainability in HEIs.

2.7 Open government and transparency as enablers of effective document management

Digital technologies have a recognized potential to create more efficient, trustworthy, and innovative public institutions (Aguerre and Bonina, 2024). Government open data are crucial drivers of DT in the public sector, as they allow for insight into how strategies are formulated, executed, and assessed for their ongoing success, aiming to encourage users to engage with and make use of these essential resources (Begany and Gil-Garcia, 2024). However, it is necessary to have governance structures that support the integration of technologies across various platforms and adapt to an increasingly digital society (Zwitter, 2024). This facilitates the development and interpretation of data visualizations that simplify information access, enhance comprehension, and bolster information literacy (Barcellos et al., 2024), this term has gained significant relevance in the digital era, marked by the abundance of information and the rapid evolution of information and communication technologies.

A study in Spain, one of the most decentralized nations globally (Curto-Rodríguez et al., 2024), discovered that open government has a favorable outlook and a promising future despite challenges such as resistance to change. Pasillas-Banda et al. (2024) in Mexico observed that there are advancements in governance through open government with the application of technologies in diverse media, emphasizing citizen engagement. Similarly, in Chilean municipalities (Hernández-Bonivento and Moller, 2024) state transparency is being promoted by involving citizens in public affairs and encouraging public accountability, which leads to insights on social and political participation, poverty levels, and information dissemination.

According to Saptarini et al. (2024), a result of the pandemic, particularly in online education, was the necessity for paperless document management, which offers benefits such as cost reduction, time efficiency, decreased physical storage needs, and access to documents anytime and anywhere. However, resistance to change, lack of technical expertise, and investment costs could hinder its implementation.

As part of the DT, Gelashvili and Pappel (2021) argue that a key component of e-governance is paperless management, which streamlines data exchange and digitized workflows, allowing for secure document recording, traceability, and immutable archiving for future access. Additionally, it is essential to complement these practices with DM policies based on technologies, tailored to each HEI's conditions, regulatory framework, and the readiness of its experts (Jiménez et al., 2022). Payment for services in DMS processes should also be considered (Glavev, 2023). However, as Ioannou et al. (2022) point out, the effectiveness of these e-government initiatives faces hurdles due to insufficient specialized knowledge, limited funding, and weak political initiatives and decisions, often resulting in flawed designs that merely transfer existing bureaucracy into the digital sphere. In Peru, the Digital Government law regulation (Decreto Supremo No 029-2021-PCM, 2021) seeks to promote the integration of digital technologies in public services, encompassing digital identity, interoperability, security, and digital architecture. Nevertheless, in practice, its application is very limited, considering that many HEIs do not even use digital signatures or have proposed automation of the processes involved in DM.

These findings underscore the significance of open government and transparency as fundamental contributions to document management, leading to the following proposal:

> *Hypothesis* 6: Open government and transparency have a substantial impact on effective document management in HEIs.

2.8 Document management as a catalyst for environmental sustainability in higher education institutions

Environmental sustainability (ES) is presently a crucial element for both economic progress and human well-being. Environmental deterioration is alarming, leading nations and global organizations to conduct conferences and agreements (Luo and Sun, 2024). It should be acknowledged that the environmental crisis is the outcome of industrial, economic, and social development, which has adversely affected the planet's ecosystem (Cóndor-Salvatierra et al., 2022). Similarly, the evolution and utilization of information and communication technologies (ICT) have brought growing prosperity and accessible information globally. Nevertheless, this advancement has not been devoid of notable environmental costs that jeopardize environmental sustainability, such as electronic waste that contaminates soil and water, releasing hazardous substances that endanger human health and biodiversity. As Tkachenko and Denisova (2022) propose, the intricate connection between digitalization, sustainability, and profitability has not garnered much focus from the academic community; however, it represents significant research domains on its own.

HEIs not only prepare professionals and future leaders but also need to heighten awareness about environmental preservation and directly influence communities to adopt sustainable practices (Karalam and Mathew, 2023). Furthermore, there is increasing concern about involving HEIs in an international effort to assume a more fitting role as champions of sustainable development (Pereira de Morais et al., 2024). This necessitates beginning with curricular incorporation of environmental sustainability viewpoints, as many countries' educational systems are limited by rigid disciplinary frameworks and do not encourage transdisciplinary perspectives, which could address environmental concerns and the need for their protection. This is supported by Vidrevich and Pervukhina (2023), who highlight the significance of embedding environmental sustainability into HEI curricula and the necessity for educators to adopt teaching methods aligned with these integrative principles. Moreover, the United Nations Sustainable Development Goals (SDGs) have prompted substantial shifts in environmental education, making it vital to reform educational research and classroom methodologies (Guevara-Herrero et al., 2023), to cultivate critical individuals and professionals with initiatives aimed at fostering a more sustainable, inclusive, and resilient world.

As Dongre et al. (2024) suggest, universities manage vital student data that must be safeguarded and protected. Consequently, they should adopt innovative strategies as a crucial step toward a sustainable future, where digitalization will play an essential role in necessary technological transformations. From the viewpoint of Alnafrah and Mouselli (2021) HEIs in low-income nations tend to be delicate and responsive to the political and economic climates in which they operate, influencing the costs of obtaining and certifying credentials for students. Hence, a hybrid national platform based on blockchain was proposed to consolidate academic record management, advancing sustainable development.

Therefore, based on the examined documentary approaches, the following hypothesis is proposed:

Hypothesis 7: Effective document management contributes to environmental sustainability in HEIs.

The following mediator hypotheses are also defined:

Hypothesis 8: Service satisfaction will mediate the connection between effective document management and environmental sustainability in HEIs, acting as a catalyst that amplifies the positive effect of document management on environmental sustainability.

Hypothesis 9: Pro-environmental organizational culture will mediate the link between effective document management and environmental sustainability in HEIs, facilitating and enhancing the beneficial impact of document management on environmental sustainability.

Next, in Figure 1, a conceptual framework is presented as a graphic design, which offers a visual understanding of the variables and their theoretical basis, as well as the hypothesis proposal where the variables involved are related. This conceptual framework allows an easy interpretation of the SEM model that will be applied, allowing an understanding of each variable in the structure of the study, without the need to have a technical background in this type of analysis.

3 Materials and methods

The investigation used a quantitative method and applied a non-experimental design. This method involved creating survey tools through an exhaustive review of existing literature, including scholarly articles and regulations.

Considering this, a questionnaire was created and administered to users of document management, such as students, alumni, and faculty members. The questionnaire aimed to assess the effectiveness of document management toward environmental sustainability within the context of a pro-environmental organizational culture and service satisfaction.

3.1 Participants

The study was applied to a population of 2,000 individuals, considering a sample of 247 participants, distributed among students, graduates and teachers of a Peruvian HEI. The inclusion criteria were higher education students, appointed teachers and graduates of the last 3 years.

A non-probabilistic convenience sampling was applied, considering only one faculty in the study, with participation being voluntary through informed consent.

The justification for the sampling method lies exclusively in the constraints of resources and time. By applying this type of sampling, our sample is diverse within the area of study, thus ensuring reliable outcomes. The applied method provided us with an initial approach to generate valuable insights on the effectiveness of document management among the different actors of the institution.

The participants come from five professional schools at a public university, offering a rich and varied depiction of the educational community. More than half belong to the Computer Engineering and Informatics program, highlighting a strong interest in how

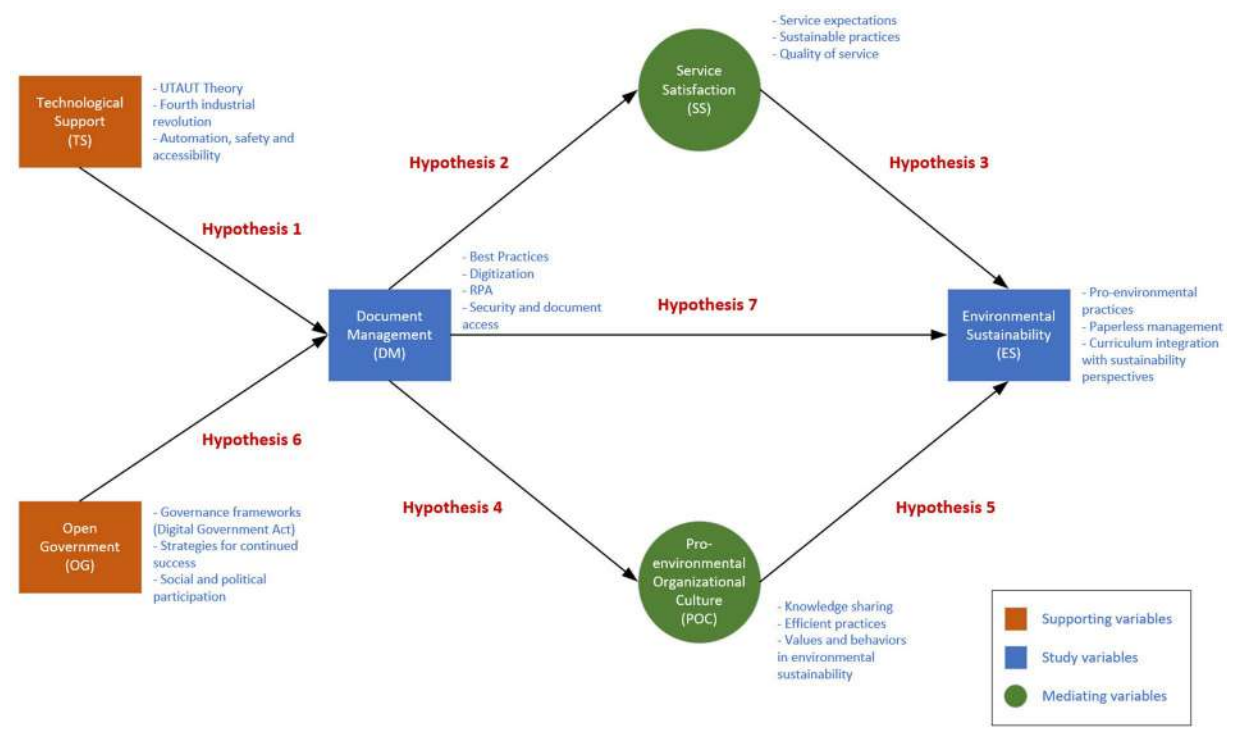


FIGURE 1
Conceptual framework of the study.

technologies can support environmental sustainability. Although fewer in number, students from Statistics, Electronic Engineering, Mathematics, and Physics also contribute valuable perspectives and are directly related to the population in each school.

Regarding roles, 51.4% are students, 34.8% are alumni, and 13.8% are faculty members. This indicates that most participants are still in their educational process or have recently completed their studies, thus providing current opinions on DM and sustainability. The age range of the participants shows that almost half (46.2%) are between 23 and 30 years old, something expected in a university setting. However, there is also a notable representation of people of different ages, which enriches the intergenerational perspective of the study. In terms of gender, the majority of participants are men (78.1%) compared to 21.9% women. This difference suggests possible trends in enrollment in certain programs or specific roles within the institution, which is important to consider when interpreting the results.

The way participants obtain information about the status of their administrative procedures reflects a preference for multiple communication channels. Most prefer email (28.7%) and face-to-face interaction (20.6%), although some combine both methods (15.4%) or use information systems and applications like WhatsApp to a lesser extent. This variety emphasizes the need to offer flexible communication tailored to individual preferences. Table 1 presents the sociodemographic data of the surveyed sample.

Finally, it is indicated that all participants in the study possess experience and expertise in the document management process within the institution.

3.2 Instruments

Based on the identification of theoretical constructs and literature review, the instrument was created, comprising 27 items using a 5-option Likert scale, where 1 means not satisfied or not fulfilled, and 5 means completely satisfied or its fulfillment is total and adequate.

For the instrument, six variables were established: **service satisfaction** with four items where the service and attention are rated, as well as the average response time and the level of staff training are assessed; **document management** with five items focused on dissemination mechanisms, clarity of procedures, support, and advice (Jiménez et al., 2022; Zambrano Plúa et al., 2021); **technological support** with three items covering the level of automation and the tracking of procedures (Kholiya et al., 2021; Monarcha-Matlak, 2021); **open government and transparency** with three items oriented to the awareness of the transparency portal and the data published on it (Vidrevich and Pervukhina, 2023); **pro-environmental organizational culture** with eight items oriented toward training, policies, initiatives, programs, and participation in activities (Ioannou et al., 2022) and finally, **environmental sustainability** with five items addressing environmental aspects and their sustainability (Gestión Documental y Sostenibilidad: Reduciendo el Impacto Ambiental, 2023).

The survey was consolidated into an online form for its application, adding sociodemographic questions such as age range, gender, academic program, role, and how they know the status of their procedure. Additionally, three open-ended questions were added for subsequent analysis.

3.3 Validation of instruments

A pilot test was conducted with a small group of 10 participants to ensure the clarity and validity of the questions. Based on the feedback received, minor adjustments were made to the questionnaires.

Cronbach's alpha coefficient and composite reliability with values above 0.7 were used (Table 2). Additionally, the square root of the average variance extracted (AVE) was applied for each of the variables, ensuring that their values are not higher than the correlations among all variables with values above 0.5.

3.4 Reliability and validity analysis of the evaluated variables

In this study, variables such as service satisfaction, document management, technological support, open government and transparency, as well as pro-environmental organizational culture and environmental sustainability were evaluated. Below is an analysis of the reliability and validity of these factors, aiming to provide a clear and accessible overview. To begin, service satisfaction (SS) was assessed through questions about the overall service rating, the attention received, response time, and the level of staff training. The results indicate that the questions used were very consistent with each other, reflecting a high Cronbach's alpha value (0.939). Furthermore, it is observed that perceptions of these facets are strongly interrelated, suggesting that SS is being effectively measured. Regarding document management (DM), aspects such as the effectiveness of procedure dissemination, clarity of instructions, staff support, information accessibility, and data privacy were analyzed. A high internal consistency was also found (Cronbach's alpha of 0.915), meaning the questions align well to measure DM. However, a question on data privacy had a slightly lower correlation with the rest, suggesting that this question could be refined to ensure it measures the same as the others. Technological support (TS) focused on process automation, information security, and procedure tracking. The results show that the questions were consistent and reliable (Cronbach's alpha of 0.879), indicating that participants view these elements as interconnected aspects of TS. This underscores the importance of technology in the efficient management of procedures. The open government and transparency (OG) variable was evaluated through questions about awareness and updates of the transparency portal, as well as deadline compliance. Again, the responses showed high consistency (Cronbach's alpha of 0.886), indicating that these questions well capture the perception of transparency in the university. Regarding pro-environmental organizational culture (POC), the questions covered topics from sustainability training to the perception of organizational values and participation in environmental activities. This variable showed excellent consistency (Cronbach's alpha of 0.937), although a question about sustainability as a core value had a lower correlation. This suggests that while most questions are well-aligned, some could be adjusted to improve the set's cohesion. Finally, environmental sustainability (ES) was evaluated through questions about investment in sustainable technologies, the use of renewable inputs, the promotion of sustainability in curricula, and sustainable printing practices. The responses also showed high consistency (Cronbach's alpha of 0.923), reinforcing the validity of the questions to measure ES in the university. The variables evaluated in this study

TABLE 1 Sociodemographic profile of the sample (n = 247).

Sociodemographic	Category	Frequency	%
Academic program	Statistics	47	19.00%
	Physical	8	3.20%
	Electronic Engineering	37	15.00%
	Computer and Informatics Engineering	127	51.40%
	Math	28	11.30%
Role	teacher	34	13.80%
	Graduate	86	34.80%
	Student	127	51.40%
Age range to which they belong	Up to 19	28	11.30%
	20–22	37	15.00%
	23–30	114	46.20%
	31–40	26	10.50%
	41–55	12	4.90%
	46–50	7	2.80%
	Over 50	23	9.30%
Gender	Female	54	21.90%
	Male	193	78.10%
How do you know about the status of your procedures? (You can select more than one option)	By mail	71	28.70%
	In person	51	20.60%
	By mail, in person	38	15.40%
	Computer system	14	5.70%
	By mail, By WhatsApp	12	4.90%
	By mail, Computer System	11	4.50%
	By WhatsApp	11	4.50%
	By mail, in person, computer system	10	4.00%
	Statistics	29	11.70%

present high reliability and validity. This means that the questions used are consistent and well capture the perceptions and attitudes of the participants.

3.5 Data collection and analysis method

Information was gathered through an online survey administered to various participants. The study was conducted between April and May 2024, spanning 5 weeks. An online questionnaire was distributed containing nine sections: the first included information about the survey and informed consent; the second section contained general user details; sections 3 to 8 corresponded to the six variables analyzed; and finally, section 9 included open-ended questions. A total of 247 responses were collected from participants.

3.6 Quantitative analysis

Descriptive statistics were used to summarize the survey results. Structural Equation Modeling (SEM) (Ávila and Moreno, 2018; Escobedo et al., 2016) was utilized to examine the relationships among pro-environmental organizational culture, service satisfaction, the effectiveness of document management, and environmental sustainability. SEM allowed for the concurrent evaluation of multiple dependent and independent relationships, measuring both observable and latent variables (Romero-Sánchez and Barrios, 2023).

The SEM approach overcomes the limitations of traditional methods such as those of Baron & Kenny and Andrew Hayes by integrating mediation and moderation analyses into a unified model, which facilitates the evaluation of direct, indirect and conditional effects in a robust manner. This approach was key to our study to capture the complex interactions between the dimensions analyzed and provide more generalizable results.

The software SmartPLS-v4 educational version (Ávila and Moreno, 2018) was used to assess the theoretical model based on partial least squares (PLS) methods using structural equation models.

3.7 Structural equation modeling (SEM)

SEM is suitable for this research due to its ability to model intricate relationships between latent and observable variables, providing a more detailed and precise understanding of the interactions between

TABLE 2 Results of the instrument quality tests evaluated by each of the model variables.

Variables	Item code	Average	DE	Factor loading	Cronbach's alpha	Composite reliability	Average Variance Extracted (AVE)
Service satisfaction	SATSER1	3.00	1.17	0.933	0.939	0.939	0.845
	SATSER2	3.10	1.20	0.921			
	SATSER3	2.55	1.29	0.909			
	SATSER4	2.99	1.14	0.913			
Document management	GESTDOC1	2.89	1.16	0.903	0.915	0.923	0.749
	GESTDOC2	3.06	1.12	0.891			
	GESTDOC3	3.01	1.11	0.898			
	GESTDOC4	2.83	1.19	0.880			
	GESTDOC5	3.59	1.19	0.746			
Technological support	SOPTEC1	2.87	1.10	0.917	0.879	0.881	0.806
	SOPTEC2	3.23	1.07	0.869			
	SOPTEC3	2.86	1.18	0.907			
Open government and transparency	GOBTRANS1	3.09	1.15	0.897	0.886	0.888	0.814
	GOBTRANS2	3.04	1.08	0.918			
	GOBTRANS3	2.72	1.22	0.891			
Pro-environmental organizational culture	COPROA1	2.79	1.19	0.912	0.937	0.96	0.755
	COPROA2	2.92	1.12	0.919			
	COPROA3	2.75	1.23	0.917			
	COPROA4	2.88	1.20	0.927			
	COPROA5	2.82	1.15	0.931			
	COPROA6	2.83	1.12	0.935			
	COPROA7	3.74	1.19	0.409			
Environmental sustainability	SOSTAMB1	3.07	1.16	0.834	0.923	0.936	0.767
	SOSTAMB2	2.88	1.11	0.917			
	SOSTAMB3	2.75	1.16	0.930			
	SOSTAMB4	2.79	1.14	0.925			
	SOSTAMB5	3.13	1.15	0.761			

pro-environmental organizational culture, service satisfaction, document management, and environmental sustainability. Relevant observable indicators were included based on the survey responses.

4 Results

The assessment of the variables examined in this study offers an in-depth perspective on how participants perceive various aspects of their experience at the institution, as illustrated in Table 3. The results concerning service satisfaction indicate that 38.06% of the participants evaluate the service as high, 35.22% as moderate, and 26.72% as low. While the majority hold a positive view of the service, it is evident that a quarter of the respondents believe there are areas that require improvement. This may highlight problems at certain times or in specific areas of attention.

Regarding DM, 50.61% of the participants view it as high-quality, indicating that most perceive the document processes as effective. However, the average and low evaluations (31.98 and 17.41%, respectively) suggest that some individuals encounter difficulties, potentially due to issues with accessibility or insufficient clarity in procedures. TS also reveals notable outcomes. 39.27% of respondents assess it positively, while 38.06% rate it as average, and 22.67% consider it poor. This implies that, although many find the technological support satisfactory, a substantial number of users experience technical issues impacting their experience. For the OG variable, 36.84% of participants rate it as high, 40.08% as average and 23.08% as low. This shows that, while transparency initiatives are recognized, there is a need to enhance accessibility and update information to build greater trust among users. The POC gets a high rating of 42.51%, average of 37.25%, and low of 20.24%. This indicates that the majority of participants acknowledge the institution's dedication to environmental sustainability. Nevertheless, one-fifth of the respondents believe that the pro-environmental policies could be more effective or better communicated. Lastly, regarding ES, 38.06% of participants rate it as high, 39.68% as average, and 22.27%

TABLE 3 Scale of the evaluated variables.

Variables		High	Average	Low
Service satisfaction (SS)	*n*	94	87	66
	%	38.06%	35.22%	26.72%
Document management (DM)	*n*	125	79	43
	%	50.61%	31.98%	17.41%
Technological Support (TS)	*n*	97	94	56
	%	39.27%	38.06%	22.67%
Open government and transparency (OG)	*n*	91	99	57
	%	36.84%	40.08%	23.08%
Pro-Environmental Organizational Culture (POC)	*n*	15	92	5
	%	42.51%	37.25%	20.24%
Environmental Sustainability (ES)	*n*	94	98	55
	%	38.06%	39.68%	22.27%

as low. The closeness of high and average ratings suggests a generally positive perception but also highlights areas where the execution of sustainable practices and their communication to the university community could be improved. Overall, these findings offer a thorough view of the current state of participant experience and perception at the institution. The variables of DM and POC stand out as strengths, which is promising for sustainability and administrative efficiency initiatives. However, the variables of SS and TS present clear opportunities for enhancement, suggesting that addressing these areas could significantly improve the overall perception of the institution. The interaction between these variables provides crucial insights into the study, emphasizing how advancements in one area can positively affect others. For example, enhancing technological support and clarity in document management can boost service satisfaction. Conversely, greater transparency and a solid organizational culture can reinforce participants' trust and commitment to sustainable practices. Thus, the study not only identifies specific areas for enhancement but also underscores the importance of a comprehensive strategy that considers how these factors interconnect to create a more positive and effective educational and administrative experience.

4.1 Proposed research model

In the current landscape of HEIs, ES has emerged as a domain of growing interest and importance. Incorporating sustainable practices not only demonstrates a commitment to environmental conservation but can also improve operational efficiency and institutional standing. This study suggests a framework to assess the factors affecting environmental sustainability within a HEIs, utilizing SEM. It will explore how various factors, such as technological support, document management, open government and transparency, as well as pro-environmental organizational culture, influence environmental sustainability. Furthermore, two crucial mediators are incorporated in this model: service satisfaction and pro-environmental organizational culture. It is posited that effective document management, supported by solid technological support and open government and transparency, can greatly improve service satisfaction, which in turn might enhance efforts toward increased environmental sustainability. Moreover, a POC is viewed as a pivotal driver in this process, fostering values and practices that advance environmental sustainability. The framework will also include sociodemographic factors such as gender, academic program, age, and role within the institution as moderators, to better understand individual variations in the perception and impact of these practices. These moderators will help reveal how personal traits and specific roles within the institution can affect the connections between the examined variables.

The diagram of the conceptual model shown in Figure 2 illustrates these associations and offers a visual basis for the analysis. This comprehensive approach aims not only to identify the direct connections between the mentioned variables but also to investigate how demographic traits and specific roles might moderate these connections. Through this study, it is anticipated to contribute to the development of more effective and adaptive strategies that reinforce HEIs' dedication to environmental sustainability and offer a more holistic and detailed understanding of the factors driving environmental sustainability in the academic context.

4.2 Summary of direct hypotheses

The examination of the proposed model unveils significant insights into how different variables impact ES in a HEI. Several direct hypotheses were tested, with their relationships and significance providing a thorough view of these factors, as presented in Table 4.

Firstly, TS demonstrates having a crucial impact on DM. With a path value of 0.699 and a *p*-value of 0.000, this correlation is clearly positive and significant. This suggests that enhancing technological infrastructure not only facilitates document management but also boosts operational efficiency. This finding highlights the importance of investing in technology to improve administrative procedures. Document management, in turn, has a notable effect on service satisfaction, as indicated by a path value of 0.857 and a *p*-value of 0.000. This positive and significant link underscores that effective document management is crucial to ensure users are content with administrative services. Clearly, efficient document handling not only results in smoother operations but also in greater user satisfaction. When examining the link between service satisfaction and

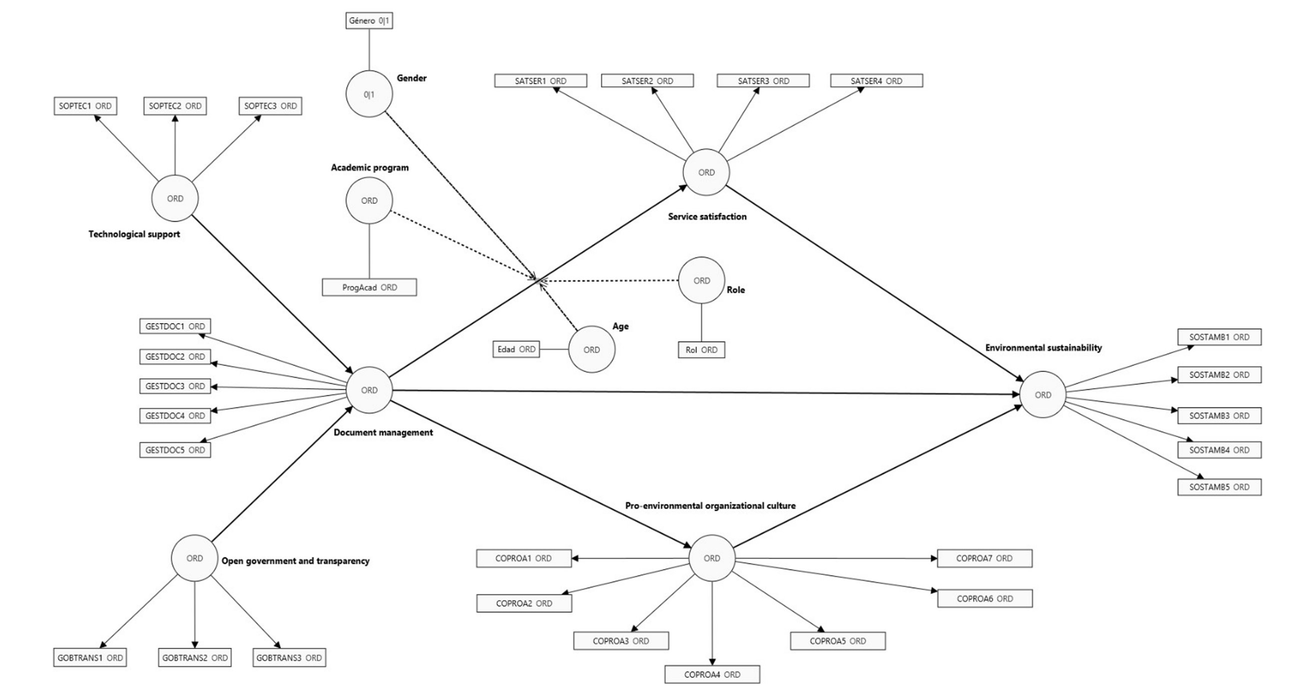


FIGURE 2
Diagram of the proposed research model.

TABLE 4 Hypotheses proposed.

Hypothesis statement	*p*-value	Path value	Condition	Interpretation
Technological Support → Document Management	0.000	0.699	Accepted	The relationship is positive and significant
Document Management → Service Satisfaction	0.000	0.857	Accepted	The relationship is positive and significant
Service Satisfaction → Environmental Sustainability	0.030	0.185	Accepted	The relationship is positive and significant but weak
Document Management → Pro-Environmental Organizational Culture	0.000	0.701	Accepted	The relationship is positive and significant
Pro-Environmental Organizational Culture → Environmental Sustainability	0.000	0.726	Accepted	The relationship is positive and significant
Open Government and Transparency → Document Management	0.000	0.219	Accepted	The relationship is positive and significant but weak
Document Management → Environmental Sustainability	0.217	0.103	Rejected	The relationship is not significant

environmental sustainability, a positive and significant, albeit relatively weak, connection is observed with a path value of 0.185 and a *p*-value of 0.030. This indicates that, although service satisfaction contributes to environmental sustainability, its impact is not as strong as other factors. Nevertheless, this result suggests that improving user satisfaction may have beneficial effects on sustainability practices, though indirectly. On the other hand, DM also shows a significant association with POC, with a path value of 0.701 and a *p*-value of 0.000. This positive correlation underscores how well-organized document management can cultivate an organizational culture that values and promotes environmental sustainability. It is evident that clear and accessible document processes not only facilitate daily tasks but also reinforce pro-environmental principles within the organization. Additionally, POC has a strong effect on SS, with a path value of 0.726 and a *p*-value of 0.000. This result emphasizes the importance of an organizational culture dedicated to sustainability for achieving positive environmental outcomes. Promoting sustainable values and practices within the institution is crucial for the success of environmental initiatives. The association between open government and document management is also positive and significant, though weaker, with a path value of 0.219 and a *p*-value of 0.000. This suggests that transparency and open access to information contribute to

TABLE 5 Moderation analysis.

Hypothesis Statement	*p*-value	Path value	Condition	Interpretation
Gender moderates the relationship between Document Management and Service Satisfaction	0.012	0.172	Accepted	The relationship is significant
The academic program moderates the relationship between Document Management and Service Satisfaction	0.019	0.059	Accepted	The relationship is significant
Age moderates the relationship between Document Management and Service Satisfaction	0.427	−0.025	Rejected	The relationship is not significant
The role moderates the relationship between Document Management and Service Satisfaction	0.207	0.040	Rejected	The relationship is not significant

TABLE 6 Mediation analysis.

Hypothesis statement	Type	*p*-value	Path value	Condition	Interpretation
Document Management → Pro-Environmental Organizational Culture → Environmental Sustainability	Mediator	0.000	0.509	Accepted	Mediation is positive and significant
Document Management → Service Satisfaction → Environmental Sustainability	Mediator	0.030	0.159	Accepted	Mediation is positive and significant but weak

enhanced document management, although its effect is not as strong as other factors. Nonetheless, fostering transparent practices remains essential for improving administrative efficiency. Finally, the hypothesis linking DM directly to ES was not supported, with a path value of 0.103 and a p-value of 0.217. This indicates that document management, on its own, does not have a significant direct impact on environmental sustainability. Its influence is likely mediated through other variables, such as service satisfaction and pro-environmental organizational culture. In summary, the results from the direct hypothesis analysis underscore the importance of technological support, document management, and a pro-environmental organizational culture as key factors in driving environmental sustainability. Although service satisfaction also plays a relevant role, its effect is more subtle.

4.3 Moderation analysis

This study examines the influence of various demographic and academic factors on the relationship between DM and SS in higher education environments providing new insights to enhance ES through customized document management practices, detailed in Table 5.

The results indicate that gender has a notable impact on the mentioned relationship ($p = 0.012$, Path = 0.172), suggesting differences in service satisfaction perceptions between men and women. This finding highlights the need to develop inclusive DM strategies that foster both environmental sustainability and fairness in service satisfaction. Additionally, the academic program was identified as a significant moderator ($p = 0.019$, Path = 0.059), emphasizing the importance of tailoring DM practices to the specific context of each program to enhance service satisfaction. This outcome underscores the need for a customized approach in DM initiatives for various academic settings. In contrast, neither age ($p = 0.427$, Path = −0.025) nor role ($p = 0.207$, Path = 0.040) demonstrated significant moderation in the studied relationship. This indicates that DM practices can be uniformly implemented in these areas without compromising their effectiveness.

Finally, this study provides empirical evidence on the importance of considering gender and academic program when designing DM strategies in universities, with the goal of advancing environmental sustainability and service satisfaction. The absence of significant moderation by age and role offers a practical perspective for the consistent application of these practices in certain domains. These results establish a solid foundation for future research and practices in sustainable DM, tailored to the specific needs of diverse groups within the university environment.

4.4 Mediation analysis

The mediation analysis in the model, as detailed in Table 6, assists in understanding how certain variables affect environmental sustainability through key mediators in the HEI under examination.

Below are the findings of the mediation hypotheses, explaining how document management, pro-environmental organizational culture, and service satisfaction interact to affect environmental sustainability. Initially, it was found that DM influences environmental sustainability through pro-environmental organizational culture. With a Path value of 0.509 and a p-value of 0.000, this mediation is positive and significant. This means that effective DM can enhance pro-environmental organizational culture, which in turn greatly increases environmental sustainability. In this case, the mediation is complete, highlighting the importance of pro-environmental organizational culture as a key channel for achieving sustainability through efficient DM. This finding underscores that cultivating a culture that values sustainability is crucial for maximizing improvements in DM. The practical implication is that universities should not only focus on enhancing DM but also on developing an organizational culture that supports and fosters sustainability.

Conversely, it was found that service satisfaction also mediates the relationship between document management and environmental sustainability. With a path value of 0.159 and a *p*-value of 0.030, this mediation is positive and significant, albeit weaker. This indicates that effective DM can increase service satisfaction, which in turn contributes to environmental sustainability. Although this mediation is also complete, the impact is less pronounced, suggesting that service satisfaction plays a role in sustainability but not as strongly as pro-environmental organizational culture. This finding highlights that while service satisfaction is important, additional complementary efforts are required to achieve a notable change in sustainability. Practically, this means that HEIs should work to enhance service satisfaction as it can positively impact their sustainability initiatives, but they should complement these efforts with other more direct actions toward sustainability.

These findings are essential for understanding how intermediate variables can amplify the effects of DM practices on environmental sustainability. POC emerges as a very important mediator, suggesting that initiatives to improve sustainability should focus on building and strengthening a culture that values and promotes environmental sustainability. On the other hand, service satisfaction, while less influential, also contributes positively, indicating that improving the service experience can have beneficial effects on sustainability practices. The mediation analysis shows that both POC and service satisfaction are key mediators in the relationship between document management and environmental sustainability. However, pro-environmental organizational culture has a much stronger and more significant impact. This provides a solid basis for designing effective strategies in HEIs, highlighting the importance of the complete mediations identified in this study.

4.5 R^2 analysis

The R^2 analysis offers a clear understanding of how much of the variability in certain critical areas can be explained by the studied factors, detailed in Table 7. At the research location, four main variables were investigated: pro-environmental organizational culture, document management, service satisfaction, and environmental sustainability.

For the POC, the outcomes show that 49.2% of the variability in this domain can be accounted for by the model, with an adjusted R^2 of 0.490. This implies that nearly half of the changes in pro-environmental organizational culture within the institution are due to factors such as DM, technological support, and transparency. These insights underscore the significance of these components in fostering a culture that values and endorses environmental sustainability. In the case of DM, it was found that 77.7% of the variability can be explained by the elements of the model, with an adjusted R^2 of 0.775. This indicates that enhancing technological support and transparency has a substantial impact on the efficacy of document management. These findings highlight the importance of these areas for efficient administrative operations and suggest that investments in technology and transparent practices are essential. SS was also examined, revealing that 73.4% of the variability can be explained by the model, with an adjusted R^2 of 0.733. This implies that document management and pro-environmental organizational culture have a significant impact on how users perceive the quality of the service. Enhancing these aspects is crucial to increasing user satisfaction with the services provided by the institution. Lastly, for ES, it was found that 78.1% of the variability can be explained by the model, with an adjusted R^2 of 0.771. These results emphasize the necessity for integrated approaches that consider multiple factors to promote sustainable practices. In summary, the R^2 and adjusted R^2 values illustrate that the studied factors adequately explain the key areas of interest. The results suggest that improving document management, fostering a pro-environmental culture, and increasing service satisfaction are vital to driving environmental sustainability.

TABLE 7 R^2 analysis.

Variables	R squared	R-squared-adjusted
Pro-environmental organizational culture	0.492	0.490
Document management	0.777	0.775
Service satisfaction	0.734	0.733
Environmental sustainability	0.781	0.771

TABLE 8 Summary of fit indices.

	Saturated model	Estimated model
SRMR	0.053	0.063
d_ULS	1.381	1.401
d_G	0.897	0.945
Chi-square	1,009.338	1,017.348
NFI	0.948	0.929

4.6 Model fit: summary of fit indices

The evaluation of the fit indices offers an assessment of how well the proposed model aligns with the observed data at the study site, with the outcomes displayed in Table 8.

The following are the findings and interpretations of the main fit indices for the saturated model and the estimated model. The value of SRMR (Standardized Root Mean Square Residual) is an indicator that measures the discrepancy between the observed and predicted correlations by the model. In the saturated model, the SRMR is 0.053, while in the estimated model it is 0.063. These values indicate a good fit, as they are below the commonly accepted threshold of 0.08. This suggests that the discrepancies between the observed and predicted correlations are small, implying that the estimated model adequately represents the data. The d_ULS (Unweighted Least Squares Discrepancy) index in the saturated model is 1.381 and in the estimated model is 1.401. These values are quite close to each other, indicating that the fit of the estimated model is similar to that of the saturated model. Although there is no specific threshold for d_ULS,

10.3389/frsus.2024.1479927

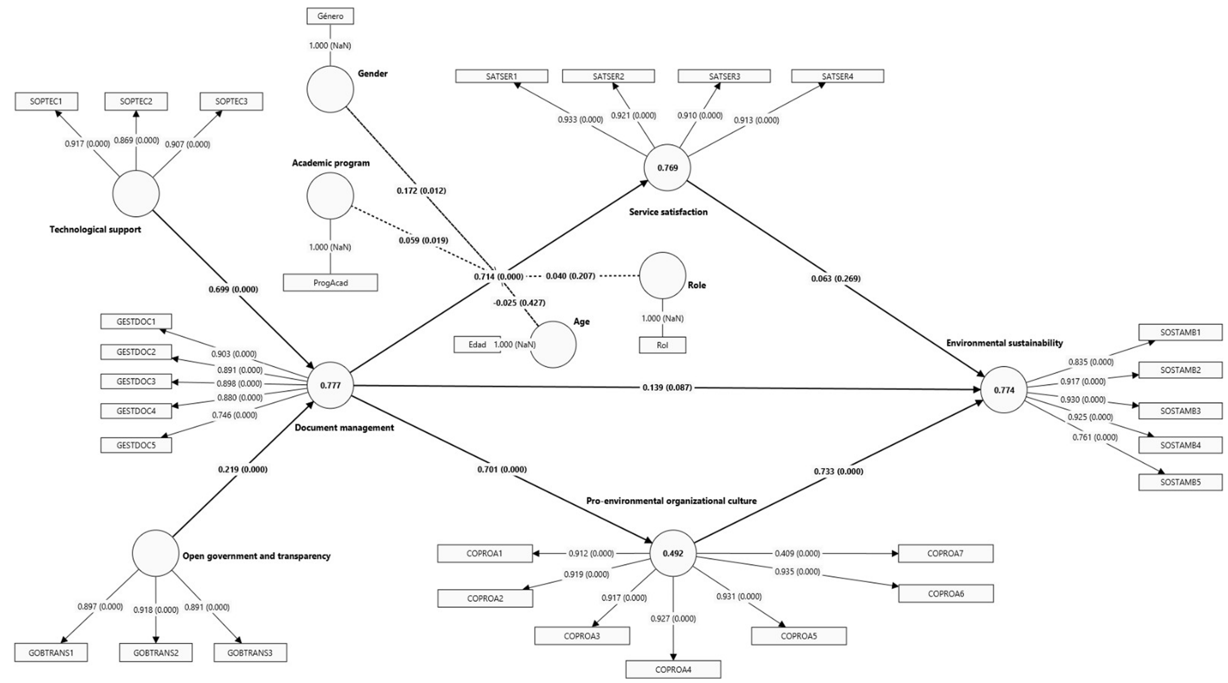


FIGURE 3
Solved research model.

lower values are preferable and these results suggest that the model has a good fit. The value of d_G (Geodesic Discrepancy) shows values of 0.897 for the saturated model and 0.945 for the estimated model. These close values also suggest a good fit of the estimated model compared to the saturated model. As with d_ULS, lower values indicate a better fit. The Chi-square value is 1,009.338 for the saturated model and 1,017.348 for the estimated model. The Chi-square measures the discrepancy between the observed data and the expected data by the model; lower values indicate a better fit. Although both values are relatively high, the small difference between them suggests that the estimated model does not differ much from the saturated model in terms of fit. The value of NFI (Normed Fit Index) is 0.948 for the saturated model and 0.929 for the estimated model. NFI values close to 1 indicate a good fit. Both values are high, suggesting that the estimated model has a reasonably good fit, although slightly inferior to the saturated model. Finally, the analyzed fit indices show that the estimated model has a good fit with the observed data. The values of SRMR, d_ULS, and d_G indicate that the discrepancies between the observed data and the predicted data by the model are small. Although the Chi-square values are high, the small difference between the saturated and estimated models suggests that the fit is adequate. Finally, the NFI value close to 0.93 supports the quality of the fit of the estimated model. These results suggest that the estimated model is a reasonably accurate representation of the relationships between the variables in the studied context.

4.7 Solved research model

The research model (see Figure 3) generated with the values: *p*-value, path coefficients and factor loadings between the constructs (direct, mediators and moderators) is presented below.

5 Discussion

The primary aim of the study was to evaluate the mediation of pro-environmental organizational culture and service satisfaction between document management and environmental sustainability. The SEM showed very satisfactory fit indices. Moreover, the R^2 values demonstrated that 49.2% of the variability in this area can be explained by the model, with an adjusted R^2 of 0.490. For document management, 77.7% of the variability can be explained by the model factors, with an adjusted R^2 of 0.775. Concerning service satisfaction, the analysis indicated that 73.4% of the variability can be explained by the model, with an adjusted R^2 of 0.733. Finally, for environmental sustainability, it was found that 78.1% of the variability can be explained by the model, with an adjusted R^2 of 0.771.

Regarding hypothesis 1, TS shows having a pivotal influence on document management. With a path value of 0.699 and a *p*-value of 0.000, this relationship is evidently positive and significant. In another context, Dwivedi et al. (2019) indicate that the role of technological support is a significant concern in research, where the acceptance and use of innovations in information systems (IS) and information technology (IT) were examined using theoretical models that investigate their acceptance; the Unified Theory of Acceptance and Use of Technology (UTAUT) stands out and suggests that the actual use of technology is determined by behavioral intention. It points out that technology adoption depends on performance and effort expectancy, social influence, and facilitating conditions, and individuals' perceptions of technology are crucial for enhancing job performance (Marikyan and Papagiannidis, 2023). Therefore, this hypothesis is validated, and although our research does not examine the acceptance theory, the findings suggest that technology use influences document management.

Concerning the second hypothesis, the outcomes of the relationship between open government and document management are also positive and significant, although weaker, with a path value of 0.219 and a *p*-value of 0.000. This suggests that transparency and open access to information contribute to better document management. As Aguerre and Bonina (2024), mention, digital technologies have recognized potential to build more efficient, credible, and innovative public institutions. Additionally, Aguerre and Bonina (2024), indicate that open government data are important agents of the DT of the public sector, allowing us to understand how strategies are designed, implemented, and evaluated for their continuous success, with the goal of engaging users and utilizing these vital resources (Begany and Gil-Garcia, 2024). It is necessary to have governance frameworks that allow the integration of technologies into different platforms and the adaptation to an increasingly digital society (Zwitter, 2024), constructing and interpreting data visualizations that simplify access to information, enhancing interpretation and strengthening information literacy (Barcellos et al., 2024). Therefore, these aspects suggest and confirm the importance of the relationship between OG as a catalyst for providing data for adequate document management.

Concerning the third research hypothesis, the outcomes show that DM has a notable impact on service satisfaction, with a path value of 0.857 and a *p*-value of 0.000. This evidences a positive and significant relationship, confirming that efficient document management is essential to ensure users are satisfied with administrative services. On the other hand, Alade (2023), indicates that an area that has experienced rapid growth in recent years is document management, a necessity in the work environment of an organization, concluding that it improves user satisfaction, increases productivity, and ensures data efficiency in a timely manner. Therefore, the results obtained in our hypothesis closely relate to what was indicated. In Peru, according to Ramirez et al. (2023), public institutions have a deficient document management service, so they implemented the automation technology to reduce the time for processing procedures and avoid citizen dissatisfaction, improving their experience. Thus, our hypothesis is significant to avoid such problems in organizations.

In the fourth hypothesis, the outcomes demonstrated that POC has a strong influence on environmental sustainability, with a path value of 0.726 and a *p*-value of 0.000. According to Nanayakkara and Wilkinson (2021), the theory of organizational culture is one of the most powerful in the workplace and could impact its processes and overall company performance. Sindakis et al. (2024) mention that the adoption and transfer of culture is achieved through knowledge exchange within and between areas. As Schlegel et al. (2023) point out in the context of DT, having an organizational culture based on data is an important factor in data analysis capabilities, innovation, and competitive advantages of companies. This allows us to infer that innovation and competitive advantage in companies are factors that contribute to environmental sustainability. According to the study by Souza and Aganette (2022), digital preservation and efficient document management are closely related to pro-environmental organizational culture. Consequently, this would generate digital use of documents, avoiding physical archives, which reaffirms the results obtained in our research. Similarly, Netshakhuma (2022) demonstrated that using the SharePoint platform as a document management system supports the development of a sustainability-oriented organizational culture. The reviewed studies provide evidence that efficient document management can be the key driver for fostering a culture committed to environmental sustainability in HEIs. Therefore, based on the results, our hypothesis is accepted, as confronting it with various authors confirms this strong relationship between the two constructs.

The fifth hypothesis, examining the direct relationship between document management and environmental sustainability, was not accepted, as it yielded a path value of 0.103 and a *p*-value of 0.217. This indicates that document management alone does not have a significant direct impact on environmental sustainability, suggesting that its influence may be indirect and mediated by other variables, such as service satisfaction and pro-environmental organizational culture.

The sixth hypothesis shows a positive and significant connection, although relatively weak, with a path value of 0.185 and a *p*-value of 0.030. The impact of service satisfaction on environmental sustainability is not very strong. Mansoor and Hussain (2024) demonstrated that effective and user-centered management can significantly influence service quality, which in turn fosters a more sustainable environment inclined toward pro-environmental practices. Consequently, this indirect fostering is represented by the weak result in the relationship between these variables. Likewise, Rolo et al. (2024), regarding service quality in HEIs in Portugal and Angola, highlight the importance of adapting service quality strategies to local needs and expectations. In the context of environmental sustainability, this implies that HEIs should consider user particularities to implement sustainable practices that are positively perceived. Nonetheless, this finding suggests that improving user satisfaction can have beneficial effects on sustainability practices, albeit indirectly.

The seventh hypothesis, relating document management directly to environmental sustainability, was not accepted, with a path value of 0.103 and a *p*-value of 0.217. This evidences that document management alone does not have a significant direct impact on environmental sustainability. In conclusion, the outcomes of the direct hypothesis analysis highlight the importance of technological support, document management, and pro-environmental organizational culture as key factors for driving environmental sustainability.

5.1 Theoretical and practical implications

In terms of theoretical implications, this study contributes to the field of environmental sustainability in HEIs by exploring how document management, mediated by pro-environmental organizational culture and service satisfaction, contributes to sustainable practices. By incorporating these factors as mediators, the study provides a conceptual framework that evidences the influence of cultural and internal satisfaction dimensions on the effectiveness of environmental initiatives. Thus, the findings suggest that sustainability in HEIs depends not only on operational actions, but also on a committed institutional culture and the satisfaction of the organization's members. These results can serve as a reference for future research seeking to understand the relationship between organizational culture, service satisfaction and sustainability in different contexts and sectors. Furthermore, the application of the SEM model proves effective in analyzing these interrelationships, which reinforces the potential of this analytical tool in sustainability and management studies in educational settings.

And in reference to the practical implications, the findings highlight the need to implement sustainable strategies in document management within HEIs, promoting the digitization of documents, a greater reduction in the use of paper and the adoption of standards and practices that favor sustainability. The digitization and proper management of digital files not only improves the efficiency of document processes, but also significantly reduces the environmental impact of the institution. Additionally, the results indicate the importance of fostering a pro-environmental culture at all levels of the organization. To this end, it is essential to implement awareness and training programs, suggesting that courses should have content on environmental care and the implications of the carbon footprint, to strengthen the collective commitment to sustainability, ensuring that the university community actively participates in environmental initiatives and that these values are part of the institutional mission. Finally, the SEM analysis suggests that HEIs could develop environmental policies based on the principles of sustainability and document management, integrating a long-term environmental strategy that consolidates them as models of sustainability within the community, thus inspiring other organizations and promoting a significant transformation toward sustainability.

Aligned with the SDGs, the TD of document management in HEIs not only optimizes internal processes, but also contributes directly to quality and accessible education, in line with SDG 4, where the digitization of documents and institutional resources reduces physical barriers and facilitates more inclusive learning, allowing teachers, students and graduates to access relevant information regardless of their location. In the area of sustainable communities, established in SDG 11, HEIs can lead the change by adopting pro-environmental practices, strengthening the role of institutions as models of sustainability in society, inspiring both students and local organizations to adopt a culture of responsible consumption and practices aimed at greater community resilience and sustainable development.

On the other hand, the shift toward digitized document management allows IES to significantly reduce its consumption of paper and other resources, complying with the SDG 12 principles on responsible production and consumption. At the same time, these proactive digitization practices help to reduce the institutional carbon footprint, in line with SDG 13 on climate action, where, by reducing the physical storage and waste derived from printed documents, it contributes to mitigate climate change, reinforcing the role of higher education not only as a knowledge educator, but also as an actor committed to climate action and environmental preservation.

5.2 Limitations and future studies

Nevertheless, the study presents certain constraints. Firstly, the specific geographical and cultural context of a single university restricts the generalization of the findings to other institutions or regions with different cultural and geographical backgrounds. Moreover, although the model encompasses several key factors, there are other potentially significant variables that were not considered in this study, such as the availability of financial resources and the commitment of top management.

For future research, it is recommended to expand the scope of the study to other faculties within the same university or to other HEIs, both nationally and internationally, to validate the generalization of the findings obtained. Additionally, it would be advantageous to include other pertinent variables that might impact environmental sustainability, such as financial resources, senior management commitment, and specific institutional policies on sustainability, which would enrich understanding in this field. Complementing quantitative analyses with qualitative studies would deepen the comprehension of the perceptions and experiences of university community members regarding sustainability practices.

6 Conclusion

In the context of HEIs, environmental sustainability has become a crucial pillar for institutional growth. This research has offered a more profound understanding of the factors affecting ES within a Peruvian HEI, using the Structural Equation Modeling (SEM) methodology through SmartPLS.

The analysis disclosed that technological infrastructure has a notable and favorable impact on document management, emphasizing the importance of investing in technology to streamline administrative operations and enable effective document management, as stated by Alade (2023), the web-based electronic DMS, obtained a 96.60% satisfaction of respondents. Consequently, efficiency in document management translates into higher service satisfaction and promotes a pro-environmental organizational culture, key elements for enhancing user experience and supporting sustainable practices within the institution. The pro-environmental organizational culture emerged as the strongest mediator, significantly influencing environmental sustainability, Barros et al. (2020) shows that in a Brazilian university introduced an electronic information system with the aim of virtualizing administrative processes (until then paper-based), resulting in savings of 57.5% in printed paper. Advancing an organizational culture dedicated to sustainability is vital to achieving favorable environmental results (valor path 0.726). Although service satisfaction also has a positive effect on environmental sustainability, its influence is less substantial (valor path 0.185) compared to other elements. Nonetheless, improving user experience is advantageous for sustainable practices. Transparency and open access to information, open government factors, aid in better document management, although their effect is not as marked (valor path 0.219) as other influences.

Additionally, sociodemographic factors such as gender and academic program within the institution moderate the relationship between the examined variables, indicating that these attributes can affect the perception and efficacy of sustainability practices.

Finally, designing and evaluating specific interventions based on the findings of the study, aimed at improving document management, technological support and pro-environmental organizational culture, would promote greater environmental sustainability in HEIs and contribute to the fulfillment of the SDGs. These interventions would not only improve the efficiency and accessibility of educational processes in line with SDG 4, but would also strengthen the role of universities as agents of change in their communities, aligning with SDG 11. Furthermore, by reducing paper consumption and promoting sustainable practices, these initiatives would be in line with SDG 12 and 13, reducing the institutional carbon footprint and contributing to global efforts against climate change.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics Committee 2024-IIICyT-ITCA. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JB: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. CV: Conceptualization, Formal analysis, Investigation, Resources, Validation, Writing – original draft, Writing – review & editing. RA: Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. NG: Conceptualization, Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing. OS: Data curation, Formal analysis, Investigation, Resources, Software, Writing – original draft, Writing – review & editing. JA: Formal analysis, Investigation, Resources, Visualization, Writing – original draft, Writing – review & editing. MA: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. LG: Data curation, Formal analysis, Resources, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was funded by the Vice-Rectorate for Research with Rectoral Resolution No. 1123-2023-R of the Pedro Ruiz Gallo National University.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aguerre, C., and Bonina, C. (2024). Open government, civic tech and digital platforms in Latin America: a governance study of Montevideo's urban app 'por mi barrio'. *Inf. Syst. J.* 34, 1037–1067. doi: 10.1111/isj.12468

Alade, S. M. (2023). Design and implementation of a web-based document management system. *Int. J. Inf. Technol. Comput. Sci.* 15, 35–53. doi: 10.5815/ijitcs.2023.02.04

Alghobiri, M., Mohiuddin, K., Khaleel, M. A., Islam, M., Shahwar, S., and Nasr, O. (2022). A novel approach of clustering documents: minimizing computational complexities in accessing database systems. *Int. Arab J. Inf. Technol.* 19, 617–628. doi: 10.34028/iajit/19/4/6

Alnafrah, I., and Mouselli, S. (2021). Revitalizing blockchain technology potentials for smooth academic records management and verification in low-income countries. *Int. J. Educ. Dev.* 85:102460. doi: 10.1016/j.ijedudev.2021.102460

Alonso, M. J. (2020). La gestión documental en las organizaciones (2a. edición). Universitat Oberta de Catalunya. Available at: https://openaccess.uoc.edu/bitstream/10609/147130/5/GestionDocumental_Modulo1_LaGestionDocumentalEnLasOrganizaciones.pdf (Accessed July 11, 2024).

Alshamsi, M., Al-Emran, M., Daim, T., Al-Sharafi, M. A., Bolatan, G. I. S., and Shaalan, K. (2024). Uncovering the critical drivers of blockchain sustainability in higher education using a deep learning-based hybrid SEM-ANN approach. *IEEE Trans. Eng. Manag.* 71, 8192–8208. doi: 10.1109/TEM.2024.3365041

Ávila, M. M., and Moreno, E. F. (2018). Aplicación de la técnica PLS-SEM en la gestión del conocimiento: Un enfoque técnico práctico. *RIDE Revista Iberoamericana para la Investigación y el Desarrollo Educativo* 8, 130–164. doi: 10.23913/ride.v8i16.336

Ayaz, A., and Yanartaş, M. (2020). An analysis on the unified theory of acceptance and use of technology theory (UTAUT): acceptance of electronic document management system (EDMS). *Comput. Hum. Behav. Rep.* 2:100032. doi: 10.1016/j.chbr.2020.100032

Bao, T., Liu, Y., Yang, Z., Wu, S., and Yan, Z. (2024). Evaluating sustainable service quality in higher education from a multi-stakeholder perspective: an integrated fuzzy group decision-making method. *Socio. Econ. Plan. Sci.* 92:101849. doi: 10.1016/j.seps.2024.101849

Barcellos, R., Viterbo, J., and Bernardini, F. (2024). A process for improving the quality and interpretability of data visualizations. *Univ. Access Inf. Soc.* 23, 779–794. doi: 10.1007/s10209-022-00955-y

Barragán-Ocaña, A., Silva-Borjas, P., Cecilio-Ayala, E., Guzmán-Guzmán, H. E., Bilyaminu, A. M., and Rene, E. R. (2024). An exploratory diagnosis and proposed index of technological change and sustainable industrial development in selected OECD member countries. *Environ. Res.* 257:119122. doi: 10.1016/j.envres.2024.119122

Barros, M. V., Puglieri, F. N., Tesser, D. P., Kuczynski, O., and Piekarski, C. M. (2020). Sustainability at a Brazilian university: developing environmentally sustainable practices and a life cycle assessment case study. *Int. J. Sustain. High. Educ.* 21, 841–859. doi: 10.1108/IJSHE-10-2019-0309

Begany, G. M., and Gil-Garcia, J. R. (2024). Open government data initiatives as agents of digital transformation in the public sector: exploring the extent of use among early adopters. *Gov. Inf. Q.* 41:101955. doi: 10.1016/j.giq.2024.101955

Chen, W., Bohloul, S. M., Ma, Y., and Li, L. (2022). A blockchain-based information management system for academic institutions: a case study of international students' workflow. *Inf. Discov. Del.* 50, 343–352. doi: 10.1108/IDD-01-2021-0010

Christou, O., Manou, D. B., Armenia, S., Franco, E., Blouchoutzi, A., and Papathanasiou, J. (2024). Fostering a whole-institution approach to sustainability through systems thinking: an analysis of the state-of-the-art in sustainability integration in higher education institutions. *Sustain. For.* 16:2508. doi: 10.3390/su16062508

Cóndor-Salvatierra, E. J., Yuli-Posadas, R. A., and Rutti-Marín, J. M. (2022). Environmental education: challenges for the 2030 sustainable development agenda. *Revista de Filosofía (Venezuela)* 39, 448–460. doi: 10.5281/zenodo.6001700

Costa, F., Alemsan, N., Bilancia, A., Tortorella, G. L., and Portioli Staudacher, A. (2024). Integrating industry 4.0 and lean manufacturing for a sustainable green transition: a comprehensive model. *J. Clean. Prod.* 465:142728. doi: 10.1016/j.jclepro.2024.142728

Curto-Rodríguez, R., Marcos-Sánchez, R., and Ferrández, D. (2024). Open government in Spain: an introspective analysis. *Admin. Sci.* 14:89. doi: 10.3390/admsci14050089

Decreto Supremo No 029-2021-PCM. (2021). Reglamento de la Ley de Gobierno Digital. Available at: https://www.gob.pe/13326-reglamento-de-la-ley-de-gobierno-digital (Accessed March 10, 2024).

Dieguez, T. (2023). Leadership and governance for higher education sustainability: exploring entrepreneurial and innovative potential. *Leadersh. Govern. Sustain.*, 263–283. doi: 10.4018/978-1-6684-9711-1.ch014

Dongre, R., Mishra, P., Prasad, L., Prasad, V., and Gupta, S. K. (2024). Institutionalizing blockchain technology in universities for sustainable development. 2024 2nd International Conference on Device Intelligence, Computing and Communication Technologies (DICCT), 1–6. doi: 10.1109/DICCT61038.2024.10533125

Dwivedi, Y. K., Rana, N. P., Jeyaraj, A., Clement, M., and Williams, M. D. (2019). Re-examining the unified theory of acceptance and use of technology (UTAUT): towards a revised theoretical model. *Inf. Syst. Front.* 21, 719–734. doi: 10.1007/s10796-017-9774-y

Escobedo, M. T., Hernández, J. A., Estebané, V., and Martínez, G. (2016). Modelos de ecuaciones estructurales: Características, fases, construcción, aplicación y resultados. *Ciencia trabajo* 18, 16–22. doi: 10.4067/S0718-24492016000100004

Fiorello, M., Gladysz, B., Corti, D., Wybraniak-Kujawa, M., Ejsmont, K., and Sorlini, M. (2023). Towards a smart lean green production paradigm to improve operational performance. *J. Clean. Prod.* 413:137418. doi: 10.1016/j.jclepro.2023.137418

Fuchs, P. G., Finatto, C. P., Birch, R. S., de Aguiar Dutra, A. R., and de Andrade Guerra, J. B. S. O. (2023). Sustainable development goals (SDGs) in Latin-American universities. *Sustainability (Switzerland)* 15:8556. doi: 10.3390/su15118556

Gamido, M. V., Gamido, H. V., and Macaspac, D. J. P. (2023). Electronic document management system for local area network-based organizations. *Indonesian J. Electric. Eng. Comput. Sci.* 31, 1154–1163. doi: 10.11591/ijeecs.v31.i2.pp1154-1163

Gelashvili, T., and Pappel, I. (2021). Challenges of transition to paperless management: readiness of incorporating AI in decision-making processes, Eighth International Conference on eDemocracy & eGovernment (ICEDEG). *Scopus*. 41–46. doi: 10.1109/ICEDEG52154.2021.9530905

Gestión Documental y Sostenibilidad: Reduciendo el Impacto Ambiental. (2023). Available at: https://www.archivocaribe.com/gestion-documental-y-sostenibilidad-reduciendo-el-impacto-ambiental/ (Accessed March 14, 2024).

Glavev, V. (2023). Integration of document management system with E-government E-payments system. *48th International Conference "Applications of Mathematics in Engineering and Economics"*. 1:2939. doi: 10.1063/5.0178859

Guevara-Herrero, I., Pérez-Martín, J. M., and Bravo-Torija, B. (2023). Impact of the sustainable development goals on educational research on environmental education. *Re. Eur. Secur.* 20, 250101–250117. doi: 10.25267/Rev_Eureka_ensen_divulg_cienc.2023.v20.i2.2501

Henriksen, D. (2023). The effect of digitalization on the daily use of and work with records in the Norwegian public sector. *Rec. Manag. J.* 33, 105–119. doi: 10.1108/RMJ-10-2022-0030

Hernández-Bonivento, J., and Moller, F. (2024). Understanding freedom of information requests: predictors of request for public information to municipalities in Chile. *Local Gov. Stud.* 50, 1–19. doi: 10.1080/03003930.2024.2337656

Hüller, K. S., Gomes, J. H. C., and Dos Santos, V. M. L. (2022). Mapping of academic document management systems and digital diploma issuance at universities. *Ciencia da Informacao* 51, 77–93. doi: 10.18225/ci.inf.v51i3.5497

Ioannou, K., Kitsios, F., and Kamariotou, M. (2022). Digital transformation strategy and organizational change in the public sector: evaluating E-government IS and user satisfaction. *Lect. Notes Bus. Inf. Process.* 437, 247–257. doi: 10.1007/978-3-030-95947-0_17

Jiménez, A. D., Batista, D. O., and Gómez, I. Z. (2022). Componentes para la conformación de políticas de gestión documental para universidades. *Informacion, Cultura y Sociedad* 47, 79–92. Scopus. doi: 10.34096/ics.i47.11515

Kalsoom, Q., and Hasan, S. (2022). Pedagogy for Living in Harmony with Nature—Sustainability in Higher Education. *En Higher Education for Sustainable Development Goals*, 206–227.

Karalam, S., and Mathew, A. R. (2023). Sustainable environment protection and waste management in higher education institutions: A case study. *En Models for Social Responsibility Action by Higher Education Institutions*. Nova Science Publishers, Inc. 1–20.

Karpenko, O., Tarnovska, I., Kravchenko, O., Vlasova, V., and Dronyuk, I. (2020). Information system "academic load distribution". *1st International Workshop on Intelligent Information Technologies and Systems of Information Security, InteIITSIS 2020.* 2623, 141–152. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-85088410460&origin=inward&txGid=57e3f7eeffb36447f02b5ad4c0259941

Khan, M. S., and Terason, S. (2022). Encouraging pro-environmental behavior in university employees: An approach toward environmental sustainability as moderated by green organizational culture. *J. Community Psychol.* 50, 1454–1469. doi: 10.1002/jcop.22726

Kholiya, P. S., Kapoor, A., Rana, M., and Bhushan, M. (2021). Intelligent process automation: the future of digital transformation. 185–190. doi: 10.1109/SMART52563.2021.9676222

Kidido, J. K., Alhassan, T., and Frimpong Nyarko, C. P. (2024). Management and sustainability of event facilities: perceptions of end-users in higher education institutions in Ghana. *J. Facil. Manag.* 22. doi: 10.1108/JFM-06-2023-0068

Kitsios, F., and Ioannou, K. (2024). Digital strategy and change in public services and enterprises: the case of IRIDA document management information system. *J. Knowl. Econ.* doi: 10.1007/s13132-024-02071-z

Korro, J., Valle-Melón, J. M., and Miranda, Á. R. (2024). Documentary data collection: An initial step for information management in the conservation and restoration of cultural heritage. *Conservar Patrimonio* 45, 21–35. doi: 10.14568/cp27370

Laporte, J. P., Román-Collado, R., and Cansino, J. M. (2024). Key driving forces of energy consumption in a higher education institution using the LMDI approach: the case of the Universidad Autónoma de Chile. *Appl. Energy* 372:123797. doi: 10.1016/j.apenergy.2024.123797

Luo, H., and Sun, Y. (2024). Effects of geopolitical risk on environmental sustainability and the moderating role of environmental policy stringency. *Sci. Rep.* 14:10747. doi: 10.1038/s41598-024-60773-5

Lyu, L., Bagchi, M., Markoglou, N., and An, C. (2024). Innovations and development of sustainable personal protective equipment: a path to a greener future. *Environ. Syst. Res.* 13:22. doi: 10.1186/s40068-024-00350-x

Mansoor, T., and Hussain, S. (2024). Impact of knowledge oriented leadership on sustainable service quality of higher education institutes. *VINE J. Inf. Knowl. Manag. Syst.* 54, 705–724. doi: 10.1108/VJIKMS-09-2021-0176

Manzanelli. (2023,). Guía completa de la Norma ISO 30300 para la gestión de documentos y archivos. NormasISO.org. Available at: https://normasiso.org/norma-iso-30300/ (Accessed July 11, 2024).

Marikyan, D., and Papagiannidis, S. (2023). Unified theory of acceptance and use of technology—TheoryHub—academic theories reviews for research and T&L. Available at: https://open.ncl.ac.uk/theories/2/unified-theory-of-acceptance-and-use-of-technology/ (Accessed July 24, 2024).

Marques, J., Franco, M., and Rodrigues, M. (2023). International universities-firms cooperation as a mechanism for environmental sustainability: a case study of EdgeWise. *J. Appl. Res. Higher Educ.* 15, 966–987. doi: 10.1108/JARHE-05-2022-0170

Monarcha-Matlak, A. (2021). Automated decision-making in public administration. *Procedia Comput. Sci.* 192, 2077–2084. doi: 10.1016/j.procs.2021.08.215

Mosweu, O., and Bwalya, K. J. (2023). The role of information architecture in the automation of records in Botswana in an e-government setting. *Collect Curat.* 42, 25–33. doi: 10.1108/CC-05-2022-0018

Mulchan, S., and Wang, Y. (2024). An analysis of digital strategy opportunities in a records management system. *Lect. Notes Electric. Eng.* 1154, 395–400. doi: 10.1007/978-981-97-0665-5_51

Nanayakkara, K., and Wilkinson, S. (2021). Organisational Culture Theories: Dimensions of organisational culture and office layouts. *En A Handbook of Theories on Designing Alignment Between People and the Office Environment*, (Routledge). Available at: https://www.taylorfrancis.com/chapters/oa-edit/10.1201/9781003128830-12/organisational-culture-theories-kusal-nanayakkara-sara-wilkinson

Netshakhuma, N. S. (2022). Implementation of the SharePoint Platform as a Record Management System in Universities: En. Ed. T. M. Masenya *Advances in Knowledge Acquisition, Transfer, and Management*. IGI Global. (pp. 105–122).

Ngoepe, M., Jacobs, L., and Mojapelo, M. (2024). Inclusion of digital records in the archives and records management curricula in a comprehensive open distance e-learning environment. *Inf. Dev.* 40, 190–201. doi: 10.1177/02666669221081812

Ozdemir, Y., Kaya, S. K., and Turhan, E. (2020). A scale to measure sustainable campus services in higher education: "sustainable service quality". *J. Clean. Prod.* 245:118839. doi: 10.1016/j.jclepro.2019.118839

Pasillas-Banda, D. G., González-Dueñas, M., Oliva-Ibarra, F. E., Domínguez-García, R. O., Zatarain-Duran, O. A., and Ávila, R. R. (2024). Technological communication model to improve citizens' trust in municipalities by reporting failures in municipal public services: an open government proposal, using mobile devices. *Lect. Notes Netw. Syst.* 817, 491–504. doi: 10.1007/978-981-99-7886-1_41

Pereira de Morais, J. C., Neves, N. C., Soveral, L. A., and Lima, J. (2024). Innovation in higher education institutions towards sustainability using LED technology. *Int. J. Innov. Sci.* 16, 296–319. doi: 10.1108/IJIS-08-2022-0153

Pleskach, M., Karpenko, O., Kravchenko, O., and Tarnovska, I. (2023). Information system "workload assignment at a university department". eds. A. Anisimov, V. Snytyuk, A. Chris, A. Pester, V. Mallet, H. Tanaka, et al. *Selected Papers of the X International Scientific Conference "Information Technology and Implementation" (IT&I 2023).* Workshop Proceedings. 3646, 86–95. Available at: https://ceur-ws.org/Vol-3646/#Paper_9.pdf

Ramirez, C. F., Reyes Guzman, J., and Cornejo, R. C. (2023). Implementation of a system for documentary procedures in public institutions applying robotic process automation (RPA). Proceedings of the 2023 IEEE 30th international conference on electronics, electrical engineering and computing, INTERCON 2023.

Regla, A. I., and Marquez, P. S. (2020). Workplace document management system employing cloud computing and social technology. *Lect. Notes Electric. Eng.* 603, 415–424. doi: 10.1007/978-981-15-0058-9_40

Reyes, A. G. F., Paraleon, C. N. A., Bibera, R. V. V., Garcia, S. J. E. B., and Estrella, N. E. (2023). FEDesk: a web and mobile document management system for the University of Santo Tomas Office for faculty evaluation and development, 58–68. doi: 10.1145/3634814.3634823

Rolo, A., Saraiva, M., Leandro, G., Nogueiro, T., and Alves, R. (2024). A comparative study of service quality in Portuguese and Angolan higher education institutions. eds. J. Reis, T. Pinho, V. Barbosa, L. Barreto, S. B. Moreira, P. Pardal, et al. *Driving Quality Management and Sustainability in VUCA Environments*. 199–208.

Romero-Sánchez, D., and Barrios, D. (2023). Modelo de ecuaciones estructurales para la evaluación de competencias tecnológicas en estudiantes universitarios. *TecnoLógicas* 26:e2470. doi: 10.22430/22565337.2470

Santos, G., Marques, C. S., Justino, E., and Mendes, L. (2020). Understanding social responsibility's influence on service quality and student satisfaction in higher education. *J. Clean. Prod.* 256. Scopus:120597. doi: 10.1016/j.jclepro.2020.120597

Saptarini, N. G. A. P. H., Ciptayani, P. I., Indrayana, I. N. E., and Pradnyana, I. P. B. A. (2024). The lecturer document management system in the COVID-19 pandemic: benefits, challenges, potential, and difficulties. En The spirit of recovery: IT perspectives, experiences, and applications during the COVID-19 pandemic (pp. 173–181).

Schlegel, D., Wallner, J., Monauni, M., and Kraus, P. (2023). Data-driven culture: a transformational framework. International conference on information systems, ICIS 2023: "Rising like a phoenix: emerging from the pandemic and reshaping human endeavors with digital technologies".

Sheela Rani, P., Janani, J., Krithika, C., Liba Keerthika, S., and Joshika, J. (2023). Blockchain-based file tracking and data management system for education sector. Proceedings of the 2nd IEEE international conference on advances in computing, communication and applied informatics, ACCAI 2023.

Sidhimantra, I. G. A. S., Dermawan, D. A., Fahmi, H. Z., Nudin, S. R., Hakim, S. R., and Asmunin (2024). Development of repository system to support accreditation process: the role of information system to vocational education. *AIP Conference Proceedings*. 3116. doi: 10.1063/5.0210441

Simwaka, K., Malanga, D. F., and Chipeta, G. T. (2023). The status of records management in Malawian private universities: the empirical case of University of Livingstonia. *Rec. Manag. J.* 33, 165–182. doi: 10.1108/RMJ-07-2022-0021

Sindakis, S., Kitsios, F., Kamariotou, M., Aggarwal, S., and Cuervo, W. J. M. (2024). The effect of organizational culture and leadership on performance: a case of a subsidiary in Colombia. *J. Gen. Manag.* 49, 115–132. doi: 10.1177/03063070221100048

Siva Rama Rao, A. V. S., Kavarakuntla, T., Kanipakam, S., Murari, T., Kumar, K. P., and Kumar, B. S. (2023). Blockchain-backed verification Systems for Enhanced Interoperability and Trust in managing legal documents across multi-cloud environments. *J. Electric. Syst.* 19, 254–269. doi: 10.52783/jes.637

Souza, L. G. S., and Aganette, E. C. (2022). Preservação digital: Perspectivas e relações com a gestão documental e a cultura organizacional. *AtoZ: novas práticas em informação e conhecimento*. 11, 1–13. doi: 10.5380/atoz.v11i0.82714

Sun, Y. (2022). Reform and optimization of university archives management under the background of big data. *Lect. Notes Electric. Eng.* 791, 1325–1332. doi: 10.1007/978-981-16-4258-6_161

Tkachenko, A. L., and Denisova, L. A. (2022). Designing an information system for the electronic document management of a university: automatic classification of documents 2182, 1–10. doi: 10.1088/1742-6596/2182/1/012035

Tsabedze, V. (2024). Managing Records in the age of artificial intelligence: how prepared are archives and records management professionals in Eswatini? *Internet Ref. Serv. Q.* 28, 77–95. doi: 10.1080/10875301.2023.2284898

Usta, Y., Carioni, G., and Mutani, G. (2024). Modeling and mapping solar energy production with photovoltaic panels on Politecnico di Torino university campus. *Energ. Effic.* 17, 53–74. doi: 10.1007/s12053-024-10233-w

Vidrevich, M., and Pervukhina, I. (2023). Higher education for sustainable environment: from theory to practice, 451:06009. doi: 10.1051/e3sconf/202345106009

Watanabe, S., Ito, H., Matsubara, M., and Morishima, A. (2024). Human-in-the-loop latent space learning for biblio-record-based literature management. *Int. J. Digit. Libr.* 25, 123–136. doi: 10.1007/s00799-023-00389-8

Žalėnienė, I., and Pereira, P. (2021). Higher education for sustainability: a global perspective. *Geogr. Sustain.* 2, 99–106. doi: 10.1016/j.geosus.2021.05.001

Zambrano Plúa, I. E., Quindemil Torrijo, E. M., and Rumbaut León, F. (2021). Gestión documental en universidades: Una mirada desde Latinoamérica: DOCUMENTARY MANAGEMENT IN UNIVERSITIES: A VIEW FROM LATIN AMERICA. *ReHuSo: Revista de Ciencias Humanísticas y Sociales* 6, 108–119. doi: 10.33936/rehuso.v6iEspecial.3779

Zhang, P., Ma, Z., Ren, Z., Wang, H., Zhang, C., Wan, Q., et al. (2024). Design of an automatic classification system for educational reform documents based on naive Bayes algorithm. *Mathematics* 12:1127. doi: 10.3390/math12081127

Zwitter, A. (2024). Cybernetic governance: implications of technology convergence on governance convergence. *Ethics Inf. Technol.* 26:24. doi: 10.1007/s10676-024-09763-9

More info

SDi@JPUTM

SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
3) An Overview of Advancing Green Energy Solutions and Environmental Protection Toward Green Universities (2024)	ES ENERGY & ENVIRONMENT (Article From : ENGINEERED SCIENCE PUBLISHER)

27th FEBRUARY 2025

SOURCE: PERPUSTAKAAN UTM

ES Energy Environ., 2024, **26**, 1338

ES Energy & Environment

DOI: https://dx.doi.org/10.30919/esee1338

An Overview of Advancing Green Energy Solutions and Environmental Protection Toward Green Universities

Ainur Seilkhan,[1, 2,*] Askhat Kuatbayev,[3] Gulmira Satybaldiyeva,[3] Веken Akbota,[1] Shicheng Zhang,[4] Gao Xiaojiang,[4] Zhanat Idrisheva[5,*] and Samal Issabayeva[6, 7,*]

Abstract

As global climate concerns escalate, higher education institutions are increasingly seen as pivotal in driving sustainability efforts. Green universities integrate environmental sustainability into education, research, operations, and community engagement, positioning themselves as critical players in mitigating climate change. This paper reviews green energy solutions and environmental protection measures in higher education, emphasizing the role of green universities in sustainable development. These institutions serve as research hubs for green technology and living labs promoting renewable energy, carbon reduction, and environmental stewardship. The study examines major global universities' green initiatives, with case studies from Europe, North America, Asia, and Kazakhstan. Highlights include how Abai University and Fudan University integrate green technologies, foster sustainability research, and develop educational programs to support environmental protection. Furthermore, the review explores challenges and opportunities for universities in shaping local, national, and global green energy policies. Insights and recommendations for future innovations in green education and campus sustainability are provided.

Keywords: Green technologies; Green University; Green Education; Methods of teaching geography; Green Energy Solutions; Sustainable development; Green economy

Received: 14 October 2024; Revised: 08 November 2024; Accepted: 13 November 2024.

Article type: Research article.

1. Introduction

An institution of higher learning that proactively incorporates environmental sustainability into all facets of its operations, governance, curriculum, research, and community outreach is known as a "Green University".[1] By implementing sustainable practices, encouraging environmental consciousness, and involving students, employees, and the larger community in initiatives to address global environmental concerns, these colleges aim to reduce their ecological footprint. By using renewable energy sources, managing trash, conserving water, and improving energy efficiency, green institutions seek to lessen the environmental effects of their campuses. In addition to their physical operations, they integrate sustainability into academic programs, supporting multidisciplinary environmental research and cultivating an environmental responsibility culture among staff and students.[2] Reducing resource usage, especially that of energy, water, and materials, is the goal of green colleges. This frequently entails energy-efficient building retrofits, the use of renewable energy sources (like solar or wind power), trash reduction through extensive recycling programs, and the promotion of sustainable modes of transportation (like cycling, public transportation, or electric cars).[3] A green institution builds its physical infrastructure with sustainability in mind. This could involve the use of low-energy technologies, green areas, and ecologically appropriate campus landscaping in addition to the use of sustainable building materials. Certifications like Leadership in Energy and Environmental Design (LEED) are frequently sought after by universities in order to certify the

[1] *Educational Program, Geography, Environment and Service Sector, Abai Kazakh National Pedagogical University, Dostyk Ave 13, Almaty, 050010, Kazakhstan*

[2] *Biomedical Research Centre, Al-Farabi Kazakh National University, Al-Farabi ave. 71, Almaty, 050040, Kazakhstan*

[3] *Faculty of forestry, wildlife and environment, S. Seifullin Kazakh agrotechnical research university, Astana city Zhenis avenue 62, 010011, Kazakhstan*

[4] *Environmental Building, Jiangwan Campus, Fudan University, No. 2205 Songhu Road, Yangpu District, Shanghai, 200437, China*

[5] *School of Earth Sciences, D. Serikbayev East Kazakhstan Technical University, Ulitsa Serikbayeva 19, Oskemen, 070000, Kazakhstan*

sustainability of their campuses and buildings.[4]

A green university's dedication to teaching sustainability is one of its defining characteristics. This may entail providing degrees, research opportunities, and courses on environmental topics, such as urban planning, biodiversity preservation, renewable energy, and climate change.[5] The goal of green institutions is to produce graduates who are not just aware of sustainability but also equipped to support sustainable solutions in the workplace.[6] Students, staff, and faculty at a green institution are all actively involved in sustainability activities. These establishments frequently provide funding for student-led environmental sustainability projects, plan campus-wide activities to encourage eco-friendly living, and promote sustainable behaviors (such as cutting back on single-use plastics, using less water, and choosing eco-friendly transportation). Involvement also includes encouraging sustainable practices among academic departments and administrative staff, as well as staff training.[7] To further sustainability efforts outside campus, green institutions usually work with other groups such as corporations, non-profits, and local governments. Through community participation, these relationships can generate sustainable innovation, offer students chances for experiential learning, and have a greater overall impact on society. In other words, "Green University" focuses not only on the environmental aspects of sustainability, but also on research and development, teaching, employee rewards, and so on.[8]

A green university needs strong institutional leadership to flourish. To supervise the incorporation of environmental concepts into university policy and operations, universities frequently establish sustainability offices or designate sustainability officers. In addition, these establishments might create sustainability action plans or strategies with objectives for cutting carbon emissions, enhancing energy economy, and promoting sustainability in research and teaching.[9] A green university aims to educate and equip the upcoming generation of professionals, researchers, and leaders to make positive contributions to a more sustainable world in addition to lessening its own environmental impact. It serves as a showcase for innovative approaches to sustainability and a model of sustainable behavior, highlighting the vital role that higher education institutions can play in tackling the world's environmental problems.[10] Over the course of several decades, the idea of the "Green University" has changed due to the increased awareness of environmental challenges and the part that educational institutions may play in finding solutions. International accords, worldwide environmental movements, and the pioneering work of universities that have incorporated sustainability into their operations, research, and teaching have all influenced this growth. An outline of the historical background and significant turning points in the evolution of green universities can be found below.[11] Several institutional, national, and international policies and frameworks have combined to force the transition of higher education towards sustainability.[12] Universities can incorporate sustainability into their operations, research, and educational missions with the help of these policies, which offer established rules, goals, and assessment methods. These universities will benefit the environment, improve their health, and save money in the long run by using renewable energy, which is more cost-effective due to its sustainable nature. While integrating this energy source on university campuses is environmentally benign, investment in this industry can also be advantageous.[13] Universities all throughout the world are becoming more and more involved in environmental stewardship as a result of laws aiming to lessen their influence on the environment and support sustainable development. The main international frameworks and policies that have influenced sustainability initiatives in higher education are examined in this section, along with the part played by institutional and government policies in facilitating the shift to green institutions.[14-19] Many universities have adopted global frameworks such as the United Nations' Sustainable Development Goals (SDGs) to align their sustainability efforts with broader global goals. Among them are Asian universities. Kazakh and Chinese universities are working comprehensively in this direction. Abai and Fudan universities, the subjects of this case study, often serve as living laboratories for sustainable technologies and practices, providing research opportunities and encouraging environmental protection among students, faculty and staff. This literature review analyzes the green technology research of Abai and Fudan Universities, explores their development as green universities, examines examples of institutions that have successfully integrated sustainability into their operations in the practice of world-leading green universities, and discusses the key components and challenges of building green campuses. At the same time, it aims to provide a comprehensive understanding of how Abai and Fudan universities are contributing to global sustainability efforts and the potential impact of green technology research initiatives on future generations and their place in green education.

2. Methodology

To gather relevant literature, the following scientific databases were systematically searched: PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar, Springer, and Wiley. The search utilized a range of MeSH terms, including: "Green economy", "Green technologies", "Green University", "Green Education", "Abai University", “Methods of teaching

[6] *Faculty of geography and environmental management, Al-Farabi Kazakh National University, Al-Farabi ave. 71, Almaty, 050040, Kazakhstan*

[7] *Institute of Biotechnology and ecology, Zhetysu University named after Ilyas Zhansugurov, 187a., Zhansugurov Street, Taldykorgan, 040000, Kazakhstan*

**Email:* ainura_seilkhan@mail.ru (A. Seilkhan), Zhanat_Idrisheva@mail (Z. Idrisheva), isabayevasamal@gmail.com (S. Issabayeva)

geography", "Fudan University" and "Sustainable development". The review included studies that met the following criteria: Relevant works phrase would allow for a broad yet concentrated search of papers about sustainable development, green technologies, energy solutions, and environmental education in higher education institutions., along with potential mechanisms of action; Publications available in English, Kazakh, Russian, and Chinese. The following types of publications were excluded from the review: duplicate and incomplete studies, abstracts without full text, letters to the editor or opinion pieces, and research involving unrelated homeopathic experiments. Data extraction was conducted using a standardized form to ensure consistency. A qualitative synthesis of the literature was then performed, categorizing studies based on themes related to sustainability practices, educational initiatives, and research outcomes. This thematic analysis enabled the identification of common trends, challenges, and best practices among the two universities. University names such as "Abai University" and "Fudan University" may not always appear as MeSH terms because they are specific institutions, so it is recommended to use their general terms (*e.g.*, "Educational Institutions" or "Universities") and link those to broader concepts such as "Sustainability" or "Energy Management". This involved Examining the scope of green technologies researched at each institution, Assessing the integration of sustainability in their respective educational curricula, and Evaluating community engagement initiatives and their impact. The review acknowledges potential limitations, including The language barrier in accessing non-English publications, The variability in the quality and focus of studies included, and The rapid evolution of green technologies, which may result in some studies becoming quickly outdated. This methodology outlines a systematic approach to evaluating the collaborative efforts in green technology research at Abai and Fudan Universities. By synthesizing existing literature, the study aims to contribute valuable insights into the role of higher education institutions in promoting sustainability and addressing global environmental challenges. This search strategy ensured a thorough examination of the subject and created a solid foundation for comprehending the current landscape of green energy solutions and environmental protection initiatives in green institutions. The findings of this assessment will help shape future suggestions for sustainable campus transitions in the face of climate change and global sustainability challenges.

3. Historical context and development of green universities

The worldwide sustainability movement has influenced the development of the idea of a "green university." The Talloires Declaration was created in 1990 as a result of higher education institutions realizing in the 1990s how important it was to address environmental challenges. Global university leaders pledged to support sustainability and environmental literacy in operations, outreach, research, and teaching by signing this declaration. Many more frameworks have been developed since then to direct colleges' environmental initiatives. Numerous colleges have been inspired to take proactive steps toward being more sustainable by the UN-initiated Higher Education Sustainability Initiative (HESI) and the sustainability goals adopted by national and regional education policies.

By incorporating sustainability into their institutional plans, universities like the University of Copenhagen in Denmark and the University of British Columbia in Canada have set the standard for what it means to be a green university. In addition to concentrating on lessening their environmental impact, they have included the neighborhood, teachers, and students in the sustainability process.[20]

In the 1960s and 1970s, the environmental movement emerged. Green universities were made possible by the current environmental movement, which had its start in the 1960s and gathered major steam in the 1970s. Environmental activism spread throughout the world as a result of growing public awareness of problems like pollution, resource depletion, and biodiversity loss, which was sparked by publications like Rachel Carson's Silent Spring (1962). Universities started to investigate their role in tackling environmental challenges during this time. The introduction of environmental science programs prompted colleges to investigate the environmental effects of their campuses. However, compared to later efforts, these earlier initiatives were frequently dispersed and lacked the institutionalized, all-encompassing approaches to sustainability.[21]

Growing Environmental Awareness in Higher Education in the 1980s. Higher education began to pay more attention to sustainability in the 1980s as a result of broader environmental concerns in society. Universities started thinking about ways to make their own operations more sustainable, but their efforts were usually focused on one or two specific projects like energy-saving techniques or recycling programs. The establishment of environmental studies and sustainability programs at various institutions throughout this decade was a significant milestone. The goal of these programs was to give pupils the information and abilities they would need to deal with environmental issues. However, most institutions did not yet fully incorporate sustainability into their operations.[22]

Institutional commitments and the Talloires Declaration in the 1990s. A watershed in the history of green universities was reached in the 1990s when the formal recognition of the necessity for institutional commitment to sustainability was achieved. Throughout the decade, a number of significant international frameworks were introduced, encouraging academic institutions to assume leading positions in the promotion of sustainability. The Talloires Declaration, which was signed in 1990 by international university leaders, was one of the biggest turning points. The Talloires Declaration, which was started by Tufts University President Jean Mayer, was the first formal pledge to sustainability made by an institution of higher learning. Universities were urged by the

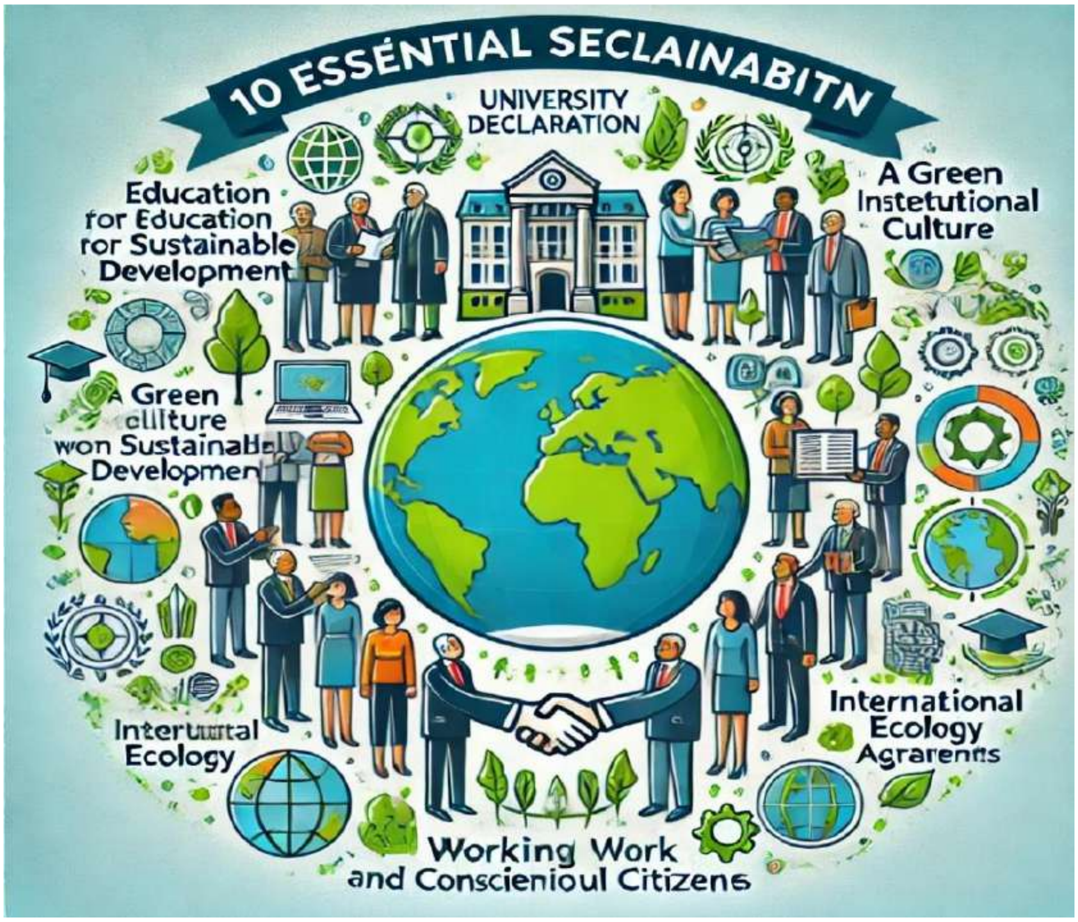


Fig. 1 Talloires declaration.

declaration to actively participate in environmental sustainability through their operations, research, and teaching.[23]

The proclamation was signed by more than 500 university presidents from more than 50 countries in the early 2000s. The declaration also includes actions for the implementation of sustainable development, which must be carried out by everyone involved in science and education: promoting UR and informing society about global problems, forming a responsible attitude of society to the environment, practicing environmental programs, involving the population in environmental programs, *etc*. d. In 2000, a document was adopted at the headquarters of UNESCO in Paris - the international declaration of the Earth Charter, promoting sustainable development, a sustainable way of life, formulating the basic values and principles necessary for humanity at this stage of development to create a sustainable, peaceful and just global society. Ten essential steps (Fig. 1) that universities should take to address environmental challenges were listed in the Talloires Declaration:

- Educate people about development that is environmentally sustainable.
- Establish sustainable institutional cultures.
- Teach students to be conscientious citizens.
- Encourage everyone to become environmentally literate.
- Use institutional ecology to run organizations in a sustainable manner.
- Engage all parties involved in sustainability activities, including staff, teachers, and students.
- Work along with outside groups.
- bolster the potential for multidisciplinary sustainability methods.
- Strive to put international accords on sustainability into effect.
- Create policies and initiatives that will promote sustainability in higher education.

With this proclamation, universities made a significant collective effort to integrate sustainability into their mission for the first time, paving the way for larger-scale sustainability initiatives in the years to come.[24]

The 2000s: Expanding Global Frameworks and Sustainability Networks. Around the world, sustainability programs at universities proliferated in the early 2000s, and international frameworks and organizations that aided in their implementation also developed during this time. There were other variables that led to this acceleration: International Environmental Treaties: With the passage of the Kyoto Protocol in 1997 and the increasing awareness of the urgency of climate change, universities have been forced to take more significant steps to minimize their carbon footprints and promote sustainability.[25,26] Rankings and Reports on Sustainability: Universities now have the means to monitor and report on their sustainability performance thanks to the growth of sustainability assessment frameworks like the Sustainability Tracking, Assessment & Rating System (STARS), created by the Association for the Advancement of Sustainability in Higher Education (AASHE). In a similar vein, the 2010 establishment of the UI GreenMetric World University Ranking established a standard for evaluating colleges' sustainability initiatives across the globe.[27] Campus Sustainability Offices: To supervise the incorporation of environmental programs into campus operations, numerous colleges during this time frame set up specific sustainability offices or hired sustainability coordinators. These offices were essential in formulating strategies for sustainability, monitoring advancements, and endorsing eco-friendly behaviors.[28] Universities started to take a more comprehensive approach to sustainability, going beyond discrete initiatives to create all-encompassing strategies that included waste management, energy, water, transportation, and sustainable food systems. Universities like the University of California and British Columbia (UBC) rose to prominence in the green university movement by establishing challenging goals for energy efficiency, carbon neutrality, and sustainable infrastructure.[29]

The 2010s: Goals for Institutional Sustainability and Climate Change. By the 2010s, several colleges had set aggressive targets to lessen their environmental effect, and sustainability had become a mainstream priority. The 2015 Paris Agreement further sparked academics' efforts to coordinate their plans with international climate action.[30] During this time, some significant developments include Goals for Carbon Neutrality: Numerous academic institutions pledged to become carbon neutral, with some establishing deadlines as early as 2030. The University of California system, for instance, promised to achieve carbon neutrality by 2025.

Green Building Guidelines: New campus buildings are now required to have green building certifications like LEED, and many colleges have upgraded their current infrastructure to meet energy efficiency requirements.[31] Sustainable Mobility and Energy Use: In addition to investing in renewable energy sources like solar and wind power, universities are pushing more and more sustainable modes of mobility, such as cycling, public transportation, and electric vehicle charging stations. Student Engagement: With students taking part in activism, research on sustainability, and climate action plans, student-led initiatives have become essential to campus sustainability efforts. Universities have also started to include sustainability into their curricula more thoroughly, providing chances for multidisciplinary degrees and research in the fields of environmental science, sustainability, and climate studies.[32]

The 2020s: Academic Institutions' Contribution to Global Sustainability. Universities now play an even more prominent role as sustainability leaders in the 2020s. Universities are taking on the duty of educating the next generation of leaders to tackle global concerns like climate change in addition to trying to lessen their own environmental footprints in light of the world's tremendous environmental challenges. This era's major trends include Sustainability in Curriculum and Research: Universities are realizing that environmental literacy is critical for all fields, from business and engineering to the arts and social sciences, and are incorporating sustainability into all areas of study.[33] Partnerships and International Networks: Universities are collaborating to share best practices and create group strategies for tackling climate change and sustainability through international networks like the Global University Leaders Forum (GULF) and the International Sustainable Campus Network (ISCN).[34]

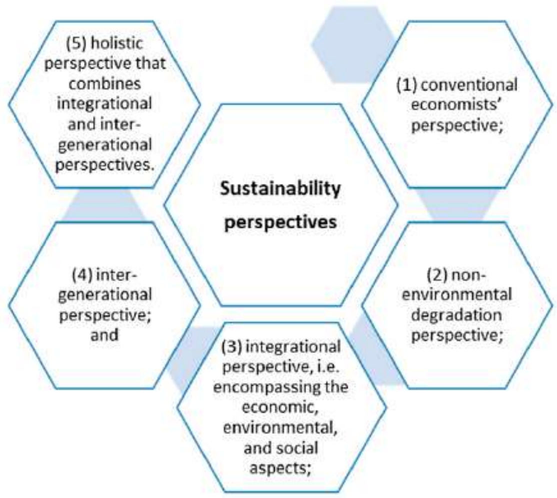


Fig. 2 Sustainability as seen from five different perspectives in published literature.[35]

Technology and Innovation: Universities can now monitor and optimize their energy and resource use in real time, leading to more sustainable and efficient operations. This is made possible by advancements in data analytics, smart campus technology, and the Internet of Things (IoT).[36] Decades of environmental awareness, international agreements, and institutional leadership have molded the growth of green universities. The idea of a "Green University" has grown from early recycling initiatives to all-encompassing sustainability plans that address every facet of campus life, making it a potent force for environmental sustainability. In the coming decades, universities' role in tackling global issues like climate change will only grow more crucial as they keep innovating and setting the standard for sustainability.[37]

4. Policy and frameworks for sustainability in higher education

Policies at the institutional, national, and international levels frequently influence sustainability in higher education.[38] While national regulations may put specific legal requirements or incentives on universities to reduce their environmental effect, international frameworks, such as the United Nations SDGs, offer a broad path for institutions to follow.

Numerous academic institutions have created sustainability plans that contain precise goals for cutting energy use, controlling waste, and advancing environmentally friendly transportation. Collaboration between several departments, including as facilities management, student services, and academic programs, is common in these strategies (Fig. 2).[39] Several institutional, national, and international policies and frameworks have combined to force the transition of higher education towards sustainability. Universities can incorporate sustainability into their operations, research, and educational missions with the help of these policies, which offer established rules, goals, and assessment methods. Universities all throughout the world are becoming more and more involved in environmental stewardship as a result of laws aiming to lessen their influence on the environment and support sustainable development. The main international frameworks and policies that have influenced sustainability initiatives in higher education are examined in this section, along with the part played by institutional and government policies in facilitating the shift to green institutions.[40]

Several global frameworks and agreements have played a significant role in encouraging universities to adopt sustainability practices. These frameworks provide a shared vision and set of goals for institutions to follow, promoting collaboration across borders and disciplines.

The Sustainable Development Goals (SDGs) of the United Nations, which were adopted in 2015, are among the most significant international frameworks for sustainability (Fig. 3). With regard to a wide range of concerns like poverty, inequality, climate change, environmental degradation, and peace, the 17 SDGs offer a comprehensive framework for attaining sustainable development. As they offer the research, instruction, and creativity required to create long-term solutions to these global issues, higher education institutions are essential to accomplishing the SDGs.[41] Universities should pay particular attention to the following SDGs:

The necessity of inclusive and equitable education, including sustainability literacy, is emphasized by SDG 4: Quality Education.

In order to lessen their carbon impact, several institutions are seeking the use of renewable energy sources, which is encouraged by SDG 7: Affordable and Clean Energy.

One of the main priorities for colleges that are committed to carbon neutrality and climate resilience is SDG 13: Climate Action, which emphasizes the necessity for immediate action to prevent climate change.

Since many universities act as urban hubs and have a significant impact on the surrounding communities through their sustainable practices, SDG 11: Sustainable Cities and Communities is pertinent.

Universities support the SDGs through research, teaching, community participation, and campus sustainability initiatives.[42] Using the SDGs as a framework for institutional policies and practices, organizations including Harvard University, the University of Edinburgh, and Nanyang Technological University have matched their sustainability initiatives with the goals.[43]

The Talloires Declaration (1990) is among the first official university commitments to sustainability, as was noted in the historical context. It was the first formal declaration of support for environmental sustainability in higher education from university administrators. The proclamation lists ten essential steps that colleges may take to advance sustainability, such as raising awareness, encouraging the study of sustainability, and integrating sustainable practices into day-to-day operations (Fig. 3). Currently, more than 500 organizations from around the globe have signed the Talloires Declaration. It is important because it pushes academic institutions to actively integrate sustainability into their operations and strategic goals rather than just teaching it. The Talloires Declaration has served as a basis for the creation of more extensive sustainability plans at universities that have signed it, including Tufts University and the University of British Columbia.[35]

Fig. 3 17 Sustainable Development Goals (Source: https://sdgs.un.org/goals).[44]

The initiative for sustainable higher education (HESI). 2012 saw the introduction of the HESI at the Rio+20 United Nations Conference on Sustainable Development. Through this program, higher education institutions from all over the world can work together on sustainability projects, exchange best practices, and report on how well they're doing at incorporating sustainability into their operations, research, and courses.[44] Universities can present their sustainability accomplishments on the HESI platform and work together to address global issues pertaining to social inclusion, economic development, and environmental sustainability. Members of HESI contribute to the greater worldwide endeavor to promote sustainable development by coordinating their objectives with global initiatives such as the SDGs.[45]

ISCN stands for the International Sustainable Campus Network. Another international structure that promotes university adoption of sustainable practices and knowledge-sharing to achieve campus sustainability is the International Sustainable Campus Network (ISCN). Members of ISCN pledge to include sustainability in three main areas:

Leadership and Strategy: To guarantee sustained dedication and integration throughout the entire university, universities are urged to establish sustainable leadership frameworks.

Campus Operations: Through waste management, water conservation, energy efficiency, and sustainable procurement, institutions try to lessen their ecological imprint.[46]

Engagement of Students and Faculty: ISCN encourages universities to function as "living labs" where new sustainable practices and technologies may be tested and put into reality. This involves students and faculty in sustainability projects.

Universities can collaborate on projects, share ideas, and establish challenging sustainability targets with ISCN. Members of the network come from all around the world, including prestigious universities like the Massachusetts Institute of Technology (MIT) and ETH Zurich.[47]

5. Policies at the federal and local levels to promote sustainability in higher education

University sustainability strategies are also heavily influenced by regional and national governments. These regulations frequently establish clear environmental goals and give colleges financial support, incentives, and legal guidelines. Policies of the European Union. The implementation of environmental rules and financial programs by the European Union (EU) has played a significant role in promoting sustainability in higher education. Universities are important players in the EU's objective of making Europe the first climate-neutral continent by 2050, as outlined in the European Green Deal. Universities are encouraged by EU policies to lower carbon emissions, support renewable energy sources, and include sustainability into their research and teaching.[48] Research and innovation-focused EU financing initiatives like Horizon Europe give substantial financial support to university projects pertaining to sustainability. Universities can receive funds, for instance, to explore mitigation measures for climate change, create clean energy technology, and support sustainable urban development. The European University Initiative, which encourages cooperation between academic institutions throughout Europe by assisting them in exchanging best practices and creating collaborative sustainability plans, is another initiative in which EU universities take part.[49]

National Policies and Strategies. National policies have been created in many nations to support sustainability in higher education. These laws frequently establish goals for reducing carbon emissions, mandate that colleges increase their energy efficiency, and allocate funds for environmentally friendly infrastructure initiatives. Under the Climate Change Act 2008, which requires a reduction in greenhouse gas emissions, universities are urged to contribute to national carbon reduction targets in the United Kingdom. Numerous universities in the United Kingdom, like the University of Exeter and Edinburgh, have implemented ambitious sustainability plans that include targets to become carbon neutral by 2030 or sooner.[50] With funding from the Higher Education Sustainability Advancement Program (HESAP), universities play a major role in national sustainability initiatives in Australia. Universities can use the funds from this program to create sustainability strategies, carry out environmental research, and lessen the environmental impact of their daily operations.[51] National policies have been created in many nations to support sustainability in higher education. These laws frequently establish goals for reducing carbon emissions, mandate that colleges increase their energy efficiency, and allocate funds for environmentally friendly infrastructure initiatives. Universities are at the forefront of China's policy attempts to promote green development. The country has undertaken several policies in this regard. Chinese colleges are urged under the Green Campus Initiative to lower their energy usage, use renewable energy sources, and include sustainability into their curricula. Notable examples of Chinese universities spearheading environmental initiatives are Tsinghua University and Peking University.[52] National policies have been created in many nations to support sustainability in higher education. These laws frequently establish goals for reducing carbon emissions, mandate that colleges increase their energy efficiency, and allocate funds for environmentally friendly infrastructure initiatives. Universities create their own sustainability frameworks and policies at the institutional level, frequently drawing inspiration from national and international frameworks. Usually, these policies have explicit objectives like lowering carbon emissions, enhancing the energy economy, encouraging environmentally friendly transportation, and involving employees and students in environmental projects.[53] Numerous academic institutions have created climate action plans or sustainability action plans that delineate their stances on sustainability and establish quantifiable goals for mitigating environmental effects. National sustainability regulations and international frameworks like the SDGs frequently serve as the basis for these programs.

A thorough Climate Action Plan created by the University of British Columbia (UBC) lays out precise goals for cutting greenhouse gas emissions, improving energy efficiency, and switching to renewable energy sources. Strategies for improving sustainability research and teaching are also included in UBC's plan. A Sustainability Design Framework developed by Stanford University incorporates sustainability into infrastructure, planning, and operations on campus. The application of green building standards, water conservation, and waste reduction techniques are highlighted in this framework.[54] Sustainability evaluation instruments are widely used by universities to track and report on their progress. The Sustainability Tracking, Assessment & Rating System (STARS), created by the Association for the Advancement of Sustainability in Higher Education (AASHE), is one of the most used instruments. Universities can evaluate their sustainability performance in a number of areas, including academics, operations, engagement, and planning, using the thorough framework that STARS offers.[55]

The UI GreenMetric World University Ranking, which rates universities according to their sustainability efforts in areas including energy and climate change, waste management, and transportation, is another well-liked evaluation instrument.[56] To steer institutions toward more sustainable futures, frameworks and policies for sustainability in higher education are crucial. Overarching objectives are provided by international frameworks such as the UN Sustainable Development Goals and the Talloires Declaration, while national policies give regulatory support and incentives for institutions to engage. Universities are creating their own sustainability plans, establishing challenging goals, and monitoring their progress with assessment tools at the institutional level. When combined, these frameworks and regulations enable universities to become leaders in sustainability, both by reducing the environmental impact of their operations and by training the next generation of leaders to take on the world's environmental concerns.[57]

6. Green university initiatives: case studies

6.1 European universities

Prominent European universities have spearheaded the green university movement, propelled by their institutional dedication and local initiatives like the European Green Deal. Comprehensive sustainability programs that incorporate green campus operations, research, education, and student engagement have been implemented by universities around Europe. In this section, case studies of eminent European institutions that have made notable progress toward becoming green universities are highlighted.[58]

6.1.1 University of copenhagen (denmark)

It is well known that the University of Copenhagen (UCPH) is making significant strides in sustainability, especially in cutting carbon emissions and incorporating sustainability into all facets of campus life. Launched in 2014, the organization's Green Campus 2020 Strategy provided a detailed plan for cutting energy use, encouraging environmentally friendly transportation, and incorporating sustainability into research and teaching. UCPH used a variety of strategies to meet its target of reducing carbon emissions by 65% by 2020 (in comparison to 2006 levels). With an emphasis on creating new, ecologically friendly buildings and enhancing the energy efficiency of already-existing ones, UCPH has made investments in sustainable campus infrastructure. With attributes like cutting-edge insulation, rainwater harvesting systems, and intelligent lighting technologies, a number of campus buildings have earned certification under the LEED program.[59] By providing a variety of programs and courses centered around environmental studies, climate change, and sustainability science, the university has included sustainability into its curriculum. It has also encouraged multidisciplinary study on important environmental issues like urban sustainability, renewable energy, and biodiversity loss. UCPH encourages environmentally friendly ways for employees and students to commute by offering a wide range of bicycle amenities, such as programs for bike sharing and parking. Additionally, the university promotes public transportation use by providing faculty and students with discounted transit passes. With the implementation of extensive recycling systems and the removal of single-use plastics from campus, the university has decreased the amount of garbage it produces overall.[60]

UCPH has been a leader in campus sustainability in Europe by emphasizing energy efficiency, carbon reduction, and sustainability education. The university's attempts to match its objectives with the SDGs of the UN serve as more proof of its dedication to taking the lead on environmental issues worldwide.[61]

6.1.2 University of edinburgh (United Kingdom)

The University of Edinburgh is well known for being a pioneer in the field of sustainability. Climate Strategy 2040, which sets lofty objectives to attain carbon neutrality and integrate sustainability across all operations, research, and teaching, reflects the university's all-encompassing approach to sustainability. The institution has implemented a sustainable procurement policy that prioritizes obtaining products and services with minimal environmental impact. This entails choosing products that are energy-efficient or constructed of recycled materials, as well as giving preference to suppliers who adhere to environmentally friendly standards. The Edinburgh Centre for Carbon Innovation (ECCI), which promotes cooperation between academics, industry, and governmental organizations to create novel responses to climate change, is housed at the university. Sustainable urban development, low-carbon transportation, and renewable energy are some of the subjects of ECCI research.[62]

One of the first colleges in the UK to pledge to divest from fossil fuel firms was the University of Edinburgh in 2015. As part of the university's larger initiatives to support moral and sustainable investment practices, this decision was made in response to persistent pressure from student activists. The institution has made sustainability a significant aspect of its curriculum, offering a wide range of undergraduate and postgraduate programs focused on environmental science, sustainability studies, and climate change. The ECCI also gives students the chance to work on multidisciplinary climate action research projects and policy development initiatives.[63] The University of Edinburgh is a role model for other universities in the UK and beyond because of its all-encompassing approach to sustainability. Higher education institutions may play a crucial role in tackling global environmental concerns, as seen by their dedication to climate-focused research, sustainable procurement, and carbon neutrality.[64]

6.1.3 Wageningen University & research (Netherlands)

A global leader in the fields of agriculture and environmental sciences, Wageningen University & Research (WUR) (Fig. 4) is renowned for emphasizing sustainability in both campus operations and research. As a major participant in international sustainability programs, WUR is dedicated to tackling the problems of climate change, biodiversity loss, and food security. With solar panels, energy-efficient buildings, and green roofs, WUR has created a very sustainable campus. The university's Sustainability Vision 2030 lays out aggressive goals to support sustainable resource management, increase biodiversity on campus, and lower energy use.[65]

A number of the buildings on the WUR campus are accredited by the Building Research Establishment Environmental Assessment Method, or BREEAM, a designation that honors sustainable building techniques. The structures are made to use sustainable materials, minimize energy use, and maximize natural light. Leading the way in agricultural research worldwide, WUR has created a number of programs to establish sustainable food systems. Research on sustainable livestock management, organic farming, and lessening the environmental effects of food production are all included in this. Additionally, the university collaborates and reaches out to farmers, governments, and businesses to help promote sustainable farming methods globally.

WUR encourages material reuse and recycling on campus and has adopted the circular economy concept. Composting, extensive recycling programs, and campaigns to promote item repair and reuse over disposal all help reduce waste.

Research on sustainability at WUR is conducted in a number of fields, such as biodiversity conservation, agricultural innovation, and environmental science. Researchers at the institution are leading the way in creating answers for urgent global problems like biodiversity loss, deforestation, and climate change. Sustainability is deeply ingrained in Wageningen University's operations, relationships, and research. It is known as one of the top green institutions in the world thanks to its efforts in advancing environmentally friendly farming methods and creating cutting-edge solutions to pressing global issues.[66]

6.1.4 Technical University of Munich (Germany)

The Technical University of Munich (TUM) is renowned for its attempts to incorporate environmentally friendly practices into campus operations and for its cutting-edge engineering and sustainability research. The main objectives of TUM's sustainability strategy include cutting carbon emissions, improving energy efficiency, and encouraging a sustainable culture among employees and students. TUM has put in place a number of energy-saving initiatives, such as deploying renewable energy sources, including solar panels and geothermal heating systems and upgrading campus buildings to increase energy efficiency. The university also encourages environmentally friendly mobility by offering staff and students access to bike sharing programs and electric vehicle charging points.

The Center for Energy and Environment at the university acts as a focal point for multidisciplinary research aiming at creating long-term solutions to environmental problems around the world. With an emphasis on environmental engineering, renewable energy, and sustainability, TUM provides a range of degree programs and courses. The institution promotes interdisciplinary collaboration and problem-solving by encouraging students from all disciplines to get involved with environmental issues. TUM has instituted trash reduction measures throughout its campuses, including extensive recycling schemes and endeavors to curtail the utilization of plastic. By giving preference to ecologically friendly goods and services in its procurement practices, the institution additionally promotes sustainable resource management. The campus operations, research endeavors, and instructional efforts of TUM all demonstrate the university's dedication to sustainability. The university is significantly contributing to the advancement of sustainability in Germany and abroad by encouraging innovation in fields like green mobility and renewable energy.[67]

Fig. 4 Wageningen University & Research (Source: https://mastergradschools.com/school/wageningen-university)

European universities like the University of Copenhagen, University of Edinburgh, Wageningen University, and Technical University of Munich establishing the standard for sustainability in higher education, European universities have been at the forefront of the worldwide green university movement. The various ways that colleges are incorporating sustainability into their operations, research, teaching, and community involvement are demonstrated by these case studies. These universities are setting an example for how higher education may support international efforts to battle climate change and advance sustainable development through their ambitious climate initiatives, construction of sustainable infrastructure, and multidisciplinary research.[68]

6.2 North American universities

Universities in North America have played a significant part in the worldwide green university movement, with numerous schools adopting a leading position in sustainability. Comprehensive sustainability strategies, ranging from carbon neutrality targets to green building projects and sustainable research programs, have been established by universities in the United States and Canada. The case studies of top North American colleges that have significantly aided in the development of sustainable campuses and communities are highlighted in this section.[69]

6.2.1 University of British Columbia (Canada)

Globally renowned for its sustainability activities, the University of British Columbia (UBC) in Vancouver, Canada, is at the forefront of the green university movement. Multidisciplinary research, community involvement, and green campus operations are all incorporated into UBC's holistic approach to sustainability.

In order to achieve sustainability across the entire campus and lower greenhouse gas emissions, UBC has created an ambitious Climate Action Plan. Achieving net-zero carbon emissions by 2050 and cutting GHG emissions by 67% by 2025 are important objectives. According to a green construction guideline that UBC has implemented, every new facility constructed on campus must achieve the highest certification levels for sustainability.[70] Located on campus, the Centre for Interactive Research on Sustainability (CIRS) is among North America's greenest structures.[62] With net-positive energy and water systems, CIRS produces more energy than it uses and has its own wastewater treatment facility.

With a large selection of degrees and courses pertaining to sustainability, UBC is dedicated to promoting sustainability in its academic programs. The goal of the university's Sustainability Initiative is to advance interdisciplinary research in order to address intricate environmental problems like biodiversity loss, climate change, and sustainable food systems. Additionally, UBC uses a "living laboratory" concept in which research and teaching are conducted using sustainability projects that are incorporated into campus operations.

UBC promotes carpooling, bicycling, and public transportation as sustainable modes of transportation. The university runs one of the biggest transit networks of any college in North America and has increased the amount of space dedicated to cycling, including bike lanes and parking.[71] The quantity of single-occupancy car journeys to campus has been greatly decreased as a result of this endeavor.

By 2030, UBC wants to have a zero-waste campus. To that end, the university is taking steps to increase recycling and composting rates and divert 80% of garbage from landfills. The institution has removed single-use plastics from campus food services and put in place extensive waste sorting systems. UBC's integrated approach to research and education, along with its ambitious climate targets and green buildings, demonstrate the university's dedication to sustainability. The university is a role model for other academic institutions across the globe because of its attempts to establish a living laboratory where sustainability is ingrained in campus life.[72]

6.2.2 University of California (USA)

With ten campuses, the University of California (UC) system is a leader in sustainability, with each institution putting ambitious sustainability projects into action. The UC system has won awards for taking the lead in lowering carbon emissions, supporting renewable energy sources, and integrating sustainability into curricula.

The University of California is the first large university system in the world to have made a commitment to achieve carbon neutrality by the year 2025. UC has launched a number of measures to do this: For new construction and significant renovations, the UC system has adopted LEED certification criteria; several buildings on campus have achieved LEED Gold or Platinum status as a result. The three main focuses of UC's green construction regulations are interior environmental quality, water conservation, and energy efficiency.[73]

Across all of its campuses, the UC system is dedicated to encouraging sustainable food procurement and minimizing food waste. Reducing the environmental effect of food production and consumption, UC is tackling food security and encouraging sustainable agriculture through the Global Food Initiative. Additionally, UC campuses have set goals to obtain 20% of their food sustainably and regionally by 2025.[74]

UC campuses are pioneers in advocating for environmentally friendly modes of mobility, including public transportation, bike-sharing programs, and growth in the usage of electric automobiles. With more than 20,000 bikes on campus, UC Davis, for instance, has one of the largest cycling infrastructures of any university in the United States. Furthermore, UC Berkeley has started a fleet electrification effort to swap out its fossil fuel-powered cars for electric ones. UC wants to remove at least 90% of its garbage from landfills by 2020 in order to reach its zero waste target.[75] Despite the fact that some campuses have not yet achieved this aim, great strides have been made. Numerous campuses have outlawed single-use plastics and established extensive recycling and composting programs. Boldly aiming for carbon neutrality and zero waste, the University of California system has established itself as a global pioneer in sustainability. Other institutions might take inspiration from UC's system-wide approach to sustainability, which places a strong focus on renewable energy, green buildings, and sustainable food systems.

6.2.3 Arizona State University (USA)

Arizona State University (ASU) has received praise for its extensive efforts toward sustainability, especially in the areas of community involvement and research. ASU's dedication to sustainability stems from its goal of setting an example for a sustainable future by emphasizing renewable energy, energy efficiency, and cutting-edge sustainability research. By 2025, ASU aims to be carbon neutral for its scope 1, scope 2, and non-transportation scope 3 emissions; by 2035, it will be carbon neutral for its transportation emissions. The core of ASU's sustainability initiatives is the Global Institute of Sustainability and Innovation (GIOSI). In order to address global sustainability issues like climate change, renewable energy, and sustainable urban development, GIOSI carries out multidisciplinary research.[76] Innovation at ASU has produced advances in fields, including solar energy and water conservation. Due to its location in the arid Southwest, ASU is a pioneer in water conservation and sustainable urban development research. ASU collaborates with local businesses and governments to advance sustainability in urban design, water management, and the utilization of renewable energy sources through programs like the Sustainable Cities Network. One of the first colleges in the country to offer a sustainability undergraduate degree was ASU, which has subsequently grown to include master's and doctoral degrees. The university's School of Sustainability provides multidisciplinary instruction that equips students to address environmental issues in a variety of fields.[77]

With an emphasis on resource management, recycling, and waste reduction, ASU advances the idea of the circular economy. ASU has put in place initiatives to encourage recycling, cut down on food waste, and repurpose items. Additionally, the university is home to Sustainable Earth, a platform that encourages cooperation on circular economy principles amongst academic institutions, business, and government officials. ASU is now regarded as a global example for sustainable universities due to its leadership in energy efficiency, community involvement, and sustainability research. By integrating sustainability into its research, education, and operations, ASU illustrates how institutions may drive significant change at both local and global levels.[78]

6.2.4 University of Michigan (USA)

The University of Michigan (U-M) has a long history of being a leader in sustainability, emphasizing sustainable research, campus operations, and climate action. U-M’s Campus Sustainability Integrated Assessment provides a roadmap for achieving its sustainability goals. The University of Michigan established a goal in 2021 for all three of its campuses to become carbon-neutral by 2040. U-M has increased the use of renewable energy sources, made investments in carbon offsets, and upgraded energy efficiency in order to achieve this aim. The Graham Sustainability Institute at the University of Michigan supports multidisciplinary research on environmental justice and climate science, among other sustainability-related themes. The institution also backs programs like the Dow Sustainability Fellows Program, which gives graduate students working on sustainability-related research funds and mentoring.[79]

Through programs like its Sustainable Food Program, which focuses on lowering the environmental impact of campus dining services and supporting local, sustainable food sourcing, U-M is dedicated to developing sustainable food systems. The institution also promotes farmers' markets and campus gardens, which give employees and students access to fresh, locally farmed food. U-M has made investments in environmentally friendly transportation infrastructure, encouraging carpooling, public transportation, and biking. The institution has constructed multiple electric vehicle charging stations on campus in addition to operating a sizable fleet of hybrid and electric buses.

With initiatives to boost recycling and composting, cut down on food waste, and do away with single-use plastics, U-M is striving to achieve zero waste.[80] The Blue Initiative promotes resource conservation and waste reduction by including the whole school community in sustainability initiatives. The University of Michigan has become a leader in the green university movement thanks to its emphasis on sustainability research, carbon neutrality, and community participation. Other universities should take note of U-M's comprehensive strategy for incorporating sustainability into its academic offerings and campus operations.

The University of British Columbia, Arizona State University, the University of California system, and the University of Michigan are just a few of the North American universities that have launched large-scale sustainability programs that combine carbon reduction, renewable energy, green building, and sustainability education. These colleges are leading the way in sustainability research, community involvement, and policy advocacy, in addition to lessening their environmental impact. These institutions are helping the worldwide movement to build more sustainable futures for higher education and beyond by sharing best practices and setting high standards.[81]

6.3 Asian universities

Asia's universities have taken the lead in sustainability, implementing creative strategies to incorporate eco-friendly practices into operations, research, and instruction. Numerous Asian institutions are situated in fast-developing areas with particularly severe environmental problems like resource depletion, urbanization, and climate change. Universities now actively participate in promoting sustainability on campus and in the larger communities they serve as a result of this setting. The case studies of top Asian green institutions are included in this area, demonstrating their dedication to sustainability.[82]

6.3.1 Nanyang Technological University (Singapore)

Renowned for its leadership in sustainability, Nanyang Technological University (NTU) is frequently named among Asia's and the world's most sustainable universities. Innovative sustainability research, renewable energy sources, and green campus infrastructure are all incorporated into NTU's complete sustainability strategy. The goal of NTU's Sustainability Manifesto, which was unveiled in 2021, is for the school to become carbon neutral by 2035. The university wants to improve trash management, encourage environmentally friendly transportation choices, and use less energy and water. The School of Art, Design and Media, one of the green buildings on the NTU campus, has a unique green roof that insulates the structure and helps cut down on energy use.[83]

With rainwater harvesting, passive cooling technologies, and smart lighting, the university's new Academic Building South is intended to be among the most energy-efficient structures in the area. With an emphasis on waste management, sustainable urban solutions, and renewable energy, NTU is a center for cutting edge sustainability research. The Nanyang Environment and Water Research Institute (NEWRI), which focuses on clean energy technology, environmental engineering, and water sustainability, is housed at the institution. NTU has created a smart transportation system that consists of electric shuttle buses, driverless cars, and a robust cycling network as part of its Eco Campus effort. Additionally, the institution is putting cutting-edge mobility solutions—like self-driving cars-to the test in an effort to lower carbon emissions and advance sustainable urban mobility.

Through programs like the Green Volunteers Programme and the Sustainability Ambassador Scheme, which encourages students to get involved in environmental projects and raise awareness of sustainability on campus, NTU actively incorporates students in its sustainability efforts. Because of its all-encompassing sustainability strategy, NTU has become a leader among Asian green colleges. NTU is positioned as a pioneer in the region's transition to a more sustainable future because of its creative application of smart technologies, dedication to renewable energy, and strong emphasis on research and education.[84]

6.3.2 University of Tokyo (Japan)

One of the most prominent colleges in Japan, the University of Tokyo, has made great progress in incorporating sustainability into its research, campus operations, and academic programs. The UTokyo Sustainability Initiative, which encourages environmental stewardship, sustainable campus growth, and multidisciplinary study on global environmental concerns, is one way the university demonstrates its commitment to sustainability.

The University of Tokyo has put in place a Campus Master Plan that prioritizes water conservation, energy efficiency, and green building design. The Kashiwa II Campus of the university is a prime example of sustainable urban development, with features.

The University of Tokyo has committed to becoming carbon neutral by 2050, in line with the national climate action targets of Japan.[85]

With a focus on topics including urban resilience, renewable energy, and climate change, the university is a pioneer in sustainability research. The Integrated Research System for Sustainability Science (IR3S), founded by UTokyo, encourages multidisciplinary study on climate change mitigation and sustainable development.

The purchasing of ecologically friendly goods and services is given priority under the University of Tokyo's Green Procurement Policy. In order to reduce the environmental effect of campus activities, the institution has also put in place extensive waste management systems, which include recycling programs and trash reduction projects. The involvement of students in sustainability activities is actively encouraged by the university. Through organizations like the UTokyo Green Office, students are participating in campus-wide sustainability efforts, including energy conservation, waste reduction, and biodiversity conservation.[86]

The university also organizes programs that encourage sustainable living and increase public understanding of environmental issues, such Sustainability Week. The University of Tokyo is a leader in sustainability in Japan thanks to its dedication to multidisciplinary research, sustainable campus development, and student engagement. Its initiatives to support environmental leadership, lower carbon emissions, and advance renewable energy show how colleges may support local, national, and international sustainability goals.[87]

6.3.3 Tsinghua University (China)

One of China's best universities, Tsinghua University is based in Beijing and has been at the forefront of advocating for sustainability in higher education. Tsinghua has incorporated sustainability into research, academic programs, and campus operations, in line with China's national objectives for environmental conservation and green development. Sustainable resource management, green building design, and energy efficiency are the main goals of Tsinghua University's Green Campus Plan.

Tsinghua University has established its own carbon reduction targets in accordance with China's national aim to achieve carbon neutrality by 2060. Leading the way in sustainability research are Tsinghua University, especially in the areas of clean energy, mitigating climate change, and sustainable urban development.[88] Tsinghua University is a major role in China's attempts to encourage green growth because of its leadership in sustainability research, green campus projects, and international engagement. Its dedication to cutting carbon emissions, advancing renewable energy, and encouraging sustainability innovation shows how colleges can help achieve local, national, and international climate goals.[89]

6.3.4 Indian Institute of Technology (IIT) Bombay (India)

One of India's top technical institutes, the Indian Institute of Technology Bombay (IIT Bombay), has launched a number of sustainability projects centered on energy efficiency, green building design, and sustainability research. IIT Bombay's endeavors to mitigate its ecological footprint and encourage sustainable practices inside the campus epitomise their dedication to sustainability. IIT Bombay has put in place a number of energy-saving initiatives, such as retrofitting structures with appliances and lighting that use less energy. Additionally, solar photovoltaic systems have been erected on campus, providing a sizable amount of the university's electrical demands. Green building techniques have been implemented by IIT Bombay for new construction projects, guaranteeing that structures are made with the least amount of energy and water.[90] The university's Victor Menezes Convention Center, which has rainwater collection, passive cooling systems, and energy-efficient lighting, is a noteworthy example of green building design. Research on sustainability is centered at IIT Bombay, especially in the fields of sustainable urban planning, water management, and clean energy. The university's Centre for Urban Science and Engineering (C-USE) carries out multidisciplinary research on sustainable cities with an emphasis on waste management, energy-efficient urban infrastructure, and air quality monitoring. The National Centre for Photovoltaic Research and Education (NCPRE) at IIT Bombay is leading the way in solar energy technology research, supporting the country of India's objectives for the development of renewable energy sources. IIT Bombay has put in place a number of water-saving projects, such as wastewater recycling and rainfall collection systems.[91] Additionally, the institution has set up a solid waste management system with an emphasis on composting, recycling, and minimizing the quantity of garbage dumped in landfills. The institution provides a variety of courses with an emphasis on sustainable development, renewable energy, and environmental science. Through efforts like the Green Campus Initiative, which encourages students to participate in energy saving, trash reduction, and environmental awareness campaigns, IIT Bombay actively engages students in sustainability. IIT Bombay is a pioneer in green university activities in India because of its emphasis on energy conservation, renewable energy, and sustainability research. The university has shown that it is committed to helping India's national sustainability goals by working to lessen its environmental impact and encourage sustainable practices on campus.[92,93]

Asia's universities, such as IIT Bombay, Tsinghua University, the University of Tokyo, and Nanyang Technological University, are setting the standard for the implementation of comprehensive sustainability projects. These universities are encouraging cutting-edge sustainability research, encouraging environmental stewardship among staff and students, and incorporating green practices into campus operations. Through the alignment of their objectives with national and international sustainability frameworks, these universities are significantly contributing to the resolution of some of the most urgent environmental issues of the twenty-first century.[94]

6.3.5 Fudan University (China)

One of the top universities in the nation, Fudan University is situated in Shanghai, China, and it has made great efforts to encourage sustainability on campus. Being one of the most prominent universities in China, Fudan has incorporated sustainability into all aspects of its operations, research, and academic programs because it understands how important it is to solve environmental issues. China's overarching objectives for green development and sustainability are furthered by Fudan University's projects, which center on energy efficiency, green buildings, sustainable transportation, and environmental education.[95]

a) Energy efficiency and renewable energy

To lessen its carbon footprint, Fudan University has boosted the usage of renewable energy sources and put in place a number of energy-efficiency initiatives. These programs support China's national objectives to increase energy efficiency and switch to greener energy sources. On a few of its campus buildings, the university has solar photovoltaic (PV) panels installed, generating electricity using renewable energy. This program is a component of the university's attempts to lessen its dependency on fossil fuels and its carbon footprint. Numerous campus buildings at Fudan have undergone energy efficiency retrofits. Upgrades to insulation, LED lighting installations in place of inefficient lighting, and energy-saving HVAC system optimization are some examples of these retrofits. A smart energy management system that tracks energy usage in real time has been put in place at the university. The institution can minimize overall energy usage on campus, pinpoint areas for efficiency improvements, and optimize energy use thanks to this system.[96]

b) Green building design

In order to ensure that new buildings are planned with sustainability in mind, Fudan University has implemented green building standards in its campus construction projects. These structures use water-efficient systems, energy-saving technologies, and ecologically friendly materials. The institution has built a number of structures that meet China's Green Building Evaluation Standard, which encourages resource- and environmentally-conscious building design. These structures have rainwater collection systems, green roofs, and passive cooling systems. A few of Fudan's most recent structures have obtained certification in LEED, a globally acclaimed green building certification program. To reduce energy consumption, these buildings have smart climate control systems, natural lighting, and cutting-edge energy-saving technologies.[97,98]

c) Sustainable transportation

Fudan University encourages environmentally friendly modes of transportation for its instructors, staff, and students in an effort to lower carbon emissions and enhance the quality of the air in Shanghai, one of the biggest and most populous cities in China. With the installation of bike lanes, bike-sharing programs, and safe bicycle parking spaces, Fudan has created a campus that is bike-friendly. By encouraging bicycle riding as a sustainable form of transportation, these programs help faculty, staff, and students travel less on campus in cars. To encourage academics and staff to drive electric cars, the university has built EV charging stations across campus. In an effort to lower the emissions from its transportation services, Fudan is also looking at incorporating electric buses into its campus shuttle system.[99] In Shanghai, Fudan is close to a number of important hubs for public transit, such as bus and subway lines. By providing subsidized transit passes, the institution encourages staff and students to use public transportation, thereby lowering the campus's overall transportation-related carbon footprint.

d) Water conservation and waste management

Fudan University is dedicated to enhancing trash management on campus and encouraging water conservation. In a city like Shanghai, these programs are crucial for tackling the problem of water scarcity and lessening the environmental damage caused by trash. Water-saving features like dual-flush toilets and low-flow faucets have been installed in all of Fudan's campus buildings. In order to further reduce its water consumption, the university has also installed rainwater harvesting systems to collect and utilize rainwater for irrigation and non-potable uses. Fudan has created a thorough waste management plan with an emphasis on recycling, efficient disposal, and trash minimization. The institution encourages recycling of paper, plastic, glass, and metal materials at the point of generation through specific recycling bins. Fudan also promotes the utilization of organic waste from campus dining services to composting systems.[100]

e) Sustainability research and innovation

Fudan University is a leader in sustainability research, concentrating on solving some of the world's and China's most urgent environmental problems. The interdisciplinary research method of the institution fosters cooperation among environmental scientists, engineers, and policymakers. The Research Center for Environmental Economics at Fudan University carries out studies on sustainable development, environmental policy, and mitigating the effects of climate change. The institution works with international organizations, NGOs, and government agencies to create plans for dealing with environmental issues, especially in cities like Shanghai. Leading the way in research on renewable energy, Fudan specializes in solar, wind, and energy storage technologies. China's national goals of lowering carbon emissions and expanding the usage of renewable energy are supported by the university's research in this field.[101]

f) Sustainability in education

Fudan University encourages environmental literacy among students through a variety of extracurricular activities, events, and courses that include sustainability into their academic offerings. The institution provides a range of doctoral and undergraduate courses with an emphasis on environmental science, climate change, and sustainability. These courses give students a thorough awareness of environmental problems around the world and give them the tools they need to create sustainable solutions. In order to address sustainability concerns from a variety of angles, Fudan encourages collaboration between students in many professions, like as engineering, economics, and environmental science. Fudan is in charge of planning campus-wide sustainability initiatives like energy-saving contests, workshops on sustainable living, and tree-planting efforts. These programs encourage staff and students to adopt more environmentally friendly practices while also increasing awareness of environmental issues.[102]

g) Student and community engagement

In order to foster a culture of environmental responsibility, Fudan University actively incorporates students and the larger community in its sustainability initiatives. Numerous student-run environmental groups and organizations that spearhead campus sustainability activities are supported by the institution. To raise awareness of environmental issues, these clubs plan events like lobbying campaigns, sustainability workshops, and clean-up initiatives. Through its sustainability outreach programs, Fudan encourages local residents to participate in green development and environmental conservation. The university works with neighborhood establishments, corporations, and governmental organizations to advance environmental education and sustainable practices in Shanghai.[103] Fudan University's initiatives to lower energy use, support renewable energy sources, and incorporate green building techniques into campus development demonstrate the university's dedication to sustainability. The university is positioned to play a significant role in China's green development aspirations due to its leadership in sustainability research and education. Fudan University's environmental measures not only lessen the university's influence on the environment, but also set an example for other Chinese and international universities. Fudan University is cultivating a culture of sustainability that permeates the wider community and transcends its campus by advancing multidisciplinary research, sustainable transportation, and community participation.

6.4 African and Latin American Universities

Universities of Africa are becoming more and more vital in advancing sustainability and tackling the particular environmental issues that the continent faces, like energy access, water shortage, biodiversity loss, and climate change. African universities are making contributions to regional, national, and international initiatives to build sustainable futures by incorporating sustainability into their academic offerings, campus operations, and community engagement. This section presents case studies of African colleges that have adopted sustainability aims and green activities.[85] Universities in Latin America have launched a number of green programs to address the region's particular environmental concerns as they have come to understand the importance of sustainability in higher education. Deforestation, water scarcity, biodiversity loss, and climate change are some of these issues. Universities in Latin America are at the forefront of the movement to promote sustainability via research, teaching, and campus operations. The case studies of top Latin American green colleges that are in the forefront of campus and community sustainability initiatives are included in this area.[104]

6.4.1 Stellenbosch University (South Africa)

On the African continent, Stellenbosch University in South Africa has been a pioneer in sustainable higher education. The institution is dedicated to integrating sustainability into its instruction, research, and campus operations, with an emphasis on sustainable food systems, water conservation, and energy efficiency in particular. By investing in renewable energy sources and implementing energy efficiency programs, Stellenbosch University has significantly decreased its energy usage. In order to lessen water consumption and encourage water conservation, Stellenbosch University has created a thorough water management strategy. Water shortage is a serious problem in South Africa. Sustainable food systems are actively promoted by Stellenbosch University through research, instruction, and campus operations.[105] Research on climate-resilient farming techniques, food security, and sustainable agriculture is carried out by the university's Sustainability Institute. The institution also keeps up a number of campus gardens that supply fresh produce for the school dining services, cutting down on emissions from food transportation and encouraging regional, sustainable agriculture. Stellenbosch University offers a variety of academic programs centered on environmental science, climate change, and sustainability, and incorporates sustainability into its curricula. In order to address the issues of energy access and sustainability in South Africa and the wider area, the Centre for Renewable and Sustainable Energy Studies (CRSES) serves as a center for research on renewable energy technologies and policy.[106] In order to lessen the need for private vehicles, Stellenbosch University offers a campus shuttle service, secure bike parking, and promotions for walking and cycling on campus. To further cut emissions related to transportation, the institution is looking into options for switching to electric or hybrid cars for its fleet. The promotion of sustainable food systems, emphasis on renewable energy research, and energy and water conservation initiatives all demonstrate Stellenbosch University's dedication to sustainability. The university acts as a prototype for how other African universities might approach environmental issues in their academic offerings and campus operations.[107]

6.4.2 University of Cape Town (South Africa)

Another prestigious university in South Africa that has made great strides toward incorporating sustainability into its academic programs and campus operations is the University of Cape Town (UCT). UCT's Environmental Sustainability Strategy, which lays out important objectives for minimizing the institution's environmental effect and advancing sustainability in all facets of university life, serves as the foundation for its initiatives. By implementing energy-saving measures and utilizing renewable energy sources, UCT has pledged to lessen its carbon footprint. The goal of UCT's Energy Efficiency and Demand Management Program is to maximize campus energy use by tracking usage and pinpointing areas for improvement.[108] UCT has put in place a number of water conservation initiatives to lower water usage and encourage sustainable water use in response to the severe droughts that have affected Cape Town. To cut down on water use, the institution has installed water-saving fixtures in the kitchen and restrooms, such as dual-flush toilets and low-flow taps. Green building practices are being implemented at UCT for both new construction and significant campus improvements. The institution uses sustainable materials, encourages natural ventilation and lighting, and strives for high levels of energy and water efficiency in its buildings. For instance, the New Engineering Building uses a lot of green design elements, such as rainwater collection, solar water heating, and energy-efficient lighting.[109] Numerous research institutes tackling environmental issues are housed at UCT, such as the African Climate and Development Initiative (ACDI), which concentrates on climate adaptation and mitigation tactics for the continent. Researchers at UCT are actively working on initiatives that tackle problems including biodiversity preservation, the development of renewable energy, and sustainable urban design. In order to give students the information and abilities they need to address urgent environmental concerns, UCT also provides a range of academic programs and courses in sustainability, climate science, and environmental management. To cut down on the quantity of waste dumped in landfills, UCT has put in place extensive recycling and waste management initiatives.[110] The institution encourages garbage separation at the source and has recycling bins available all throughout campus for metal, glass, plastic, and paper waste. Additionally, UCT has started programs to reduce plastic waste, including efforts to phase out single-use plastics in dining services and campus activities.

The University of Cape Town's initiatives to lessen its carbon footprint, efficiently manage its water resources, and advance environmental research and education are examples of its dedication to sustainability. UCT's response to the drought in Cape Town demonstrates the university's involvement in tackling regional environmental issues and supporting international sustainability initiatives.[111]

6.4.3 Pontifical Catholic University of Chile (Chile)

In Latin America, the Pontifical Catholic University of Chile (PUC), which is based in Santiago, is a pioneer in sustainable higher education. The institution has put into practice a thorough sustainability plan that combines energy conservation, sustainability research, and green campus operations. Through its programs, PUC is dedicated to tackling environmental issues on a local and global scale. PUC has made great efforts to lessen its influence on the environment by encouraging water conservation, energy efficiency, and sustainable waste management on campus. Since there is a severe water shortage in Chile, PUC has created a number of programs to support water management and conservation.[112] The university is a center for study on sustainability, with an emphasis on environmental policy, climate change, and renewable energy. PUC researchers are active in projects that address critical environmental concerns like as sustainable agriculture, water resource management, and clean energy technology. The university's Center for Global Change is a pioneer in studying the effects of climate change and creating mitigation and adaptation plans.

PUC provides a range of academic programs and courses with a sustainability focus that promote multidisciplinary environmental research and instruction. The institution offers degrees in environmental science, climate change, and sustainable development, further integrating sustainability into its curriculum. Through its Bicycle-Friendly Campus Initiative, which encourages cycling as a sustainable means of transportation for staff and students, PUC promotes sustainable mobility. To encourage riding and lessen dependency on cars, the institution has built bike lanes and parking lots. The Pontifical Catholic University of Chile is one of Latin America's top green universities thanks to its emphasis on sustainability research, water conservation, and energy efficiency. PUC is tackling environmental issues and advancing sustainable practices in both academic and practical contexts with its all-encompassing sustainability strategy.[113]

6.4.4 University of São Paulo (Brazil)

One of the biggest and most prominent universities in Brazil, the University of São Paulo (USP), has taken the lead in encouraging sustainability on all of its campuses. The university's sustainability programs are concentrated on waste management, energy saving, and climate change research. To lessen its influence on the environment, USP has made large expenditures in energy efficiency and renewable energy. Part of the university's electrical demands are met by solar panels that are mounted on campus buildings. In the upcoming years, USP wants to use more renewable energy sources. USP has put in place a thorough waste management system with an emphasis on waste minimization, composting, and recycling. The institution encourages waste separation at the source by placing recycling bins specifically for glass, plastic, and paper materials all across campus.[114] USP's Zero Waste Initiative encourages the recycling and composting of organic waste from campus dining services in an effort to lessen the quantity of waste that is dumped in landfills. Numerous research centers on sustainable development, renewable energy, and climate change are located at USP. Multidisciplinary research on energy efficiency, sustainable energy systems, and environmental policy is carried out at the university's Institute of Energy and Environment (IEE). Researchers from USP are also working on initiatives that tackle some of Brazil's particular environmental problems, like biodiversity preservation and Amazon deforestation. The academic programs and courses offered by USP center on sustainability, climate change, and environmental science. In addition to encouraging students to participate in community service and sustainability research, the university supports multidisciplinary education.[115] Students can also get involved in campus sustainability projects through USP's Green Campus Program. Through programs like bike-sharing, electric vehicle charging stations, and public transportation options, USP encourages the use of sustainable transportation. The institution encourages employees and students to use other forms of transportation in order to lessen their carbon footprint. As a pioneer in advancing sustainability in Brazil and Latin America, the University of São Paulo is known for its work in waste management, renewable energy, and climate change research. The university's dedication to environmental teaching and research supports larger initiatives to solve the most important environmental issues facing the area.[116]

6.5 Kazakhstani Universities

One of the biggest nations in Central Asia, Kazakhstan has particular environmental problems, such as desertification, climate change, water scarcity, and sustainable energy sources. Universities in Kazakhstan are starting to integrate green initiatives into their operations, curricula, and research to address environmental difficulties and promote sustainability as a solution to these challenges. While Kazakhstan's green university movement is still in its infancy, a number of universities have made notable progress toward sustainability. The main case studies of Kazakhstani universities undertaking sustainability programs are highlighted in this part, with an emphasis on community involvement, energy efficiency, green campus design, and environmental research.[117]

6.5.1 Nazarbayev University (Astana)

Nazarbayev University (NU) is one of the most esteemed universities in Kazakhstan. Sustainability has been actively implemented by NU into its operations, research, design, and educational programs. Being a relatively new university-it was founded in 2010—NU has had the chance to design its campus from the ground up using cutting-edge sustainable technologies. The campus of Nazarbayev University was planned with environmental sustainability and energy efficiency in mind. Energy-efficient technologies, like automatic HVAC systems, high-performance insulation, and energy-efficient lighting, were used in the construction of several campus buildings. These characteristics enhance indoor thermal comfort while lowering energy usage.[118] The goal of NU's new campus buildings is to minimize energy and water use while adhering to green building standards. The structures use sustainable building materials, cutting-edge ventilation technologies, and natural lighting. In Kazakhstan, NU serves as a center for sustainability research, especially in the fields of smart grid technology and renewable energy. Interdisciplinary research on renewable energy technologies, including as solar, wind, and bioenergy, is carried out by the Nazarbayev University Research and Innovation System (NURIS). In order to decrease Kazakhstan's energy sector's carbon footprint and increase energy efficiency, NU experts are also focusing on creating smart grid solutions. Kazakhstan wants to reduce its greenhouse gas emissions and switch to 50% renewable energy by 2050. The university's research initiatives help achieve this aim.[119] Nazarbayev University encourages staff, teachers, and students to use sustainable modes of transportation. In response to the increased demand for environmentally friendly mobility options, the university supports the use of electric vehicles and has placed charging stations on campus. Along with creating dedicated pathways for cyclists and walkers as well as plenty of bike parking spaces, NU is also upgrading its infrastructure to encourage walking and bicycling. NU has implemented a thorough recycling and trash management program. The institution encourages staff and students to segregate their waste and promote recycling by placing recycling bins for paper, plastic, glass, and metal throughout the campus. In order to manage the organic waste from its dining services, NU also takes part in composting projects. This practice helps to create nutrient-rich soil that can be used for landscaping while lowering the quantity of waste that is dumped in landfills.[120] The institution provides graduate and undergraduate courses in energy studies, sustainable development, and environmental science. These initiatives support sustainability in Kazakhstan and place a strong emphasis on interdisciplinary approaches to environmental problem solutions. In response to growing concerns about water scarcity in Central Asia, NU is actively participating in research initiatives pertaining to water resource management. The institution works with global partners to provide sustainable water conservation and use solutions.[121] Nazarbayev University has become one of Kazakhstan's top green universities thanks to its dedication to energy efficiency, sustainable building design, renewable energy research, and sustainability education. By emphasizing sustainability research and maintaining a state-of-the-art campus, NU supports Kazakhstan's national objectives for green development and environmental preservation.[122]

6.5.2 Al-Farabi Kazakh National University (Almaty)

Kazakhstan's oldest and most esteemed university is Al-Farabi Kazakh National University (KazNU), situated in Almaty. With an emphasis on waste management, green campus construction, and environmental education, KazNU has made efforts to incorporate sustainability into its academic programs and campus operations. A Green Campus Initiative has been introduced by Al-Farabi Kazakh National University with the goal of encouraging sustainability on campus and getting students involved in environmental projects (Fig. 5). To enhance biodiversity and provide recreational areas for staff and students, the university has established a number of green spaces, including parks and gardens, around the campus. In Almaty, a city notorious for its poor air quality, these green areas also aid in lowering pollution levels and the impact of the urban heat island.[123]

In order to lower energy usage, the university has installed energy-efficient technologies in campus buildings, such as automatic heating and cooling systems and energy-saving lighting systems. In Kazakhstan, KazNU leads the way in sustainability research, especially when it comes to topics like climate change adaptation, water resource management, and environmental preservation. Multidisciplinary research on environmental concerns, such as air pollution, water quality, and land degradation, is carried out at the university's Research Institute of Ecology. In Kazakhstan's fast-urbanizing regions, KazNU academics are working to develop techniques for sustainable resource management. Along with supporting research on climate change adaption techniques and renewable energy technologies, KazNU also adds to the national agenda on lessening Kazakhstan's environmental effects. Through courses and degree programs centered on environmental science, climate change, and sustainable development, KazNU incorporates sustainability into its curriculum.[124] With the help of the university's Master of Environmental Management degree, students can acquire the knowledge and abilities necessary to tackle environmental issues in Kazakhstan and Central Asia. The program places a strong emphasis on environmental policy, climate resilience, and sustainable resource management.

Additionally, KazNU organizes sustainability lectures, workshops, and other activities that spark conversations among students regarding regional and worldwide environmental problems. A thorough waste management system has been put in place at Al-Farabi Kazakh National University in an effort to cut trash and encourage recycling on campus. The university encourages staff and students to take part in trash reduction initiatives and provides recycling bins for paper, plastic, and glass throughout the campus. In addition, KazNU has launched student-led campaigns to clean up neighborhood parks and public areas and implemented measures to limit the use of single-use plastics in campus

Fig. 5 Campus map of Al-Farabi Kazakh National University (Source: Kaznu.kz)

dining services.[125] The institution promotes walking, bicycling, and public transportation as ways to lessen the impact of commuting on the environment. The institution is easily accessible via Almaty's well-developed public transportation system, and KazNU is aiming to increase the amount of space it has for walking and bicycling. Al-Farabi Kazakh National University is a major institution for sustainability promotion in Kazakhstan thanks to its dedication to green campus development, environmental education, and sustainability research. With its emphasis on multidisciplinary research and Green Campus Initiative, KazNU is significantly tackling Kazakhstan's environmental concerns.[126]

6.5.3 Kazakh-British Technical University (Almaty)

The engineering, technology, and innovation departments at the Kazakh-British Technical University (KBTU) in Almaty are well-known for their emphasis. KBTU has been incorporating sustainability into its academic programs and campus operations in the last few years, especially with regard to energy efficiency and green technologies. Research on solar, wind, and bioenergy technologies is carried out by the university's Institute of Renewable Energy, which supports Kazakhstan's national goals of raising the proportion of renewable energy in the country's energy mix. KBTU places a strong emphasis on research in renewable energy technologies and energy efficiency. In addition, KBTU concentrates on energy-saving initiatives, collaborating with business associates to create solutions that lower energy usage in buildings and industrial operations.[127] KBTU is dedicated to enhancing the campus's sustainability by implementing green infrastructure and energy-efficient building designs. The institution has installed energy-saving lighting and HVAC systems in a number of its buildings as part of retrofits to increase overall energy efficiency. In order to lessen its influence on the environment, KBTU is also investigating the use of smart technology to monitor and optimize campus energy use. By providing courses and degrees in environmental engineering, renewable energy, and sustainable development, KBTU incorporates sustainability into its academic programs. In order to prepare students to contribute to Kazakhstan's green economy, the university's School of Engineering and Information Technology provides specialized degrees in environmental engineering and renewable energy technology.[128] Through a range of extracurricular activities and student-led projects, KBTU promotes student involvement in sustainability: The university provides funding to student groups that promote green technology innovation and environmental awareness. These organizations host sustainability hackathons, where students come up with creative answers to pressing environmental issues. In addition, KBTU students have participated in neighborhood initiatives like cleanup days and tree planting drives, which encourage environmental responsibility off campus. With its emphasis on energy efficiency, sustainability education, and renewable energy research, Kazakh-British Technical University has established itself as a major force in the advancement of green technology in Kazakhstan. The university is committed to assisting the nation's transition to a more sustainable energy future, as seen by its efforts to incorporate sustainability into its academic programs and campus operations.[129]

6.5.4 Abai Kazakh National Pedagogical University (Almaty)

One of Kazakhstan's oldest and most esteemed educational establishments is the Abai Kazakh National Pedagogical

University, also known as Abai University. It is situated in Almaty. Abai University, a school that specializes in training teachers, has realized how critical it is to incorporate environmental consciousness and sustainability into its research, curriculum, and campus operations. Abai University has started implementing a number of green programs to encourage environmental responsibility and sustainable practices on campus, even though they are still in the early stages when compared to other universities in Kazakhstan. This section outlines Abai University's green activities, emphasizing the institution's attempts to raise awareness of sustainability, encourage energy efficiency, and involve students and the public in environmental projects (Fig. 6).[130] Abai University, a top educational institution, places a strong emphasis on how education may advance sustainability. The organization encourages environmental education for aspiring teachers and has incorporated sustainability into its curricula.[131]

Environmental Education for Teachers: Future teachers at Abai University receive training in sustainable practices and environmental awareness so they can impart these ideals in Kazakhstani classrooms. The Department of Environmental Science at the university provides courses on climate change, environmental protection, and sustainability, giving students the skills they need to integrate sustainability into their future jobs as teachers.

Sustainability Awareness in Pedagogy: among an effort to instill a sustainable culture among educators, the university's curriculum includes courses on environmental ethics, conservation, and sustainable development. Through incorporating sustainability into the pedagogical framework, Abai University contributes to the dissemination of environmental consciousness throughout Kazakhstan's educational system.

a) Green campus initiatives

Abai University is attempting to encourage sustainability on campus through energy-saving initiatives and green areas, even if it is still in its infancy. Energy Efficiency Projects: The institution is starting to put energy-saving strategies into place all around the campus. In order to lower the amount of electricity consumed, these activities include installing energy-efficient lighting systems and promoting the use of energy-saving appliances in campus buildings. In order to further minimize energy use, especially during Almaty's winter months, the university is also looking into other possibilities for building retrofits that can enhance insulation and optimize heating systems. Campus Green Spaces: Upkeep of the campus's green areas has been given top priority by Abai University. These spaces preserve biodiversity while providing an outdoor experience for workers and students. The university promotes tree-planting initiatives and encourages students to take part in efforts to create and preserve green areas on campus, contributing to a healthier environment.

b) Waste management and recycling

Abai University has started concentrating on enhancing recycling programs and encouraging sustainable behaviors among employees and students in order to improve trash management on campus. Recycling Program: To encourage students and staff to separate recyclable materials including paper, plastic, and glass, the institution placed recycling bins throughout the campus. The objective of this effort is to decrease the quantity of waste that is dumped in landfills and to encourage resource management that is more sustainable. Waste Reduction Awareness: The institution works to reduce waste by educating staff and students about the need to use fewer single-use plastics and other throwaway items. These initiatives draw attention to how garbage affects the environment and support sustainable alternatives.

c) Sustainability research and community engagement

Additionally, Abai University is promoting sustainability by involving students and the neighborhood in environmental activities and doing research and community outreach. Studying Environmental Education: Abai University is investigating the best ways to include sustainability into teacher preparation courses and school curricula. The Institute of Pedagogical Sciences at the university is working on projects that investigate the most effective ways to teach environmental science and encourage sustainability among school-age pupils. Student-led environmental initiatives: Abai University supports student involvement in environmental clubs and organizations, which lead efforts to clean up the environment and prepare activities like workshops on sustainability and tree planting. Students participate in practical sustainability projects and learn about environmental responsibility through these activities. Community Outreach Programs: By collaborating with Almaty's local schools and communities, Abai University hopes to take its sustainability initiatives off campus. The university encourages environmental education and increases public understanding of the value of sustainability in daily life through outreach initiatives. These programs, which concentrate on environmental conservation and reforestation, frequently entail cooperative projects between university students and people of the local community.

d) Sustainable transportation

Abai University is working to promote more environmentally friendly modes of transportation for employees and students as part of its efforts to support sustainability. Infrastructure for Bicycling and Walking: The university is looking into the possibilities of adding more facilities to facilitate these activities on campus. The institution wants to encourage healthier, more environmentally friendly modes of transportation and lessen dependency on cars by expanding the availability of bike lanes and walking trails. Access to Public transit: Bus and subway systems, as well as other public transit networks, are all conveniently close to Abai University

Fig. 6 Concepts of green university (Abai University).

in Almaty. To lessen their carbon impact when traveling to and from campus, the university encourages staff and students to take advantage of these public transportation choices.[132]

Even though they are still in the early stages, Abai Kazakh National Pedagogical University's sustainability initiatives demonstrate their dedication to encouraging sustainable behaviors and raising environmental awareness. The institution is setting the stage for a greener campus and a more sustainable future by incorporating sustainability into its curriculum, increasing energy efficiency, and involving students and the community in environmental projects. Abai University, a prominent educational establishment in Kazakhstan, possesses the capacity to impact upcoming generations of educators, who will in turn instill sustainability principles in classrooms and communities around the nation.

Leading the way in advancing sustainability in higher education are Kazakhstani universities, such as Nazarbayev University, Al-Farabi Kazakh National University, Abai Kazakh National Pedagogical University and Kazakh-British Technical University. These academic institutions are incorporating sustainability into their courses, putting energy saving measures into practice, and doing cutting edge research on renewable energy. These universities are making a significant contribution to Kazakhstan's efforts for sustainable development and climate resilience by tackling the nation's environmental issues and promoting student involvement, sustainability-focused research, and green campus projects.

7. Influence of leading universities' practices and educational programs on green energy policy

Leading universities' practices and teaching programs have a substantial and complex impact on global green energy policy. Universities have emerged as key players in the worldwide transition to a sustainable, low-carbon economy.[133] As research, innovation, and teaching institutions, they have a significant impact on not just technological breakthroughs in green energy, but also public discourse and policy frameworks relating to sustainability. Leading universities have an impact on national and global green energy policies by incorporating sustainability into their operations, courses and research. Leading institutions globally are at the forefront of research into green energy technologies and environmental protection initiatives. University research frequently serves as the foundation for policy formulation and informs the creation of green energy policies on both a national and worldwide scale.[134]

a) Renewable energy research: Many prominent universities, including Stanford, MIT, and UC Berkeley in the United States and Tsinghua University in China, are performing cutting-edge research on renewable energy sources such as solar, wind, bioenergy, and energy storage. This study has direct implications for policy. For example, research advances may result in new technologies that form the foundation for large-scale deployment, prompting government support, funding, and regulatory reforms. In certain cases, universities work with governments to implement pilot projects that provide real-world examples of how green energy technologies might be integrated into national grids.[135]

b) Cross-disciplinary Approaches: Universities are promoting cross-disciplinary approaches to green energy policy, bringing together experts from engineering, economics, law, and social sciences to identify effective ways to reduce carbon emissions and transition to sustainable energy systems. For example, Harvard University has a Masters in Sustainability degree that blends technology, policy, and management, allowing students to influence and drive change in energy policy. Universities have established think tanks, research centers, and policy institutes to advance sustainable energy policies. For example, Oxford University's Environmental Change Institute and Columbia University's Earth Institute in the United States do policy-relevant research and frequently advise governments and international organizations on green energy.[136,137]

7.1 Educational programs: shaping the next generation of leaders

Universities are critical in preparing the next generation of professionals and leaders to implement and advocate for green energy policy. Educational programs that focus on sustainability, renewable energy, and environmental management prepare graduates to influence policy, business practices, and community engagement.[138]

Curriculum design: Leading universities are progressively incorporating sustainability and green energy into their curricula, providing specialized programs that teach students about the difficulties and solutions associated with global energy systems. For example, Fudan University in China provides master’s degrees in environmental engineering and Sustainable Development, and Abai University in Kazakhstan incorporates sustainability concepts into its curricula. These schools not only prepare students for professions in the energy and environmental sectors, but they also encourage them to influence energy policies.

Global reach and knowledge transfer: Many institutions provide online courses or work on worldwide projects to share knowledge and best practices across borders. For example, the United Nations Sustainable Development Goals (SDGs) are now integrated into many higher education programs around the world, enabling students to understand sustainability from a global perspective. Universities in the Global South, such as the University of Cape Town in South Africa, are increasingly exchanging expertise with universities in Europe and North America, helping to shape a global policy discussion on energy and sustainability.

Samal Issabayeva, one of the authors of this article, presents the concept of long-term planning in geographic education and the goals of teaching these topics as part of the research on preparing future geography teachers for innovative pedagogical practices (Table 1). According to her, the updated model curriculum in Kazakhstan includes a nomenclature section that outlines the geographic names students must master. This section focuses on the in-depth study of geographical features related to the topography of both the southern and northern continents, water bodies, territorial natural complexes, and economic and political geographical objects, as well as basic geographical concepts. These topics are intended to provide a foundation for future specialists to apply green technologies and develop a green energy perspective. Additionally, an overview of green energy solutions and environmental protection strategies at leading green universities around the world is considered a crucial prerequisite for the theoretical and methodological framework necessary to integrate green knowledge into innovative pedagogical activities. This, in turn, helps establish the didactic conditions required to effectively implement such knowledge in teaching.

Policy Advocacy: University-led groups such as AASHE (Association for the Advancement of Sustainability in Higher Education) and The Green Campus Initiative enable universities to discuss policies, triumphs, and difficulties relating to energy sustainability.[139] Universities frequently use these venues to push for more aggressive national policies on climate change and renewable energy.

Table 1. The concept of long-term planning topics and their teaching goals in geographic education.

Section	Topics	Learning objectives
1.1 Research and researchers	Forms of geography research	7.1.1.1 - defines geography research forms
	Development of the science of geography	7.1.1.2 - describes and evaluates the contribution of travelers and researchers to the development of the science of geography
	Geographical data sources	7.1.1.3- can graphically show features of geographical sources (map, text, photographs, graphic materials), explain their properties
	Geographic experiments	7.1.1.4 - determine the properties of geographical objects in an experimental way
	Field research methods	7.1.1.5 - uses geographic field research methods, records, compiles, processes, and analyzes indicators.
	Use of graphic methods in geography	7.1.1.6 - can graphically show features of geographical objects, phenomena, and processes (diagram, profile, graph)

7.2 Campus sustainability initiatives: leading by example

Universities are increasingly implementing sustainability policies on their campuses, creating living laboratories for green energy and environmental protection methods.[140,141] These programs not only lower universities' carbon footprints, but they also influence local, national, and even worldwide policy by establishing a good example.

a) Carbon neutrality goals: Several major colleges have pledged to become carbon neutral in the coming decades. Stanford University and the University of California, Berkeley, for example, have set lofty carbon neutrality targets for 2050. These colleges' activities, which include the installation of solar panels, energy-efficient buildings, and sustainable transportation systems, illustrate the viability of low-carbon campuses and encourage local governments to adopt similar measures.

Renewable energy use on campus: Many colleges are taking the lead in implementing renewable energy technologies on their campuses. The University of Iowa is a leader in wind-powered electricity generation, and Arizona State University has one of the largest solar arrays in the country. Universities also use their campuses to test new green technologies, including microgrids, energy-efficient building designs, and electric vehicle charging infrastructure. These practical applications have an impact on local governments and policymakers, illustrating how green energy can be incorporated into larger urban and regional energy programs.

b) Partnerships with industry: Universities frequently collaborate with corporations and governments to test new technologies and systems. For example, the University of Edinburgh's "Urban Lab" project collaborates with local governments to evaluate the efficacy of smart grids and energy-efficient technology in urban settings.[142] These collaborations serve to turn academic research into real policy consequences, impacting how governments and corporations' approach green energy solutions.

7.3 Global influence and policy leadership

Leading universities have a tremendous impact on green energy policies not only in their home nations, but on a global scale. Many of them play a direct role in creating worldwide climate policy, frequently through collaboration with intergovernmental institutions such as the United Nations and the World Bank.[143] Universities frequently host and participate in global conferences and policy conversations on climate change, renewable energy, and sustainability. Cambridge University and Yale University, for example, are active organizers of events such as the UN Climate Change Conference of the Parties (COP), where university representatives contribute vital insights based on cutting-edge research and sustainable practices.

a) University networks: Global university networks, such as the Universitas Indonesia Green Campus Network and the International Alliance of Research Universities (IARU), promote sustainability and green energy on campuses around the world. These alliances shape policy by pooling resources and research from top universities to inform global discussions about energy systems and climate change mitigation.

b) Influence on national and regional policies: By working directly with policymakers, leading universities can help shape national energy policies. Tsinghua University in China, for example, has helped shape China's energy policy, particularly in the field of renewable energy, by making research-based recommendations to the Chinese government. Leading universities' educational practices and sustainability initiatives have far-reaching implications for global green energy policy.[144] Universities contribute to national and international energy policies by undertaking new research, training future leaders, modeling sustainable behaviors, and advocating for policy changes. As the globe grapples with climate change and the need for a green energy revolution, universities will play an increasingly important role in shaping both the technology and policy frameworks required for a sustainable future.

Integrating sustainability into university curricula and campus operations also helps to instill environmental ideals in society, ensuring that future lawmakers, industry leaders, and citizens are prepared to establish and implement comprehensive green energy legislation around the world.

8. Conclusions and perspectives

In conclusion, with the growing urgency of solving global environmental concerns such as climate change and resource depletion, universities have emerged as essential stakeholders in advancing green energy solutions and supporting environmental conservation. Green universities, by incorporating sustainability into education, research, and campus management, contribute to the global transition to a more sustainable future. This review emphasizes the crucial role of higher education institutions in promoting green energy innovation, lowering carbon footprints, and building sustainable communities. The case studies of Abai University and Fudan University demonstrate how Asian universities are promoting green technologies and incorporating sustainability into curricula and campus practices. Both colleges, like many others throughout the world, are developing innovative sustainability projects that serve as living laboratories for renewable energy technology, sustainable building practices, and waste management systems. These projects not only minimize environmental effects, but also educate future generations of leaders who will have a significant impact on global sustainability legislation. While green campuses are making great progress, some hurdles remain in properly incorporating sustainability into higher education. These include limited financial resources, the difficulty of scaling up green technologies, and the need for more governmental support at the local, national, and global levels. Universities have the continual issue of connecting their educational missions with fast-changing sustainability requirements, necessitating continuous innovation in both teaching and infrastructure. Furthermore, integrating green energy solutions on university campuses frequently necessitates overcoming institutional inertia while encouraging involvement and collaboration among students, teachers, and employees. Moving forward, colleges must continue to evolve as leaders in green energy research and education. The potential influence of these institutions on global sustainability efforts cannot be overestimated. Universities that promote interdisciplinary approaches to sustainability can give new solutions to environmental challenges while also creating the policies and tactics required to address climate change on a global scale. Furthermore, the development of green energy technologies and sustainable practices on campuses can serve as a model for other industries, illustrating how to incorporate environmental stewardship into daily operations and policy. In the future, universities, governments, and companies must work together more closely to share knowledge and best practices in green technology. Universities should also try to link their sustainability programs with global frameworks such as the United Nations Sustainable Development Goals (SDGs) in order to establish a consistent, globally recognized approach to sustainability. Furthermore, green colleges can set a good example by decreasing their own environmental footprints and encouraging the rest of the community to embrace sustainable practices. Finally, universities' contributions to promoting green energy solutions and environmental preservation will be vital to the success of global sustainability efforts. Universities can help future generations build a more sustainable, energy-efficient society by continuing to invest in green (ecological, environmental, geographical) education, research, and campus sustainability.

Acknowledgement

This research was funded by the Abai University in collaboration with foreign higher educational institutions-partners grants for the implementation of international scientific projects. Order No 05-04/554 dated 07/30/2024. The community of authors would like to thank Abai University (Almaty, Kazakhstan).

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

[1] B. Anthony Jnr, Green campus paradigms for sustainability attainment in higher education institutions–a comparative study, *Journal of Science and Technology Policy Management*, 2021, **12**, 117-148, doi: 10.1108/jstpm-02-2019-0008.

[2] J. Finlay, J. Massey, Eco-campus: applying the ecocity model to develop green university and college campuses, *International Journal of Sustainability in Higher Education*, 2012, **13**, 150-165, doi: 10.1108/14676371211211836.

[3] B. Anthony Jnr, Green campus paradigms for sustainability attainment in higher education institutions–a comparative study, *Journal of Science and Technology Policy Management*, 2021, **12**, 117-148, doi: 10.1108/jstpm-02-2019-0008.

[4] S. Aykan, Green *vs*. sustainable: analyzing and expanding LEED (leadership in energy and environmental design), 2014.

[5] A. B. Akhmetova, N. M. Mukhitdinov, A. Ydyrys, A. A. Ametov, Z. A. Inelova, M. Öztürk, Studies on the root anatomy of rubber producing endemic of Kazakhstan, Taraxacum kok-saghyz LE Rodin, *Journal of Animal & Plant Sciences*, 2018, **28**, 1400-1404, doi: 10.36899/JAPS.2018.5.0371.

[6] P. Hopkinson, P. Hughes, G. Layer, Sustainable graduates: linking formal, informal and campus curricula to embed education for sustainable development in the student learning experience, *Environmental Education Research*, 2008, **14**, 435-454, doi: 10.1080/13504620802283100.

[7] H. M. Alshuwaikhat, I. Abubakar, An integrated approach to achieving campus sustainability: assessment of the current campus environmental management practices, *Journal of Cleaner Production*, 2008, **16**, 1777-1785, doi: 10.1016/j.jclepro.2007.12.002.

[8] X. Yuan, J. Zuo, D. Huisingh, Green universities in China–what matters? *Journal of Cleaner Production*, 2013, **61**, 36-45, doi: 10.1016/j.jclepro.2012.12.030.

[9] L. Sharp, Green campuses: The road from little victories to systemic transformation, *International Journal of Sustainability in Higher Education*, 2002, **3**, 128-145, doi: 10.1108/14676370210422357.

[10] A. Beynaghi, G. Trencher, F. Moztarzadeh, M. Mozafari, R. Maknoon, W. Leal Filho, Future sustainability scenarios for universities: moving beyond the united nations decade of education for sustainable development, *Journal of Cleaner Production*, 2016, **112**, 3464-3478, doi: 10.1016/j.jclepro.2015.10.117.

[11] J. Mensah, Sustainable development: meaning, history, principles, pillars, and implications for human action: literature review, *Cogent Social Sciences*, 2019, **5**, 1653531, doi: 10.1080/23311886.2019.1653531.

[12] P. J. Ramísio, L. M. C. Pinto, N. Gouveia, H. Costa, D. Arezes, Sustainability strategy in higher education institutions: lessons learned from a nine-year case study, *Journal of Cleaner Production*, 2019, **222**, 300-309, doi: 10.1016/j.jclepro.2019.02.257.

[13] T. Kimmell, P. Kimmell, M. Sorensen, C. Ruggiero, B. Coit, Investing in a green future: universities and renewable energy, *Bryant University Undergraduate Journal*, 2020, **1**, 5.

[14] A. Ydyrys, A. Serbayeva, S. Dossymbetova, A. Akhmetova, A. Zhuystay, The effect of anthropogenic factors on rare, endemic plant species in the Ile Alatau, *E3S Web of Conferences*, 2020, **222**, 05021, doi: 10.1051/e3sconf/202022205021.

[15] A. Ydyrys, B. Yeszhanov, N. Baymurzaev, S. Sharakhmetov, A. Mautenbaev, B. Tynybekov, T. Baidaulet. Technology of landscaping in arid zones by using biohumus from sheep wool, *E3S Web of Conferences*, 2020, **169**, 02012, doi: 10.1051/e3sconf/202016902012.

[16] E. A. Bukenova, Z. M. Bassygarayev, A. B. Akhmetova, Z. K. Zhunusbayeva, A. Ydyrys, Development of the method of obtaining the endogenic biostimulator from wheat green spike glumes, *Research on Crops*, 2019, **20**, 210-214, doi: 10.31830/2348-7542.2019.030.
[17] A. Ydyrys, N. Mukhitdinov, A. Ametov, B.Tynybekov, A. Akhmetova, K. Abidkulova, The states of coenpopulations of endemic, relict and rare species of plant Limonium michelsonii and their protection, *World Applied Sciences Journal*, 2013, **26**, 934-940, doi: 10.5829/idosi.wasj.2013.26.07.13525.
[18] A. S. Seilkhan, R. À. Mirzadinov, A. Aksoy, A. Abulgaziyev, G. Kanat, Assessment of recovery of medicinal plants of the Kurti district of the Almaty region, Kazakhstan, *Ecology, Environment and Conservation*, 2018, **24**. 1653-1658.
[19] A. Ydyrys, N. Abdolla, A. Seilkhan, M. Masimzhan, L. Karasholakova, Importance of the geobotanical studying in agriculture (with the example of the Sugaty region), *E3S Web of Conferences*, 2020, **222**, 04003, doi: 10.1051/e3sconf/202022204003.
[20] A. Guerra, J. E. Holgaard, Encyclopedia of sustainability in higher education, 2019.
[21] P. Shabecoff, A fierce green fire: the American environmental movement, 2003.
[22] W. Calder, R. M. Clugston, Progress toward sustainability in higher education, *Environmental Law Reporter: News & Analysis*, 2003, **33**, 10003, doi: 10.2139/ssrn.3751602.
[23] M. Shriberg, H. Tallent, Beyond principles: implementing the Talloires Declaration, *Greening of the Campus V: Connecting to Place*, 2003, **3**, 203-212, doi: 10.1177/097171862020050202.
[24] A. Zutshi, A. Creed, B. L. Connelly, Education for sustainable development: emerging themes from adopters of a declaration, *Sustainability*, 2018, **11**, 156, doi: 10.3390/su11010156.
[25] L. P. Amaral, N. Martins, J. B. Gouveia, Quest for a sustainable university: a review, *International Journal of Sustainability in Higher Education*, 2015, **16**, 155-172, doi: 10.1108/ijshe-02-2013-0017.
[26] J. Depledge, The organization of the Kyoto Protocol negotiations: Lessons for global environmental decision-making, 2001.
[27] A. Lauder, R. F. Sari, N. Suwartha, G. Tjahjono, Critical review of a global campus sustainability ranking: GreenMetric, *Journal of Cleaner Production*, 2015, **108**, 852-863, doi:10.1016/j.jclepro.2015.02.080.
[28] C. Washington-Ottombre, G. L. Washington, J. Newman, Campus sustainability in the US: environmental management and social change since 1970, *Journal of Cleaner Production*, 2018, **196**, 564-575, doi: 10.1016/j.jclepro.2018.06.012.
[29] K. Y. Lau, British Columbia's 'carbon neutral government' mandate: influence on infrastructure decisions. PhD diss., University of British Columbia, 2013. doi:10.14288/1.0058462
[30] C. Streck, P. Keenlyside, M. von Unger, The Paris agreement: a new beginning, *Journal for European Environmental & Planning Law*, 2016, **13**, 3-29, doi: 10.1163/18760104-01301002.
[31] Potbhare, Varun, Matt Syal, and Sinem Korkmaz, Adoption of green building guidelines in developing countries based on US and India experiences, *Journal of Green Building*, 2009, **4**, 158-174, doi: 10.3992/jgb.4.2.158.
[32] G. Dall'O', E. Bruni, A. Panza, Improvement of the sustainability of existing school buildings according to the leadership in energy and environmental design (LEED)® protocol: a case study in Italy, *Energies*, 2013, **6**, 6487-6507, doi: 10.3390/en6126487.
[33] H. M. Leslie, G. Banks, G. Prinsen, R. Scheyvens, R. Stewart-Withers, Complexities of development management in the 2020s: aligning values, skills and competencies in development studies, *Asia Pacific Viewpoint*, 2018, **59**, 235-245, doi: 10.1111/apv.12199.
[34] N. Network. International Sustainable Campus Network: Best Practices–Future Challenges, Second Annual Conference, 2008.
[35] R. Boyer, N. Peterson, P. Arora, K. Caldwell, Five approaches to social sustainability and an integrated way forward, *Sustainability*, 2016, **8**, 878, doi: 10.3390/su8090878.
[36] N. Cavus, S. E. Mrwebi, I. Ibrahim, T. Modupeola, A. Y. Reeves, Internet of Things and its applications to smart campus: a systematic literature review, *International Journal of Interactive Mobile Technologies* , 2022, **16**, 17-35, doi: 10.3991/ijim.v16i23.36215.
[37] J. Finlay, J. Massey, Eco-campus: applying the ecocity model to develop green university and college campuses, *International Journal of Sustainability in Higher Education*, 2012, **13**, 150-165, doi: 10.1108/14676371211211836.
[38] F. Casarejos, M. N. Frota, L. M. Gustavson, Higher education institutions: a strategy towards sustainability, *International Journal of Sustainability in Higher Education*, 2017, **18**, 995-1017, doi: 10.1108/ijshe-08-2016-0159.
[39] L. Carlsen, R. Bruggemann, The 17 united nations' sustainable development goals: a status by 2020, *International Journal of Sustainable Development & World Ecology*, 2022, **29**, 219-229, doi: 10.1080/13504509.2021.1948456.
[40] A. M. Aleixo, S. Leal, U. M. Azeiteiro, Conceptualization of sustainable higher education institutions, roles, barriers, and challenges for sustainability: an exploratory study in Portugal, *Journal of Cleaner Production*, 2018, **172**, 1664-1673, doi: 10.1016/j.jclepro.2016.11.010.
[41] L. Carlsen, R. Bruggemann, The 17 united nations' sustainable development goals: a status by 2020, *International Journal of Sustainable Development & World Ecology*, 2022, **29**, 219-229, doi: 10.1080/13504509.2021.1948456.
[42] W. Leal Filho, F. Frankenberger, A. L. Salvia, U. Azeiteiro, F. Alves, P. Castro, M. Will, J. Platje, V. O. Lovren, L. Brandli, E. Price, F. Doni, M. Mifsud, L. V. Ávila, A framework for the implementation of the Sustainable Development Goals in university programmes, *Journal of Cleaner Production*, 2021, **299**, 126915, doi: 10.1016/j.jclepro.2021.126915.
[43] J. Salmi, Do rankings promote academic excellence? World-class universities in perspective, *Research Handbook on University Rankings.Edward Elgar Publishing*, 2021, 455-472, doi: 10.4337/9781788974981.00046.

[44] S. L. B. Santa, J. M. P. Ribeiro, J. B. S. O. de Andrade Guerra, Green universities and sustainable development, *Encyclopedia of Sustainability in Higher Education*, 2019, 851-856, doi: 10.1007/978-3-030-11352-0471.

[45] B. Hansen, P. Stiling, W. F. Uy, Innovations and challenges in SDG integration and reporting in higher education: a case study from the university of South Florida, *International Journal of Sustainability in Higher Education*, 2021, **22**, 1002-1021, doi: 10.1108/IJSHE-08-2020-0310.

[46] G. Sonetti, P. Lombardi, L. Chelleri, True green and sustainable university campuses? toward a clusters approach, *Sustainability*, 2016, **8**, 83, doi: 10.3390/su8010083.

[47] H. Sun and O. Buyukozturk, The MIT Green Building benchmark problem for structural health monitoring of tall buildings, *Structural Control and Health Monitoring*, 2018, **25**, e2115, doi: 10.1002/stc.2115

[48] Y. Lu, Z. A. Khan, M. S. Alvarez-Alvarado, Y. Zhang, Z. Huang, M. Imran, A critical review of sustainable energy policies for the promotion of renewable energy sources, *Sustainability*, 2020, **12**, 5078, doi: 10.3390/su12125078.

[49] B. Jongbloed, Universities as hybrid organizations, *International Studies of Management & Organization*, 2015, **45**, 207-225, doi: 10.1080/00208825.2015.1006027.

[50] K. Farag, and C.B. Aktas, A survey of the most prevalent sustainability initiatives at universities, *International Journal of Sustainability in Higher Education*, 2024, **25**, 1581-1609, doi: 10.1108/IJSHE-07-2023-0285.

[51] E. Kaşkaval Okyay, Understanding the role of the national human rights institutions in implementing the sustainable development agenda: the case of Europe, 2020.

[52] R. A. Rhoads, X. Wang, X. Shi, Y. Chang, China's rising research universities: A new era of global ambition, 2014.

[53] L. Velazquez, N. Munguia, A. Platt, J. Taddei, Sustainable University: what can be the matter? *Journal of Cleaner Production*, 2006, **14**, 810-819, doi: 10.1016/j.jclepro.2005.12.008.

[54] A. Dale, J. Robinson, L. King, S. Burch, R. Newell, A. Shaw, F. Jost, Meeting the climate change challenge: local government climate action in British Columbia, Canada, *Climate Policy*, 2020, **20**, 866-880, doi: 10.1080/14693062.2019.1651244.

[55] M. Urbanski, W. L. Filho, Measuring sustainability at universities by means of the sustainability tracking, assessment and rating system (STARS): early findings from STARS data, *Environment, Development and Sustainability*, 2015, **17**, 209-220, doi: 10.1007/s10668-014-9564-3.

[56] B. Galleli, N. E. B. Teles, J. A. R. dos Santos, M. Santos Freitas-Martins, F. Hourneaux Jr, Sustainability university rankings: a comparative analysis of UI green metric and the times higher education world university rankings, *International Journal of Sustainability in Higher Education*, 2022, **23**, 404-425, doi: 10.1108/ijshe-12-2020-0475.

[57] W. Adlong, Rethinking the talloires declaration, *International Journal of Sustainability in Higher Education*, 2013, **14**, 56-70, doi: 10.1108/14676371311288958.

[58] Rodrigo Lozano, Kim Ceulemans, Mar Alonso-Almeida, Donald Huisingh, Francisco J. Lozano, Tom Waas, Wim Lambrechts, Rebeka Lukman, Jean Hugé, A review of commitment and implementation of sustainable development in higher education: results from a worldwide survey, *Journal of Cleaner Production*, 2015, **108**, 1-18, doi: 10.1016/j.jclepro.2014.09.048.

[59] N. C. H. Kongsholm, S. T. Christensen, J. R. Hermann, L. A. Larsen, T. Minssen, L. B. Pedersen, N. Rajam, N. Tommerup, A. Tupasela, J. Schovsbo, Challenges for the Sustainability of University-Run Biobanks, *Biopreserv Biobank*, 2018, **16**, 312-321. doi: 10.1089/bio.2018.0054.

[60] S. S. Mandai, F. da Rocha Brando, Experiences in sustainability of two public universities in different contexts: the University of Copenhagen and the University of São Paulo, *Energy, Climate and Sustainable Development Initiatives at Universities*, 2018, 653-668, doi: 10.1007/978-3-319-76885-4_44.

[61] B. Stensaker, H. Hermansen, Global, Nordic, or institutional visions? An investigation into how Nordic universities are adapting to the SDGs, *Higher Education*, 2023, 1-17, doi: 10.1007/s10734-023-01047-3.

[62] Z. Li, Low carbon multi-vector energy systems: a case study of the University of Edinburgh's 2040 'Net Zero' target. PhD diss., University of Edinburgh, 2023.

[63] Z. Pourmirza, S. H. R. Hosseini, S. Walker, D. Giaouris, P. Taylor, The landscape and roadmap of the research and innovation infrastructures in energy: a review of the case study of the UK, *Sustainability*, 2022, **14**, 7197, doi: 10.3390/su14127197.

[64] T. Cui, Understanding public and private value: the case of carbon reduction projects in Edinburgh. 2021.

[65] P. V. Thinh, Developing green education: The path for Wageningen University to become smart university in the Netherlands, *International Journal of Multidisciplinary Research and Growth Evaluation*, 2024, **5**, 775-782, doi: 10.54660/.ijmrge.2024.5.1.775-782.

[66] M. J. Kropff, J. A. M. van Arendonk, H. J. M. Löffler, Food for all: sustainable nutrition security: 95 years Wageningen University, 2013.

[67] P. Droege, 100% renewable: energy autonomy in action, 2012.

[68] S. Fissi, A. Romolini, E. Gori, M. Contri, The path toward a sustainable green university: the case of the university of Florence, *Journal of Cleaner Production*, 2021, **279**, 123655, doi: 10.1016/j.jclepro.2020.123655.

[69] I. Alam, A sustainable campus for the higher education institutions in the US, 2018.

[70] F. Adam, F. Sami, Review of the US 2050 long term strategy to reach net zero carbon emissions, *Energy Reports*, 2024, **12**, 845-860, doi: 10.1016/j.egyr.2024.06.031.

[71] A. Buckley, T. Gan, P. Gregorowicz, H. Xu, M. Yang, Why Not Bike?: Exploring the Cycling Behaviours of UBC Cyclists. 2020.

[72] S. Apostolidis, S. Wilson, C. Chesher, J. Tinker, Improving Waste Sorting in the AMS Nest at UBC, 2023.

[73] S. Humbert, H. Abeck, N. Bali, A. Horvath, Leadership in

Energy and Environmental Design (LEED): A critical evaluation by LCA and recommendations for improvement, *International Journal of Life Cycle Assessment*, 2007, **12**, 46-57, doi: 10.1065/lca2006.01.207.
[74] A. Schulte, Universities and sustainable food practices: an international comparison along the pacific coast of North America, 2016.
[75] A. McIlwraith-Black, Zero emissions through zero waste : reducing greenhouse gas emissions at UBC through waste reduction, 2020.
[76] S. Frost, B. Tor, R. Agrawal and A. G. Forbes, CompostNet: An Image Classifier for Meal Waste, 2019 IEEE Global Humanitarian Technology Conference (GHTC), Seattle, WA, USA, 2019.
[77] A. Wiek, A. Xiong, K. Brundiers, S. van der Leeuw, Integrating problem- and project-based learning into sustainability programs, *International Journal of Sustainability in Higher Education*, 2014, **15**, 431-449, doi: 10.1108/ijshe-02-2013-0013.
[78] M. Cohen, A. Wiek, B. Kay, J. Harlow, Aligning Public Participation to Stakeholders' Sustainability Literacy—A Case Study on Sustainable Urban Development in Phoenix, Arizona. *Sustainability*, 2015, **7**, 8709-8728. doi: 10.3390/su7078709
[79] E. Woo, M. Wooldridge, E. A. LaPorte, A case study on the effectiveness of cocurricular interdisciplinary sustainability programming for graduate students to create sustainability leaders, *International Journal of Sustainability in Higher Education*, 2024, doi: 10.1108/ijshe-06-2023-0239.
[80] Q. A. Heiser, Moral responsibility and other visceral attitudes of western michigan university students toward food waste. Master's thesis, Western Michigan University, 2024.
[81] S. Ghosh, Participation in the green power partnership: An analysis of higher education institutions as partners in the program, *International Journal of Sustainability in Higher Education*, 2011, **12**, 306-321.
[82] W. Leal Filho, M. A. P. Dinis, S. Sivapalan, H. Begum, T. F. Ng, A. Q. Al-Amin, G. M. Alam, A. Sharifi, A. L. Salvia, Q. Kalsoom, M. Saroar, S. Neiva, Sustainability practices at higher education institutions in Asia, *International Journal of Sustainability in Higher Education*, 2022, **23**, 1250-1276, doi: 10.1108/ijshe-06-2021-0244.
[83] I. C. Konstantakopoulos, A. R. Barkan, S. He, T. Veeravalli, H. Liu, C. Spanos, A deep learning and gamification approach to energy conservation at nanyang technological university, 2018.
[84] Y. S. Tan, T. J. Lee, K. Tan, Clean, green and blue: Singapore's journey towards environmental and water sustainability, 2009.
[85] D. Ferrer-Balas, J. Adachi, S. Banas, C. I. Davidson, A. Hoshikoshi, A. Mishra, Y. Motodoa, M. Onga, M. Ostwald, An international comparative analysis of sustainability transformation across seven universities, *International Journal of Sustainability in Higher Education*, 2008, **9**, 295-316, doi: 10.1108/14676370810885907.
[86] A. Sumi, New initiatives of the university of Tokyo toward establishing a strategy for sustainability through knowledge structuring and a transdisciplinary approach, *A Vision of Transdisciplinarity: EFPL Press*, 2008, 167-172, doi: 10.1201/9781439808023.ch5.5.
[87] G. Trencher, T. Terada, M. Yarime, Student participation in the co-creation of knowledge and social experiments for advancing sustainability: experiences from the university of Tokyo, *Current Opinion in Environmental Sustainability*, 2015, **16**, 56-63, doi: 10.1016/j.cosust.2015.08.001.
[88] Z. Zhong, F. Feng, J. Li, X. Liu, Y. Cao, Y. Liao, Making University and curricular sustainable entrepreneurship: a case study of tsinghua university, *Asia Pacific Education Review*, 2022, **23**, 559-569, doi: 10.1007/s12564-022-09797-y.
[89] W. Zhao, Y. Zou. Green university initiatives in China: A case of Tsinghua University, *International Journal of Sustainability in Higher Education*, 2015, **16**, 491-506, doi: 10.1108/IJSHE-01-2015-0008.
[90] V. V. N. Kishore, Renewable energy engineering and technology: principles and practice, 2010.
[91] S. Jain, A. Srivastava, D. K. Vishwakarma, J. Rajput, N. L. Rane, A. Salem, A. Elbeltagi, Protecting ancient water harvesting technologies in India: strategies for climate adaptation and sustainable development with global lessons, *Frontiers in Water*, 2024, **6**, 1441365, doi: 10.3389/frwa.2024.1441365.
[92] N. Parvez, A. Agrawal, Assessment of sustainable development in technical higher education institutes of India, *Journal of Cleaner Production*, 2019, **214**, 975-994, doi: 10.1016/j.jclepro.2018.12.085.
[93] S. K. Banshal, T. Solanki, V. K. Singh, Research performance of the national institutes of technology in India, *Current Science*, 2018, **115**, 2025, doi: 10.18520/cs/v115/i11/2025-2036.
[94] Y. Choi, C. Bone, N. Zhang, Sustainable policies and strategies in Asia: challenges for green growth, *Technological Forecasting and Social Change*, 2016, **112**, 134-137, doi: 10.1016/j.techfore.2016.05.021.
[95] Ping Jiang, Yihui Chen, Bin Xu, Wenbo Dong, Erin Kennedy, Building low carbon communities in China: The role of individual's behaviour change and engagement, *Energy Policy*, 2013, **60**, 611-620, doi: 10.1016/j.enpol.2013.05.017.
[96] X. Kang, Z. Zhu, T. Zhao, W. Zhai, J. Xu, Z. Lin, K. Zeng, B. Wang, X. Sun, P. Chen, H. Peng, Hierarchically assembled counter electrode for fiber solar cell showing record power conversion efficiency, *Advanced Functional Materials*, 2022, **32**, 2207763, doi: 10.1002/adfm.202207763.
[97] P. Jiang, H. Dong, Y. Zhu, A. Alimujiang, Z. Zhang, W. Ma, Individual environmental behavior: A key role in building low-carbon communities in China, *Frontiers in Energy*, 2018, **12**, 456-465, doi: 10.1007/s11708-018-0566-y.
[98] S. J. You Guo Jiang, 4 fudan university, Shanghai Jiaotong University, and East China normal university: background and context. *Liberal Arts Education in a Changing Society*: BRILL, 2014, 75-98, doi: 10.1163/9789004282315_005.
[99] Y. Jia, D. Ding, K. Gebel, L. Chen, S. Zhang, Z. Ma, H. Fu, Effects of new dock-less bicycle-sharing programs on cycling: a retrospective study in Shanghai, *BMJ Open*, 2019, **9**, e024280,

doi: 10.1136/bmjopen-2018-024280.
[100] Y. Fang, H. Xie, B. Chen, Z. Han, D. An, W. Cai, W. Zhang, Y. Wang, Achieving carbon neutrality in Shanghai's municipal wastewater treatment sector requires coordinated water conservation and technical improvement, *Journal of Cleaner Production*, 2024, **443**, 141134, doi: 10.1016/j.jclepro.2024.141134.
[101] X. D. Qian, J. Xia, W. Liu, S. B. Tsai, An empirical study on sustainable innovation academic entrepreneurship process model, *Sustainability*, 2018, **10**, 1974, doi: 10.3390/su10061974.
[102] C. Xiao, X. Du, Education for sustainability as a way-out to nurture citizens: a reframing in policy practices of Chinese higher education, 2024.
[103] D. Guttman, O. Young, Y. Jing, B. Bramble, M. Bu, C. Chen, K. Furst, T. Hu, Y. Li, K. Logan, L. Liu, L. Price, M. Spencer, S. Suh, X. Sun, B. Tan, H. Wang, X. Wang, J. Zhang, X. Zhang, R. Zeidan, Environmental governance in China: Interactions between the state and "nonstate actors", *Journal of Environmental Management*, 2018, **220**, 126-135, doi: 10.1016/j.jenvman.2018.04.104.
[104] M. Muñoz-Suárez, N. Guadalajara, J. M. Osca, A comparative analysis between global university rankings and environmental sustainability of universities, *Sustainability*, 2020, **12**, 5759, doi: 10.3390/su12145759.
[105] G. F. B. Slabbert, The emergence of green building practices: case study of stellenbosch, PhD dissertaiton, Stellenbosch: Stellenbosch University, 2013.
[106] Y. Lu, Z. A. Khan, M. S. Alvarez-Alvarado, Y. Zhang, Z. Huang, M. A. Imran, Critical review of sustainable energy policies for the promotion of renewable energy sources, *Sustainability*, 2020, **12**, 5078, doi: 10.3390/su12125078.
[107] R. W. Pretorius, D. W. Hedding, M. D. Nicolau, E. S. Nkooe, Campus greening in open and distance learning: curriculum initiatives in the department of geography, university of South Africa, *Implementing Campus Greening Initiatives: Approaches, Methods and Perspectives,* 2015, 277-293, doi: 10.1007/978-3-319-11961-8_21.
[108] C. McGibbon, J. P. Van Belle, Integrating environmental sustainability issues into the curriculum through problem-based and project-based learning: a case study at the university of cape town, *Current Opinion in Environmental Sustainability*, 2015, **16**, 81-88, doi: 10.1016/j.cosust.2015.07.013.
[109] H. A. Pearce, T. S. Campbell, P. Craig, K. Le Roux, Nathoo, and E. Vicatos. The articulation between the mainstream and extended degree programmes in engineering at the University of Cape Town: Reflections and possibilities, *South African Journal of Higher Education*, 2015, **29**, 150-163.
[110] T. C. M. Letete, N. W. Mungwe, M. Guma, A. Marquard, Carbon footprint of the university of cape town, *Journal of Energy in Southern Africa*, 2011, **22**, 2-12, doi: 10.17159/2413-3051/2011/v22i2a3208.
[111] J. Irlam, Z. Razzak, Q. A. Parker, H. A. Rother, Student knowledge and perceptions of climate change and environmental sustainability at the Faculty of Health Sciences, University of Cape Town, South Africa, *African Journal of Health Professions Education*, 2023, **15**, 2-6, doi: 10.7196/AJHPE.2023.v15i1.1432.
[112] D. Guillermo, Management of water resources in agriculture in Chile and its challenges, *International journal of agriculture and natural resources*, 2021, **48**, 171-185, doi: 10.7764/ijanr.v48i3.2328.
[113] C. Mac-lean, P. Núñez-Cárdenas, B. X. Rodríguez, C. Aldea, Green buildings in Chilean public higher education: a trend or a must-have in university strategic guidelines? *International Journal of Sustainable Development & World Ecology*, 2022, **29**, 756-770, doi: 10.1080/13504509.2022.2095452.
[114] J. E. Rutkowski, E. W. Rutkowski, Recycling in Brasil: Paper and Plastic Supply Chain, *Resources*, 2017, **6**, 43. doi: 10.3390/resources6030043.
[115] D. C. Sudan, A. M. de Meira, M. Sorrentino, F. da Rocha Brando Fernandez, R. L. F. Silva, L. A. Martirani, D. M. G. Alves, P. E. D. Rocha, S. A. M. dos Santos, T. K. Bonzanini, M. E. G. Moro, W. B. C. Delitti, M. de Andrade Romero, Environmental education for staff at the university of São Paulo, Brazil: capillarity and critical environmental education put into action, *Integrating Sustainability Thinking in Science and Engineering Curricula: Innovative Approaches, Methods and Tools*, 2015, 543-558, doi: 10.1007/978-3-319-09474-8_38.
[116] T. Diniz Oliveira, T. C. dos Santos, J. Weiler, A. de Oliveira Aguiar, C. C. Fernandes, L. Ziglio, The contribution of the University of São Paulo to the scientific production on climate change: a bibliometric analysis. *Discov Sustain,* 2024, **5**, 148, doi: 10.1007/s43621-024-00301-7.
[117] R. Berstembayeva, S. Niyazbekova, D. Tleuzhanova, V. Varzin, The impact of the green economy on the sustainable development of Kazakhstan, *BIO Web of Conferences*, 2024, **116**, 07040, doi: 10.1051/bioconf/202411607040.
[118] F. Nazipov, S. Tokbolat, D. Khussainova, M. Mustafa, A. Almahadin, Integration of renewable energy technologies in university campuses: a case study, *IOP Conference Series: Materials Science and Engineering*, 2021, **1044**, 012015, doi: 10.1088/1757-899x/1044/1/012015.
[119] D. Aitkulov, Z. Assylova, E. Suanbekova, L. Rojas-Solórzano, On-grid PV opportunities in university campuses: a case study at nazarbayev university in Astana, Kazakhstan, *Green Energy and Technology*, 2018, 589-601, doi: 10.1007/978-3-319-89845-2_41.
[120] A. Kaliyeva, The development of MA programs at Nazarbayev University, 2023.
[121] Suleimenova, Zulfiya, Water security in Central Asia and the Caucasus: A key to peace and sustainable development, 2018.
[122] S. Zh, Sapanov, K. ZH Zhumabayeva, K. N. Makasheva, G. Kairgaliyeva, B. S. Nigmetov, Ecology of Kazakhstan: Problems and ways of their solutions, *Journal of Physics: Conference Series*, 2021, **1860**, 012020. doi: 10.1088/1742-6596/1860/1/012020.
[123] B. Rakhimbekova, R. Seisebayeva, G. Abdigaliyeva, Higher education in Kazakhstan: global trends and state policy,

Farabi Journal of Social Sciences, 2022, **8**, 4-12, doi: 10.26577/FJSS.2022.v8.i2.01.
[124] R. Abazov, Education for sustainable development and ICT: The case of MDP program at Al-Farabi KazNU, *Journalism Series*, 2020, **58**, 34-43, doi: 10.26577/HJ.2020.v58.i4.04.
[125] P. Yelubayeva, E. Tashkyn, G. Berkinbayeva, Addressing challenges in Kazakh education for sustainable development, *Sustainability*, 2023, **15**, 14311, doi: 10.3390/su151914311.
[126] R. Abazov, Redefining global citizenship education: a case study of Kazakhstan, *Journal of Philosophy, Culture and Political Science*, 2021, **75**, 90-99, doi: 10.26577/jpcp.2021.v75.i1.09.
[127] G. Economy, Realities and prospects in Kazakhstan, World Bank Group, 2018.
[128] Y. Abuov, D. Zhakupov, B. Suleimenova, B. Ismagulov, A. Kim, S. Zholdayakova, Realizing the benefits of a hydrogen industry in Kazakhstan, *International Journal of Hydrogen Energy*, 2024, **54**, 37-48, doi: 10.1016/j.ijhydene.2023.05.259.
[129] A. Sarsenbayeva, I. Makarikhina, Globalisation influence on higher education in Kazakhstan and Russia (on the example of Engineering University), *E3S Web of Conferences*, 2020, **210,** 22010, doi: 10.1051/e3sconf/202021022010.
[130] A. Seilkhan, A. Akhmet, Developing green university concepts innovations for environmental education in Kazakhstan, *Pedagogy and Psychology*, 2023, **55**, 63-70, doi: 10.51889/2077-6861.2023.30.2.028.
[131] Y. Sailaukhanuly, A. Popova, T. Mansur, K. Bexeitova, S. Azat, K. Toshtay, A. Tasmagambetova, Preliminary study and assessment of drinking water from Almaty, Kazakhstan, *Eurasian Chemico-Technological Journal*, 2022, **24**, 341-350, doi: 10.18321/ectj1478.
[132] A. Kulanov, M. Aitkazina, Elvira Ruzieva, Alma Karshalova, and Anelya Saulembekova. The impact of green instruments on the state of the financial system, *Scientific Journal Bulletin of the NAS RK*, 2023, **403**, 470-482, doi.org/10.32014/2023.2518-1467.522.
[133] Z. Zhang, G. Hu, X. Mu, L. Kong, From low carbon to carbon neutrality: a bibliometric analysis of the status, evolution and development trend, *Journal of Environmental Management*, 2022, **322**, 116087, doi: 10.1016/j.jenvman.2022.116087.
[134] L. Mundaca, A. Markandya, Assessing regional progress towards a 'green energy economy', *Applied Energy*, 2016, **179**, 1372-1394, doi: 10.1016/j.apenergy.2015.10.098.
[135] Toktarbaiuly, O., Kurbanova, A., Imekova, G., Abutalip, M., & Toktarbay, Z. Desert water saving and transportation for enhanced oil recovery: bridging the gap for sustainable oil recovery, *Eurasian Chemico-Technological Journal*, 2023, **25**, 193-200, doi: 10.18321/ectj1522.
[136] P. Harborne, C. Hendry, Pathways to commercial wind power in the US, Europe and Japan: The role of demonstration projects and field trials in the innovation process, *Energy Policy*, 2009, **37**, 3580-3595, doi: 10.1016/j.enpol.2009.04.027.
[137] M. Yarime, G. Trencher, T. Mino, R. W. Scholz, L. Olsson, B. Ness, N. Frantzeskaki, J. Rotmans, Establishing sustainability science in higher education institutions: towards an integration of academic development, institutionalization, and stakeholder collaborations, *Sustainability Science*, 2012, **7**, 101-113, doi: 10.1007/s11625-012-0157-5.
[138] F. Annan-Diab, C. Molinari, Interdisciplinarity: Practical approach to advancing education for sustainability and for the Sustainable Development Goals, *The International Journal of Management Education*, 2017, **15**, 73-83, doi: 10.1016/j.ijme.2017.03.006.
[139] L. Hancock, S. Nuttman, Engaging higher education institutions in the challenge of sustainability: sustainable transport as a catalyst for action, *Journal of Cleaner Production*, 2014, **62**, 62-71, doi: 10.1016/j.jclepro.2013.07.062.
[140] I. S. Zen, Exploring the living learning laboratory, *International Journal of Sustainability in Higher Education*, 2017, **18**, 939-955, doi: 10.1108/ijshe-09-2015-0154.
[141] W. M. Purcell, H. Henriksen, J. D. Spengler, Universities as the engine of transformational sustainability toward delivering the sustainable development goals, *International Journal of Sustainability in Higher Education*, 2019, **20**, 1343-1357, doi: 10.1108/ijshe-02-2019-0103.
[142] G. W. Hunter, D. Vettorato, G. Sagoe Creating smart energy cities for sustainability through project implementation: a case study of Bolzano, Italy, *Sustainability*, 2018, **10**, 2167, doi: 10.3390/su10072167.
[143] D. L. Nielson, M. J. Tierney, Delegation to international organizations: agency theory and world bank environmental reform, *International Organization*, 2003, **57**, 241-276, doi: 10.1017/s0020818303572010.
[144] D. W. Husic, Reframing sustainability initiatives in higher education, *Sustainable Earth Reviews*, 2024, **7**, 5, doi: 10.1186/s42055-024-00076-9.

More info

UTM Library

UTM
UNIVERSITI TEKNOLOGI MALAYSIA

SDi@JPUTM
SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
4) Building Sustainability in Higher Education through Green Management and Innovation: A Case Study of Private Universities in Jakarta (2024)	JOURNAL OF ECOHUMANISM (Article From : ECOHUMANISM.CO.UK)

27th FEBRUARY 2025
SOURCE: PERPUSTAKAAN UTM

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

Building Sustainability in Higher Education through Green Management and Innovation: A Case Study of Private Universities in Jakarta

Ahmad Hidayat Sutawaidjaya[1], Muhammad Yusuf[2], Edi Hamdi[3]

Abstract

This study analyzes the causal relationship between green management, supply chain management, and organizational culture on the sustainability of higher education institutions, with green innovation as a mediating factor. Data were collected from private universities in Jakarta and compared with global benchmarks such as the Times Higher Education Impact Rankings and the UI GreenMetric World University Rankings. Using SEM-PLS for analysis, the results show that green management, supply chain management, and organizational culture each positively influence the sustainability of higher education institutions. The study demonstrates how green management practices and organizational culture affect sustainability in higher education. International comparisons reveal similar trends globally, with green innovation playing a crucial mediating role.

Keywords: *Green Management, Supply Chain Management, Organizational Culture, Green Innovation, Higher Education Sustainability, Private Universities.*

Introduction

A green campus represents the efforts of the academic community to synergize goals, objectives, and work productivity to achieve maximum collective results in terms of health (Novianti et al., 2020). It encompasses the management of green building dimensions, water strength, food, transportation, waste, education, and environmental research (Calder & Dautremont-Smith, 2020). This commitment from the higher education sector aims to prioritize sustainability and promote improved living and learning environments (Tamiami, 2020; Vázquez-Brust et al., 2023). Essentially, a green campus environment is characterized by a harmonious coexistence between eco-conscious practices and education, where the implementation reflects environmental protection principles (Zaidi & Jamshed, 2021).

Sustainable higher education institutions refer to universities' concern for the environment, economy, and society, including the health impacts of resource use (Velazquez et al., 2020). Therefore, organizations must invest in, exploit, and use eco-friendly technologies and innovations that aim to efficiently use resources while enhancing ecological activities and productivity (Galdeano-Gómez et al., 2020).

Private universities in Indonesia participate in rankings based on the greenest and most sustainable campuses, such as the UI Green Metric World University Rankings (UIGM) 2023. UIGM is a Universitas Indonesia (UI) program that ranks world universities to assess their greening and sustainability efforts. The ranking criteria include Setting & Infrastructure (SI) 15%, Energy & Climate Change (EC) 21%, Waste (WS) 18%, Water (WR) 10%, Transportation (TR) 18%, and Education & Research (ED) 18%. These six criteria serve as indicators to measure green space levels, university zoning profiles, setting and infrastructure, water usage, transportation, waste management, energy and climate change, and impactful education and research. The top 10 private universities in Indonesia according to UI Green Metric 2023 are Telkom University (Tel-U), Universitas Islam Indonesia (UII), Universitas Muhammadiyah Yogyakarta (UMY), Universitas Multimedia Nusantara (UMN), Universitas Medan Area (UMA), Universitas Muhammadiyah Malang (UMM), Universitas Budi Luhur (UBL), Universitas Pancasila (UP), Universitas Esa Unggul (UEU), and Universitas Teknokrat Indonesia (UTI).

[1] Faculty Economics and Business, University of Esa Unggul, Indonesia, Email: ahmad.hidayat@esaunggul.ac.id, (Corresponding Author), ORCID: 0000-0001-8310-2528
[2] University of Cyber, Indonesia, Email: muhammad.yusuf@cyber-univ.ac.id
[3] Faculty Economics and Business, University of Esa Unggul, Indonesia, Email: edi.hamdi@esaunggul.ac.id

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

Green innovation is a determinant of higher education sustainability, which Faucheux & Nicolaï (2020) describe as new solutions to minimize environmental challenges while promoting sustainability goals. According to Albort-Morant et al. (2020), green technology provides two main benefits for organizations: commercial rewards from creating eco-friendly products and financial benefits that can enhance competitiveness.

Antecedents of green innovation and higher education sustainability include green management, which focuses on the voluntary prevention or reduction of pollution, waste, and emissions sustainably (Hart, 2020); green supply chain management practices used by businesses in their daily operations to help the environment (Laari et al., 2020); and organizational culture, which can be understood as an opportunity for a company to shape human behavior according to the company's desires (Esha & Dwipayani, 2021).

This research aims to analyze the impact of green management, supply chain management, and organizational culture on higher education sustainability, mediated by green innovation.

Literature Review

Higher Education Sustainability

Universities have a responsibility to protect the "health and well-being of humans and ecosystems" and use knowledge to "address current and future ecological and social challenges" (Cole, 2020). Efforts in energy and resource conservation, waste reduction, advancement of social justice, and ideas of equity must be transferred to society (Alshuwaikhat & Abubakar, 2020). Cortese (2020) defines universities as a four-dimensional system: education, research, campus operations, and community outreach. Sebire & Isabeles-Flores (2023) add a fifth dimension, stating that these dimensions need to be assessed and reported (Choi & Ng, 2020; Lozano, 2020). The triple bottom line, encompassing environmental, economic, and social dimensions, is traditionally seen as relevant for sustainability and sustainable development (Choi & Ng, 2020). Institutional sustainability is considered a separate dimension due to its relevance in supporting sustainable development (Pfahl, 2020).

From an environmental perspective in sustainable development, the aim is to reduce negative environmental impacts, such as waste management and utilizing ecological processes (Galdeano-Gómez et al., 2020). The challenges associated with the social dimension of sustainability involve finding a balance between the "needs" of communities and individuals, the capacity of nature, and economic well-being (Choi & Ng, 2020; Galdeano-Gómez et al., 2020). The institutional dimension of sustainability is related to governance aspects in sustainable development (Pfahl, 2020). It includes regulatory elements, policies established at the community level, and political support for development (Lozano, 2020). Economic sustainability can be recognized as the efforts of communities and organizations to manage their own impacts and business networks on life on Earth and its ecosystems (Wagner & Svensson, 2020; Shikalgar et al., 2024; Choi & Ng, 2020).

In summary, sustainability can be understood as development that includes environmental, social, institutional, and economic dimensions. Assessing sustainability and its individual dimensions is seen as a crucial driver of eco-friendly innovation (Kemp & Horbach, 2020).

Green Management

Green management is environmentally conscious business management that focuses on the voluntary prevention or reduction of pollution, waste, and emissions in a sustainable manner (Hart, 2020; Dwyer et al., 2020). This concept is rooted in the theory of sustainable development, which emphasizes the need to balance economic growth, environmental protection, and social equity (Brundtland Commission, 1987). According to the resource-based view (RBV) of the firm, companies that adopt green management practices can gain a competitive advantage by leveraging their unique capabilities to create value in a way that is difficult for competitors to replicate (Barney, 1991). Therefore, a company's green management must address legal issues and involve practices and conceptual tools such as eco-friendly production, green

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

marketing, eco-friendly design, and integrating environmental considerations into the organization's long-term goals (Lee, 2020). Additionally, stakeholder theory suggests that companies that engage in green management can enhance their relationships with key stakeholders, including customers, employees, and investors, by demonstrating their commitment to environmental stewardship (Freeman, 1984).

Green Suply Management

Green supply chain management is the integration of eco-friendly initiatives into every aspect of the supply chain, from resource design to end-product management services (Agyapong et al., 2023; Laari et al., 2020; Wiredu et al., 2024). Green supply chain management includes product creation, distribution processes to customers, and the initial stages of product design through to product use (Chiu & Hsieh, 2020). It involves internal environmental management, eco-friendly design, external green supply chain practices, eco-friendly practices, and customer collaboration used by businesses to implement green supply chain management (Ahmed et al., 2020; Choi et al., 2020). Some aspects include stakeholder support, legitimacy, and resources, which are more easily obtained when companies focus on green supply chain management strategies (Bu et al., 2020; Choi et al., 2020).

Organizational Culture

Organizational culture is a set of rules that must be collectively understood as a form of behavior within a company (Ardis et al., 2023; Esha & Dwipayani, 2021). There are four dimensions to measure corporate culture: clan culture, which emphasizes intimacy among members; adhocracy culture, which fosters creativity and entrepreneurship; market culture, which creates competitive advantage; and hierarchy culture, which focuses on proper rules desired by an organization (Liu et al., 2020). This research measures organizational culture using clan culture and hierarchy culture. These cultures can create unity across all levels of management (ElKelish & Hassan, 2020).

Green Inovation

Green innovation is related to sustainable performance including environmental and social dimensions (Ramus, 2020). This perspective is supported by (Asadi et al., 2020) in the business context developing a framework that assesses the relationship between green innovation and sustainable performance (Faucheux & Nicolaï, 2020) describing green innovation as a new solution to minimize environmental challenges while driving sustainability goals. (Shahzad et al., 2020)

Hypothesis Development

Green Management and Sustainability of Higher Education

Strategies and competitive advantages are likely to be based on qualities that enable eco-friendly economic activities (Raut et al., 2020). According to the triple bottom line (TBL) approach, a company's sustainable performance is measured through three key indicators: social, environmental, and economic (Hourneaux et al., 2020). Economic performance is evaluated based on operational and financial indicators, which are operationally linked to the organization's capacity to reduce input costs, energy consumption, and waste processing and disposal (Afum et al., 2020). Environmental performance relates to a business's ability to conserve energy, reduce waste, and minimize the use of harmful inputs (Yang et al., 2020). Social performance evaluates the extent to which an organization contributes to society beyond economic interests, ensuring that industries generate profit without harming the community (Huo et al., 2020).

However, some investigations have found no relationship between eco-friendly management and financial performance (Link & Naveh, 2020). Novianty (2024) found that green management positively impacts financial and operational performance through reduced production costs, minimized environmental damage, energy consumption efficiency, and the potential to open new green market opportunities. Additionally, it enhances corporate image and eco-friendly technology, improves competitive strategies,

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

and increases social and health benefits (Shrivastava, 2020), ultimately positively affecting economic performance. Therefore, the following hypothesis can be proposed:

H1 = Green Management Positively Affects Higher Education Sustainability

The implementation of Green Supply Chain Management (GSCM) practices has been linked to various organizational benefits, such as cost reduction, enhanced environmental sustainability, improved corporate image, and increased customer loyalty (Mohanty & Prakash, 2020). Therefore, Green Supply Chain Management has attracted significant attention from both academic researchers and industry professionals as a strategy to achieve sustainability goals and comply with environmental mandates (Lin et al., 2020).

The adoption of Green Supply Chain Management (GSCM) practices is influenced by various factors. The impact of environmental regulations and policies on organizational environmental initiatives and the implementation of Green Supply Chain Management is considered significant (Bolaji et al., 2024). The regulatory framework sets guidelines and incentives that encourage businesses to adopt sustainable practices throughout their supply chains. Complying with environmental regulations not only helps to avoid legal consequences but also contributes to the advancement of corporate social responsibility (CSR) and reputation (Türkeş et al., 2024). The implementation of Green Supply Chain Management (GSCM) has been shown to be significantly influenced by consumer demand for eco-friendly products and services (Lin et al., 2020).

H2 = Supply Chain Management Positively Affects Higher Education Sustainability

A good corporate culture can enhance the company's value. Research by Savić et al. (2023) states that a superior organizational culture has built investor confidence and positively impacted the company's value. It is emphasized that the goal is to encourage the creation, acquisition, dissemination, and use of knowledge (Durmus, 2024). Therefore, it can be assumed that different types of organizational culture influence how employees understand and implement corporate sustainability (Linnenluecke & Griffiths, 2020).

H3 = Organizational Culture Positively Affects Higher Education Sustainability

Eco-friendly innovation is often classified into eco-friendly product innovation and eco-friendly process innovation (Chang & Chen, 2020). Ismail et al. (2020) categorize eco-friendly innovation into product design and manufacturing process aspects. Senior management support is one of the main drivers of successful innovation implementation (Kola, 2020; Zhu & Sarkis, 2020). Therefore, this study defines eco-friendly innovation as comprising eco-friendly product innovation, eco-friendly process innovation, and eco-friendly managerial innovation (Rao & Holt, 2020). They identify that supplier greening initiatives indeed result in greener suppliers and more eco-friendly innovations. Finally, research shows that internal managerial support for eco-friendly initiatives is one of the main drivers of successful implementation of environmental management systems and practices (Zhu & Sarkis, 2020).

H4: The Effect of Green Innovation Mediates Green Management on Higher Education Sustainability

Environmental issues have become a part of strategic planning within organizations due to increasing customer concerns about environmental issues (Handfield et al., 2020). As a result, long-term strategic advantages can be developed through close collaboration with suppliers (Chan, 2020). Partnership and evaluation systems are necessary to ensure that appropriate quality levels of products and services can be achieved (Sarkis, 2020). This involves significant changes in the attitudes of companies that wish to form closer relationships with suppliers, which require time and resource investment from both parties (Lettice et al., 2020). These companies need to work with their suppliers to provide adequate guidance, advice, and assistance, and to share knowledge and skills to help them become more 'eco-friendly'. To achieve this, many large companies have established their own environmental standards for their suppliers (Rao & Holt, 2020).

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

H5: The Effect of Green Innovation Mediates Supply Chain Management on Higher Education Sustainability

Savić et al. (2023) state that organizational culture encompasses values and behaviors that contribute to an organization's unique social and psychological environment. Organizational culture is also linked to performance. Ardis et al. (2023) found that a positive organizational culture is significantly related to company performance. In addition to creating an innovative eco-friendly culture, it is essential for every company to manage green innovation. According to Linnenluecke & Griffiths (2020), a green organizational culture influences business performance by enhancing the company's value image and increasing green innovation, which also positively impacts company performance.

H6: The Effect of Green Innovation Mediates Organizational Culture on Higher Education Sustainability

Research reveals that knowledge management processes drive eco-friendly innovation, which in turn impacts a company's sustainable performance, including environmental, economic, and social dimensions (Burki et al., 2020). In the education sector, Gu (2023) shows a significant positive impact of eco-friendly innovation on economic performance. Saunila et al. (2020) found that eco-friendly innovation effectively reduces environmental pollution and resource consumption. Li et al. (2020) and Huong et al. (2021) propose that the interaction between eco-friendly innovation and company performance is moderated by environmental management. Research combining the terms innovation and sustainability (Franceschini et al., 2020) has promoted four key terms: environmental innovation, eco-innovation, green innovation, and sustainable innovation (Schiederig et al., 2020). Chen et al. (2020) state that green innovation can refer to eco-friendly products and eco-friendly processes. Green innovation refers to innovations in products, processes, and organizations to achieve sustainable competitive advantage in an eco-friendly manner (Schiederig et al., 2020). According to Albort-Morant et al. (2020), green technology provides two main benefits for organizations: commercial rewards from creating eco-friendly products and financial benefits that can enhance competitiveness. Regarding company performance, the achievement of green innovation in the fields of environment, market, finance, and knowledge is crucial at all stages of green innovation implementation (Huang et al., 2021).

H7: Green Innovation Positively Affects Higher Education Sustainability

The Methodology

The research methodology employs Structural Equation Modeling (SEM-PLS) to analyze data collected from tenured lecturers at private universities in Jakarta. SEM-PLS was chosen for its ability to evaluate both direct and indirect effects of independent variables on dependent variables.

To broaden the study's global relevance, future research could expand data collection to include universities from regions such as Europe, North America, and Asia. Comparative analysis using global frameworks like the Times Higher Education Impact Rankings will provide a clearer understanding of how different regions approach sustainability in higher education.

This study aims to analyze the causal relationship between green management, supply chain management, and organizational culture on green innovation and sustainability in higher education institutions. Data was collected from 100 tenured lecturers at various private universities in Jakarta, all of which have superior accreditation from the National Accreditation Board for Higher Education (BAN-PT). The universities involved in this study include Esa Unggul University (UEU), Atma Jaya Catholic University of Indonesia (Unika Atma Jaya), Bina Nusantara University (BINUS), Pelita Harapan University (UPH), Tarumanagara University (UNTAR), Trisakti University, Gunadarma University, and Mercu Buana University (UMB). Data collection was conducted through questionnaires distributed to the tenured lecturers at these universities.

Using this methodology, the study hopes to provide better insights into how green management, supply chain management, and organizational culture can promote green innovation and sustainability in higher

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

education institutions. The results of this research are expected to offer practical recommendations for other universities in implementing sustainability and green innovation strategies.

Operationalization of Variables

The indicators for Green Management (X1) include Environmental Policy, Resource Management, and Emission and Waste Reduction (Dwyer et al., 2020). For Supply Chain Management (X2), the indicators are Process Efficiency, Quality and Customer Satisfaction, and Collaboration with Suppliers and Partners (Agyapong et al., 2023). Organizational Culture (X3) is measured by Organizational Values, Internal Communication, and Employee Involvement and Participation (Linnenluecke & Griffiths, 2020). Indicators for Green Innovation (Z) are Green Product Development, Green Production Processes, and the Use of Renewable Energy (Shahzad et al., 2020). Lastly, the indicators for Higher Education Sustainability (Y) include Policy and Governance, Resource Management, and Education and Curriculum (Velazquez et al., 2020).

By clearly defining these indicators, the study ensures that each variable is measured accurately and consistently. This operationalization allows for a more precise analysis of how green management, supply chain management, and organizational culture impact green innovation and sustainability in higher education institutions. Each indicator is grounded in previous research, providing a solid foundation for the study's methodology and contributing to the reliability and validity of the findings.

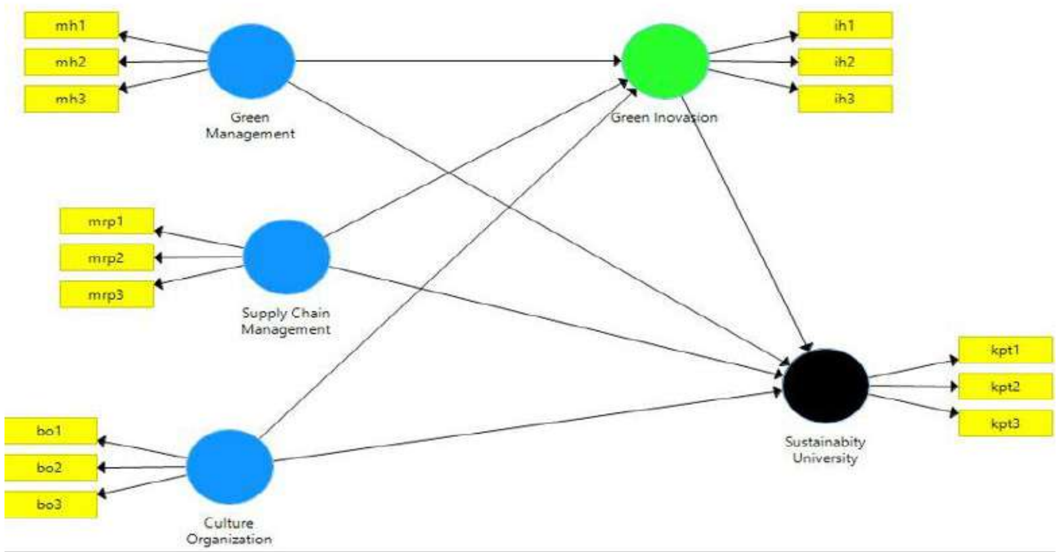


Figure 1. Model of Green Management, Supply Chain Management and Culture Organization and Sustainability University

Source: developed by Author, 2024

Results

Below are the results of statistical test processing as follows:

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

Tables 1. Outer Loadings

Below are the results of statistical test processing as follows:

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
bo2 <- Culture Organization	0.821	0.817	0.054	15.276	0.000
bo3 <- Culture Organization	0.841	0.842	0.041	20.753	0.000
ih1 <- Green Inovasion	0.709	0.707	0.070	10.095	0.000
ih2 <- Green Inovasion	0.806	0.807	0.036	22.292	0.000
ih3 <- Green Inovasion	0.864	0.864	0.027	31.906	0.000
kpt1 <- Sustainabity University	0.778	0.775	0.049	15.906	0.000
kpt2 <- Sustainabity University	0.758	0.765	0.056	13.450	0.000
kpt3 <- Sustainabity University	0.795	0.794	0.041	19.491	0.000
mh1 <- Green Management	1.000	1.000	0.000		
mrp1 <- Supply Chain Management	0.709	0.704	0.100	7.124	0.000
mrp2 <- Supply Chain Management	0.821	0.825	0.040	20.447	0.000
mrp3 <- Supply Chain Management	0.810	0.804	0.065	12.527	0.000

Source: developed by Author, 2024

Based on the outer loading, the Original Sample value is greater than 0.7 with a p value stat of less than 0.05, meaning it is valid.

Quality Criteria

Based on R square, it shows the strength of the model of green innovation of 0.471 and sustainable university of 0.552 which can be explained by the independent variables.

Tables 2. R Square

	R Square	R Square Adjusted
Green Inovasion	0.471	0.455
Sustainabity University	0.552	0.533

Tables 3. Construct Reliability and Validity

	Cronbach's Alpha	rho_A	Composite Reliability	Average Variance Extracted (AVE)
Culture Organization	0.552	0.553	0.817	0.690
Green Inovasion	0.708	0.724	0.837	0.633
Green Management	1.000	1.000	1.000	1.000
Supply Chain Management	0.680	0.688	0.824	0.611

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

Sustainabity University	0.674	0.678	0.820	0.604

Source: developed by Author, 2024

Composite reliability, Cronbach alpha and AVE values greater than 0.05 mean valid and reliable

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
Culture Organization -> Green Inovasion -> Sustainabity University	0.360	0.368	0.091	3.950	0.000
Green Management -> Green Inovasion -> Sustainabity University	0.099	0.101	0.056	2.764	0.078
Supply Chain Management -> Green Inovasion -> Sustainabity University	0.026	0.030	0.058	2.443	0.058

Source: developed by Author, 2024

- Culture Organization -> Green Innovation -> Sustainabity University of 0.360 with a p value of t-stat less than 0.10
- Green Management -> Green Innovation -> Sustainabity University of 0.099 with a p value of t-stat less than 0.10
- Supply Chain Management -> Green Innovation -> Sustainabity University of 0.026 with a p value of tstat less than 0.10

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
Culture Organization -> Green Inovasion	0.576	0.583	0.084	6.828	0.000
Culture Organization -> Sustainabity University	0.334	0.336	0.123	2.728	0.007
Green Inovasion -> Sustainabity University	0.625	0.632	0.126	4.960	0.000

Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

Green Management -> Green Inovasion	0.159	0.159	0.080	2.001	0.046
Green Management -> Sustainabity University	0.210	0.210	0.080	2.640	0.009
Supply Chain Management -> Green Inovasion	0.041	0.045	0.092	2.450	0.065
Supply Chain Management -> Sustainabity University	0.175	0.187	0.126	2.383	0.016

Source: developed by Author, 2024

- Culture Organization -> Green Innovation of 0.576 with p values t-stat 0.10
- Culture Organization -> Sustainabity University of 0.334 with p values t-stat 0.10
- Green Innovation -> Sustainabity University of 0.625 with p values t-stat 0.10
- Green Management -> Green Innovation of 0.159 with p values t-stat 0.10
- Green Management -> Sustainabity University of 0.210 with p values t-stat 0.10
- Supply Chain Management -> Green Innovation of 0.041 with p values t-stat 0.10
- Supply Chain Management -> Sustainabity University of 0.175 with p values t-stat 0.10

Discussion

Green Management Towards Higher Education Sustainability

Green management positively impacts higher education sustainability, supporting the hypothesis and aligning with the views of Hart (2020), Dwyer et al. (2020), Lee (2020), Novianty (2024), and Shrivastava (2020). Green management involves environmentally conscious business practices that focus on the voluntary prevention or reduction of pollution, waste, and emissions in a sustainable manner.

Green management positively influences financial and operational performance by reducing production costs, minimizing environmental damage, improving energy consumption efficiency, and creating opportunities in untapped green markets. Additionally, it enhances corporate image, promotes eco-friendly technologies, strengthens competitive strategies, and provides social and health benefits.

Supply Chain Management Towards Higher Education Sustainability

Supply chain management positively impacts higher education sustainability, supporting the second hypothesis in alignment with Agyapong et al. (2023), Laari et al. (2020), Wiredu et al. (2024), Mohanty & Prakash (2020), and Lin et al. (2020). Green supply chain management (GSCM) integrates internal environmental management initiatives, eco-friendly design, external green supply chain practices, and customer collaboration used by businesses to implement sustainable supply chain management. The implementation of GSCM practices has been linked to various benefits for organizations, such as cost reduction, enhanced environmental conservation, improved corporate image, and increased customer loyalty.

Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071

Organizational Culture Towards Higher Education Sustainability

Organizational culture positively impacts higher education sustainability, supporting the views of Ardis et al. (2023), Esha & Dwipayani (2021), Savić et al. (2023), Durmus (2024), and Linnenluecke & Griffiths (2020). Organizational culture is a set of rules collectively understood as a form of behavior within a company. A good corporate culture can enhance the company's value. Superior organizational culture has built investor confidence and positively impacted the company's value. Therefore, it can be assumed that different types of organizational culture influence how employees understand and implement corporate sustainability.

Green Innovation Mediates the Effect of Green Management on Higher Education Sustainability

Green innovation mediates the effect of green management on higher education sustainability, supporting the views of Chang & Chen (2020), Kola (2020), Zhu & Sarkis (2020), and Rao & Holt (2020). Senior management support is one of the main drivers of successful innovation implementation. Therefore, this study defines eco-friendly innovation as comprising eco-friendly product innovation, eco-friendly process innovation, and eco-friendly managerial innovation. Supplier greening initiatives indeed result in greener suppliers and more eco-friendly innovations. Finally, the research indicates that internal managerial support for eco-friendly initiatives is a key driver of successful implementation of environmental management systems and practices.

Green Innovation Mediates the Effect of Supply Chain Management on Higher Education Sustainability

Green innovation mediates the effect of supply chain management on higher education sustainability, aligning with the views of Handfield et al. (2020), Chan (2020), Sarkis (2020), Lettice et al. (2020), and Rao & Holt (2020). Strategic planning within organizations is essential due to increasing customer concerns about environmental issues. As a result, long-term strategic advantages can be developed through close collaboration with suppliers. Partnership and evaluation systems are necessary to ensure that the appropriate quality levels of products and services are achieved. To accomplish this, many large companies have established their own environmental standards for their suppliers (Rao & Holt, 2020).

Green Innovation Mediates the Effect of Organizational Culture on Higher Education Sustainability

Green innovation mediates the effect of organizational culture on higher education sustainability, supporting the views of Savić et al. (2023), Ardis et al. (2023), and Linnenluecke & Griffiths (2020). Organizational culture is also linked to performance, with findings showing that a positive organizational culture is significantly related to company performance. In addition to creating an eco-friendly innovative culture, it is important for each company to manage green innovation. A green organizational culture influences business performance by enhancing the company's value image, and increased green innovation also positively impacts company performance.

Green Innovation Towards Higher Education Sustainability

Innovations such as mobile hospitals and field clinics were also deployed to manage patient overflow in critical regions (Sarjito & Sutawidjaya 2024), Green innovation positively impacts higher education sustainability, supporting the views of Ramus (2020), Asadi et al. (2020), Faucheux & Nicolaï (2020), Shahzad et al. (2020), Chen et al. (2020), Schiederig et al. (2020), and Huang et al. (2021). Green innovation offers new solutions to minimize environmental challenges while promoting sustainability goals. Green technology provides two main benefits for organizations: commercial rewards from creating eco-friendly products and financial benefits that can enhance competitiveness.

Conclusion

Green management influences higher education sustainability due to increased environmental policies, while supply chain management contributes by improving quality and customer satisfaction. Additionally, organizational culture impacts higher education sustainability through increased employee involvement and participation. Green innovation plays a mediating role in the effects of green management on higher education sustainability by promoting the use of renewable energy and implementing environmental policies. It also mediates the impact of supply chain management on sustainability by enhancing the use of renewable energy and improving quality and customer satisfaction. Furthermore, green innovation mediates the influence of organizational culture on sustainability by fostering renewable energy use and increasing employee involvement and participation. Overall, green innovation directly influences sustainability in higher education due to the increased use of renewable energy.

A green campus program aims to integrate environmental awareness into the intellectual activities of higher education institutions' three pillars: education, research, and community service. Higher education institutions have the capability and resources to incorporate environmental knowledge and values into their mission and programs. The importance of a green campus program is based on the following considerations:

-The complexity of environmental issues, - The potential for knowledge transfer that can be distributed through formal and non-formal education, involving students actively to foster awareness and concern for environmental management, - The increased interaction of students with their environment.

Implications

Actions Higher Education Institutions Can Take to Support Green Campus Programs in Education and Research.

Higher education institutions can support green campus programs in the education and research categories by implementing the following actions: 1) offering mandatory courses on environmental topics; 2) organizing seminars on green campus initiatives; 3) conducting public lectures on green campus initiatives; 4) running green campus campaigns through posters and stickers; 5) creating a dedicated green campus website; 6) using technology-enhanced learning methods; and 7) encouraging students to undertake environmental research projects. Additionally, higher education institutions should understand the significance of campus features that connect to the past (campus history) with current environmental issues.

Higher education institutions are central to sustainable development, as they play a crucial role in knowledge dissemination and communication through student initiatives. They are key stakeholders in policy-making and have experts who can address environmental issues.

For universities to be sustainable, they must not only teach concepts and philosophies of sustainability to their students but also embrace these concepts in their daily organizational management. Universities have been defined as four-dimensional systems (education, research, community outreach, and campus operations). Therefore, a sustainable university must implement, assess, and report on the three dimensions of sustainability (economic, environmental, and social).

References

Afum, E., Agyabeng-Mensah, Y., Sun, Z., Frimpong, B., Kusi, L. Y., & Acquah, I. S. K. (2020). Exploring the link between green manufacturing, operational competitiveness, firm reputation and sustainable performance dimensions: a mediated approach. Journal of Manufacturing Technology Management, 31(7), 1417–1438. https://doi.org/10.1108/JMTM-02-2020-0036

Agyapong, A., Aidoo, S. O., Acquaah, M., & Akomea, S. (2023). Environmental orientation and sustainability performance; the mediated moderation effects of green supply chain management practices and institutional pressure. Journal of Cleaner Production, 430(October), 139592. https://doi.org/10.1016/j.jclepro.2023.139592

Ahmed, W., Najmi, A., & Khan, F. (2020). Examining the impact of institutional pressures and green supply chain management practices on firm performance. Management of Environmental Quality: An International Journal, 31(5), 1261–1283. https://doi.org/10.1108/MEQ-06-2019-0115

Albort-Morant, G., Leal-Millán, A., & Cepeda-Carrión, G. (2020). The antecedents of green innovation performance: A model of learning and capabilities. Journal of Business Research, 69(11), 4912–4917. https://doi.org/10.1016/j.jbusres.2016.04.052

Alshuwaikhat, H. M., & Abubakar, I. (2020). An integrated approach to achieving campus sustainability: assessment of the current campus environmental management practices. Journal of Cleaner Production, 16(16), 1777–1785. https://doi.org/10.1016/j.jclepro.2007.12.002

Ardis, A., Rina Siregar, A., Br Lubis, B., Efendi, R., & Permadi, S. (2023). Pengaruh Budaya Organisasi Sekolah Terhadap Kinerja Guru SMA Negeri Labura. Jurnal Edukasi Nonformal, 4(1), 2715–2634.

Asadi, S., OmSalameh Pourhashemi, S., Nilashi, M., Abdullah, R., Samad, S., Yadegaridehkordi, E., Aljojo, N., & Razali, N. S. (2020). Investigating influence of green innovation on sustainability performance: A case on Malaysian hotel industry. Journal of Cleaner Production, 258, 120860. https://doi.org/10.1016/j.jclepro.2020.120860

Bolaji, B. H., Rahim, M. K. I. A., & Omar, S. (2024). Environmental Factors and Adoption of Green Supply Chain Management among SMEs in Nigeria: Moderating Role of Environmental Uncertainty. International Journal of Energy Economics and Policy, 14(1), 640–650. https://doi.org/10.32479/ijeep.15456

Bu, X., Dang, W., Wang, J., & Liu, Q. (2020). Environmental-orientation-green-supply-chain-management-and-firm-performance-empirical-evidence-from-Chinese-small-and-mediumsized-enterprisesInternational-Journal-of-Environmental-Research-and-Public-Health.pdf. Internal Journal of Environmental Research and Publlic Health, 17(4), 1–17.

Burki, U., Ersoy, P., & Najam, U. (2020). Top management, green innovations, and the mediating effect of customer cooperation in green supply chains. Sustainability (Switzerland), 11(4). https://doi.org/10.3390/su11041031

Calder, W., & Dautremont-Smith, J. (2020). Higher education: more and more laboratories for inventing a sustainable future. For a Sustainable, 93–107. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Higher+Education:+More+and+More+Laboratories+for+Inventing+a+Sustainable+Future#0

Chan, H. K. (2020). A pro-active and collaborative approach to reverse logistics - A case study. Production Planning and Control, 18(4), 350–360. https://doi.org/10.1080/09537280701318736

Chang, C. H., & Chen, Y. S. (2020). Green organizational identity and green innovation. Management Decision, 51(5), 1056–1070. https://doi.org/10.1108/MD-09-2011-0314

Chen, Y. S., Chang, C. H., & Lin, Y. H. (2020). The determinants of green radical and incremental innovation performance: Green shared vision, green absorptive capacity, and green organizational ambidexterity. Sustainability (Switzerland), 6(11), 7787–7806. https://doi.org/10.3390/su6117787

Chiu, J. Z., & Hsieh, C. C. (2020). The impact of restaurants' green supply chain practices on firm performance. Sustainability (Switzerland), 8(1), 1–14. https://doi.org/10.3390/su8010042

Choi, S. B., Min, H., Joo, H. Y., & Choi, H. B. (2020). Assessing the impact of green supply chain practices on firm performance in the Korean manufacturing industry. International Journal of Logistics Research and Applications, 20(2), 129–145. https://doi.org/10.1080/13675567.2016.1160041

Choi, S., & Ng, A. (2020). Environmental and Economic Dimensions of Sustainability and Price Effects on Consumer Responses. Journal of Business Ethics, 104(2), 269–282. https://doi.org/10.1007/s10551-011-0908-8

Cole, L. (2020). Assessing sustainability on Canadian university campuses: development of a campus sustainability assessment framework (Vol. 301, Issue May).

Cortese, A. D. (2020). The critical role of higher education in creating a sustainable future. Planning for Higher Education, 15–22. http://www.scup.org/asset/48483/cortese.pdf

Durmus, İ. (2024). Sustainable knowledge and organization culture. International Journal of Business, Economics and Management Perspectives, June. https://doi.org/10.29228/ijbemp.74281

Dwyer, R., Lamond, D., Pane Haden, S. S., Oyler, J. D., & Humphreys, J. H. (2020). Historical, practical, and theoretical perspectives on green management: An exploratory analysis. Management Decision, 47(7), 1041–1055. https://doi.org/10.1108/00251740910978287

Esha, D., & Dwipayani, M. (2021). Pengaruh Kepemimpinan Dan Budaya Organisasi Terhadap Perilaku Kerja Inovatif Di Pt Smart Meter. Prosiding Simposium Nasional Multidisiplin (SinaMu), 2, 279–285. https://doi.org/10.31000/sinamu.v2i0.3522

Faucheux, S., & Nicolaï, I. (2020). IT for green and green IT: A proposed typology of eco-innovation. Ecological Economics, 70(11), 2020–2027. https://doi.org/10.1016/j.ecolecon.2011.05.019

Franceschini, S., Faria, L. G. D., & Jurowetzki, R. (2020). Unveiling scientific communities about sustainability and innovation. A bibliometric journey around sustainable terms. Journal of Cleaner Production, 127, 72–83. https://doi.org/10.1016/j.jclepro.2016.03.142

Galdeano-Gómez, E., Aznar-Sánchez, J. A., & Pérez-Mesa, J. C. (2020). Sustainability dimensions related to agricultural-based development: The experience of 50 years of intensive farming in Almería (Spain). International Journal of Agricultural Sustainability, 11(2), 125–143. https://doi.org/10.1080/14735903.2012.704306

Gu, S. (2023). Green innovation; a way to enhance economic performance of Chinese hotels. International Journal of Innovation Science, 15(3), 406–426. https://doi.org/10.1108/IJIS-07-2021-0128

Handfield, R., Sroufe, R., & Walton, S. (2020). Integrating environmental management and supply chain strategies. Business Strategy and the Environment, 14(1), 1–19. https://doi.org/10.1002/bse.422

Hart, S. L. (2020). Innovation , Creative Destruction and Sustainability. Research-Technology Management, 48:5(November), 20–27. http://dx.doi.org/10.1080/08956308.2005.11657334

Volume: 3, No: 6, pp. 1034 – 1047
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4071
Hourneaux, F., Gabriel, M. L. da S., & Gallardo-Vázquez, D. A. (2020). Triple bottom line and sustainable performance measurement in industrial companies. Revista de Gestao, 25(4), 413–429. https://doi.org/10.1108/REGE-04-2018-0065

Huang, X. X., Hu, Z. P., Liu, C. S., Yu, D. J., & Yu, L. F. (2021). The relationships between regulatory and customer pressure, green organizational responses, and green innovation performance. Journal of Cleaner Production, 112, 3423–3433. https://doi.org/10.1016/j.jclepro.2015.10.106

Huo, B., Gu, M., & Wang, Z. (2020). Green or lean? A supply chain approach to sustainable performance. Journal of Cleaner Production, 216, 152–166. https://doi.org/10.1016/j.jclepro.2019.01.141

Huong, P. T., Cherian, J., Hien, N. T., Sial, M. S., Samad, S., & Tuan, B. A. (2021). Environmental management, green innovation, and social–open innovation. Journal of Open Innovation: Technology, Market, and Complexity, 7(1). https://doi.org/10.3390/JOITMC7010089

Ismail, R. M., Razak, R. C., & Lazim, H. M. (20204). Manufacturing Technology Impact on Environmental Factors and Manufacturing Performance. Applied Mechanics and Materials, 541–542(March), 1532–1536. https://doi.org/10.4028/www.scientific.net/AMM.541-542.1532

Kemp, R., & Horbach, J. (2020). Measurement of competitiveness of eco-innovation. Measuring Eco-Innovation Project (MEI), March, 1–32.

Kola, S. (2020). Enhancing the Concept of Strategic Intent (Issue January 2020).

Laari, S., Töyli, J., Solakivi, T., & Ojala, L. (2020). Firm performance and customer-driven green supply chain management. Journal of Cleaner Production, 112, 1960–1970. https://doi.org/10.1016/j.jclepro.2015.06.150

Lee, K. H. (2020). Why and how to adopt green management into business organizations?: The case study of Korean SMEs in manufacturing industry. Management Decision, 47(7), 1101–1121. https://doi.org/10.1108/00251740910978322

Lettice, F., Wyatt, C., & Evans, S. (2020). Buyer-supplier partnerships during product design and development in the global automotive sector: Who invests, in what and when? International Journal of Production Economics, 127(2), 309–319. https://doi.org/10.1016/j.ijpe.2009.08.007

Li, D., Zheng, M., Cao, C., Chen, X., Ren, S., & Huang, M. (2020). The impact of legitimacy pressure and corporate profitability on green innovation: Evidence from China top 100. Journal of Cleaner Production, 141, 41–49. https://doi.org/10.1016/j.jclepro.2016.08.123

Lin, C. Y., Alam, S. S., Ho, Y. H., Al-Shaikh, M. E., & Sultan, P. (2020). Adoption of green supply chain management among SMEs in Malaysia. Sustainability (Switzerland), 12(16), 1–15. https://doi.org/10.3390/su12166454

Link, S., & Naveh, E. (2020). Standardization and discretion: Does the environmental standard ISO 14001 lead to performance benefits? IEEE Transactions on Engineering Management, 53(4), 508–519. https://doi.org/10.1109/TEM.2006.883704

Linnenluecke, M. K., & Griffiths, A. (2020). Corporate sustainability and organizational culture. Journal of World Business, 45(4), 357–366. https://doi.org/10.1016/j.jwb.2009.08.006

Liu, Q., Deng, S., & Wang, Y. (2020). Mechanism of recombinant human growth hormone accelerating burn wound healing in burn patients. In Zhonghua shao shang za zhi = Zhonghua shaoshang zazhi = Chinese journal of burns (Vol. 16, Issue 1).

Lozano, R. (2020). A holistic perspective on corporate sustainability drivers. Corporate Social Responsibility and Environmental Management, 22(1), 32–44. https://doi.org/10.1002/csr.1325

Mohanty, R. P., & Prakash, A. (2020). Green supply chain management practices in India: a confirmatory empirical study. Production and Manufacturing Research, 2(1), 438–456. https://doi.org/10.1080/21693277.2014.921127

Novianti, V., Wayan Sumberartha, I., & Amin, M. (2020). Production and Waste Management for Initiation of Green Campus Program at Universitas Negeri Malang. IOP Conference Series: Earth and Environmental Science, 276(1). https://doi.org/10.1088/1755-1315/276/1/012039

Novianty, R. (2024). Enhancing green innovation performance : the impact of green entrepreneurial orientation and green dynamic capability. Enrichment : Journal of Management, 14(2).

Pfahl, S. (2020). Institutional sustainability. Int. J. Sustainable Development, 8(2), 80–96.

Ramus, C. A. (2020). Encouraging innovative environmental actions: What companies and managers must do. Journal of World Business, 37(2), 151–164. https://doi.org/10.1016/S1090-9516(02)00074-3

Rao, P., & Holt, D. (2020). Do green supply chains lead to competitiveness and economic performance? International Journal of Operations & Production Management, 25(9), 898–916.

Raut, R. D., Luthra, S., Narkhede, B. E., Mangla, S. K., Gardas, B. B., & Priyadarshinee, P. (2020). Examining the performance oriented indicators for implementing green management practices in the Indian agro sector. Journal of Cleaner Production, 215, 926–943. https://doi.org/10.1016/j.jclepro.2019.01.139

Sarkis, J. (2020). Greening the supply chain. Greening the Supply Chain, January 2006, 1–407. https://doi.org/10.1007/1-84628-299-3

Saunila, M., Ukko, J., & Rantala, T. (2020). Sustainability as a driver of green innovation investment and exploitation. Journal of Cleaner Production, 179, 631–641. https://doi.org/10.1016/j.jclepro.2017.11.211

Sarjito, Aris, & Sutawidjaya, Hidayat Ahmad, (2024) Indonesia's National Defense Resilience During Covid-19: Key Lessons, Journal of Ecohumanism, Vol. 3 No. 4 (2024) https://ecohumanism.co.uk/joe/ecohumanism/article/view/3806

Savić, B., Jelić, S., & Ostojić, V. V. (2023). The Impact of Organizational Culture on Financial Performance of the Company. Economic Themes, 61(2), 235–248. https://doi.org/10.2478/ethemes-2023-0012

Schiederig, T., Tietze, F., & Herstatt, C. (2020). Green innovation in technology and innovation management - an exploratory literature review. R and D Management, 42(2), 180–192. https://doi.org/10.1111/j.1467-9310.2011.00672.x

Sebire, R. H., & Isabeles-Flores, S. (2023). Sustainable Development in Higher Education Practices. Revista Lengua y Cultura, 5(9), 89–96. https://doi.org/10.29057/lc.v5i9.10971
Shahzad, M., Qu, Y., Javed, S. A., Zafar, A. U., & Rehman, S. U. (2020). Relation of environment sustainability to CSR and green innovation: A case of Pakistani manufacturing industry. Journal of Cleaner Production, 253, 119938. https://doi.org/10.1016/j.jclepro.2019.119938
Shikalgar, A., Menon, P., & Mahajan, V. C. (2024). Towards customer-centric sustainability: how mindful advertising influences mindful consumption behaviour. In Journal of Indian Business Research (Vol. 16, Issue 1). https://doi.org/10.1108/JIBR-06-2023-0207
Shrivastava, P. (2020). Environmental technologies and competitive advantage. Business Ethics and Strategy, Volumes I and II, 16(1 995), 317–334. https://doi.org/10.4324/9781315261102-20
Tamiami, H. F. (2020). Green campus concept based on architect perspective. IOP Conference Series: Materials Science and Engineering, 801(1). https://doi.org/10.1088/1757-899X/801/1/012028
Türkeş, M. C., Bănacu, C. S., & Stoenică, L. (2024). The Effect of Supply Chain Sustainability Practices on Romanian SME Performance. Sustainability (Switzerland) , 16(7). https://doi.org/10.3390/su16072887
Vázquez-Brust, D., Jabbour, C. J. C., Plaza-Úbeda, J. A., Perez-Valls, M., de Sousa Jabbour, A. B. L., & Renwick, D. W. S. (2023). The role of green human resource management in the translation of greening pressures into environmental protection practices. Business Strategy and the Environment, 32(6), 3628–3648. https://doi.org/10.1002/bse.3319
Velazquez, L., Munguia, N., Platt, A., & Taddei, J. (2020). Sustainable university: what can be the matter? Journal of Cleaner Production, 14(9–11), 810–819. https://doi.org/10.1016/j.jclepro.2005.12.008
Wagner, B., & Svensson, G. (2020). A framework to navigate sustainability in business networks: The transformative business sustainability (TBS) model. European Business Review, 26(4), 340–367. https://doi.org/10.1108/EBR-12-2013-0146
Wahid ElKelish, W., & Kamal Hassan, M. (2020). Organizational culture and corporate risk disclosure: An empirical investigation for United Arab Emirates listed companies. International Journal of Commerce and Management, 24(4), 279–299. https://doi.org/10.1108/IJCoMA-06-2012-0035
Wiredu, J., Yang, Q., Sampene, A. K., Gyamfi, B. A., & Asongu, S. A. (2024). The effect of green supply chain management practices on corporate environmental performance: Does supply chain competitive advantage matter? Business Strategy and the Environment, 33(3), 2578–2599. https://doi.org/10.1002/bse.3606
Yang, F., Yang, M., Xue, B., & Luo, Q. (2020). The effects of China's western development strategy implementation on local ecological economic performance. Journal of Cleaner Production, 202, 925–933. https://doi.org/10.1016/j.jclepro.2018.08.203
Zaidi, S. Y. A., & Jamshed, S. (2021). The Role of Green Human Resource Management Practices towards Attaining Sustainable Development Goals through Corporate Sector. Sustainable Business and Society in Emerging Economies, 3(4), 665–682. https://doi.org/10.26710/sbsee.v3i4.2128
Zhu, Q., & Sarkis, J. (2020). An inter-sectoral comparison of green supply chain management in China: Drivers and practices. Journal of Cleaner Production, 14(5), 472–486. https://doi.org/10.1016/j.jclepro.2005.01.003.

More info

UTM
UNIVERSITI TEKNOLOGI MALAYSIA
UTM Library

SDi@JPUTM
SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
5) Collaborative Green Initiatives: Integrating Human Resources, Intellectual Capital, and Innovation for Environmental Performance (2024)	SUSTAINABILITY (Article From : MDPI)

27th FEBRUARY 2025
SOURCE: PERPUSTAKAAN UTM

sustainability

MDPI

Article

Collaborative Green Initiatives: Integrating Human Resources, Intellectual Capital, and Innovation for Environmental Performance

Xilai Qiu [1], Tayyeba Bashir [2], Rana Faizan Gul [1], Burhan Sadiq [2,*] and Ammara Naseem [3]

[1] Business School of Hohai University, Nanjing 211100, China; 20200028@hhu.edu.cn (X.Q.); ranafaizangul@hhu.edu.cn (R.F.G.)
[2] School of Economics and Management, North China Electric Power University, Beijing 102206, China; tayyebabashir@ncepu.edu.cn
[3] College of Economics and Management, Beijing University of Technology, Beijing 100126, China; naseem.ammara@emails.bjut.edu.cn
* Correspondence: burhansadiq@ncepu.edu.cn

Abstract: The purpose of this study is to assess the ecological efficiency of manufacturing small and medium-sized enterprises (SMEs) by analyzing their adoption of green human resource management practices (GHRMPs), green intellectual capital (GIC), and green innovation (GIN). The study was carried out on a representative sample of 367 manufacturing SMEs in Pakistan, and data were gathered using a particular survey questionnaire. The results were analyzed using the partial least squares–structural equation modeling (PLS-SEM) technique in SmartPLS4. This research indicates that the adoption of GHRMPs significantly impacts environmental performance (EP), GIC, and GIN. Additionally, the study found that the correlation among GHRMPs is positively mediated by GIC and GIN. The study contributes to the body of knowledge by investigating EP based on the Ability-Motivation-Opportunity Theory (AMO) through empirical evidence on hypothesized relationships. The paper provides a valuable understanding and novel approach for managers of SMEs in developing countries to improve their EP through the adoption of GHRMP, GIC, and GIN.

Keywords: green human resource management; green intellectual capital; green innovation; environmental performance

check for updates

Academic Editor: Jun (Justin) Li

Received: 29 November 2024
Revised: 19 December 2024
Accepted: 25 December 2024
Published: 31 December 2024

Citation: Qiu, X.; Bashir, T.; Gul, R.F.; Sadiq, B.; Naseem, A. Collaborative Green Initiatives: Integrating Human Resources, Intellectual Capital, and Innovation for Environmental Performance. *Sustainability* **2025**, *17*, 224. https://doi.org/10.3390/su17010224

1. Introduction

Green human resource management (GHRM) involves supporting environmentally sustainable practices and promoting eco-conscious attitudes and values among an organization's employees, particularly those who are actively involved in these efforts. Personnel are utilized to implement environmental concepts into the organizational structure in accordance with GHRM. It comprises three critical components: motivation in enhancing employee engagement, offering green opportunities, and creating green abilities among employees. Green abilities comprise the systematic procedures involved in the selection and recruitment of personnel in addition to their specialized education and growth in ecologically sustainable endeavors. Conversely, green opportunities refer to actions that involve the application of green leadership and actively engage employees in efforts to improve ecological sustainability. Lastly, motivation for employee engagement is made up of green rewards, green performance management, and par systems [1]. The way in which a business implements environmental management systems is substantially impacted by the establishment and maintenance of the internal infrastructure and skills. However, a significant percentage of SMEs demonstrate a substantial tendency to default in this area, primarily due to constraints related to the motivation and capabilities of their employees. Furthermore, this problem is compounded by the organizations' shortcomings in their abilities to effectively tackle complex difficulties associated with the pursuit of environmental sustainability [2]. Recent studies have expanded the understanding of GHRM's role in fostering GIN, highlighting its critical impact on green product and process development. For instance, recent works such as Jehangir et al. [3] and Nisar et al. [4] emphasize that green human resource practices play a pivotal role in embedding sustainability-focused innovation capabilities within organizations. These studies have identified green innovation as a mediator that amplifies the effect of GHRM on achieving organizational EP. According to past studies, psychological traits, employees' voices, and organizational culture influence the organization's performance [5]. However, in this study, the most effective indicator for improving the organization's EP is the GHRMPs, GIC and GIN, which focus on managing the processes and systems that impact the EP of an organization.

Moreover, extensive research has been carried out on the hypothesis that the financial performance of organizations declines when environmental initiatives are introduced, e.g., Yadegaridehkordi et al. [6]. But current scholarly investigations recognize tangible benefits that emerge from particular environmentally friendly practices [7]. However, there is a limited amount of research that thoroughly examines the process by which companies implement their environmental strategies to achieve economic success as well as the key resources required to enhance their green performance [8]. The significance of intangible assets, particularly GIC, is highlighted as an essential variable that holds greater importance compared with tangible assets [9]. Recent research, such as Sahan et al. [10] and Sohu et al. [11], underscores the role of GIC in enabling organizations to integrate sustainable innovation practices effectively, driving both environmental and economic performance. These studies suggest that aligning GIC with environmental strategies is critical to achieving superior outcomes. While there has been extensive research on GIC at the firm level, these studies have not provided a clear understanding of how GIC impacts performance due to the lack of incorporation of environmental strategies into GIC [12]. Recent studies further emphasize that integrating green human resource practices with green innovation capabilities provides a sustainable competitive advantage to firms while addressing environmental concerns [13]. In line with this theoretical framework, Khan et al. [14] highlighted the need for investigating the mechanisms by which GIC influences the performance of both the economy and the environment. To address this gap, this study aims to give support to the examination of GIC and to uncover the processes in which various components of GIC, including GHC, GSC, and GRC, affect the environmentally sustainable operations of an organization.

Furthermore, businesses must exhibit their concern for the environment by integrating sustainable practices into their activities that conserve energy, reduce pollution, and enhance product design [15]. Both process and product innovation can be regarded as components of GIN. Recent years have seen growing attention to the synergy between GHRMPs and GIN in improving environmental performance, particularly in the manufacturing sectors [16,17]. The scholarly discourse recognizes the impact of GHRM on GIN's ability to enhance green EP, and the majority of research articles primarily concentrate on three main areas: general green innovation, ecological innovation in products, and innovation performance in processes. The distinction between green process innovation (GPRI) and green product innovation (GPDI) is ambiguous at best; to thoroughly clarify this gap, further academic research is needed [18]. Additionally, emerging studies by Afzal et al. [19] and Tahir et al. [20] call for a more nuanced exploration of the interplay between GHRM and GIN, emphasizing the importance of contextual factors such as organizational culture and external regulatory environments. This study also aims to investigate the potential role of GIN in the relationship between sustainable EP and GHRMPs to fill the knowledge gap discussed above and to enhance knowledge.

According to this study, an organization's top management must adopt GHRMPs to build the sustainable internal competencies essential to GIC and GIN to attain EP. We conducted this empirical study using quantitative data of 367 responses by senior managers in the manufacturing SMEs of Pakistan. We used the survey method to collect the data and performed PLS-SEM analysis to explore the hypothesized effects. This study aims to answer two questions:

(a) How do GHRMPs influence an organization's EP?
(b) Is GIC and GIN crucial to the use and implementation of GHRMPs in an organization's EP?

Our study used AMO theory to demystify the role of GHRMPs in assessing GIC, GIN, and EP. This research integrates recent theoretical and empirical advancements, making it more aligned with current scholarly debates in green innovation and green human resource management. Our study provides a distinct contribution to the existing knowledge by investigating the impact of GHRMPs on the EP efforts of manufacturing SMEs and also contributes significantly to the AMO theory, demonstrating how SMEs can create a core competency for achieving sustainable, environmentally responsible performance by means of the integration of GIC and GIN. In addition, our research focuses on both the direct and indirect effects of GHRMPs on the development of process and product innovation and GIC that are generated in sustainable ways as well as the improvement of EP.

The choice of Pakistan as the focus for this study on the impact of GHRM practices on environmental performance is driven by a critical gap in the existing body of research. While much of the previous research has centered on GHRM practices within developed economies, there is a notable scarcity of studies that investigate these practices in developing countries, particularly within the context of SMEs. The manufacturing sector in Pakistan, which is integral to the country's economy, faces significant environmental challenges such as pollution, inefficient resource use, and waste management issues. Despite the global push toward sustainability, SMEs in Pakistan often struggle with the adoption and implementation of GHRM practices due to constraints such as limited financial resources, inadequate awareness, and insufficient regulatory support.

The rest of the paper is structured as follows. In the next section, we overview some key developments in the domain of GHRMPs, followed by a presentation of the GIC and GIN concept and its theoretical underpinnings. Next, we develop a research model and a set of hypotheses. In Section 3, we describe the method used to collect data and the variable selection, followed by the analysis and results in Section 4. Finally, in Section 5, we discuss the research implications of our findings, as well as what they mean for practice, concluding with some important limitations of this work and ways that future research can overcome them.

2. Literature Review and Framework Development

Green human resource management practices have gained increasing attention in sustainability literature, focusing on their role in driving organizational environmental performance. GHRMPs encompass a range of eco-centric policies, including recruitment, training, performance appraisal, and rewards systems, designed to align employee behavior with environmental goals [21].

2.1. Theoretical Foundation: Ability-Motivation-Opportunity Theory

The Ability-Motivation-Opportunity (AMO) theory serves as a robust theoretical foundation for this study by elucidating the mechanisms through which GHRMPs influence environmental performance. AMO theory posits that organizational performance is a function of employees' abilities, motivations, and opportunities to perform [22]. In the context of GHRM, this translates to the implementation of green ability (training and development for environmental skills), green motivation (incentives and rewards for eco-friendly behaviors), and green opportunity (structures and processes that facilitate environmental initiatives) as critical drivers of environmental performance. By focusing on these components, the study underscores how GHRM practices can enhance green intellectual capital, which refers to the collective knowledge and skills geared toward environmental management, and green innovation, which involves the development and implementation of eco-friendly products and processes [23]. These mediating variables bridge the link between GHRMPs and EP, providing a nuanced understanding of how fostering a green-oriented workforce can lead to substantial environmental benefits. This theoretical framework not only aligns with the principles of AMO theory but also expands its application to the realm of sustainability, offering a comprehensive model for examining the impact of GHRMPs on environmental outcomes.

2.2. Hypotheses Development

2.2.1. Green Human Resource Management Practice and Green Intellectual Capital

The aim of combining GHRMPs with GIC is to enhance the organization's EP. GIC can be analyzed through GHC, GSC, and GRC. Green human capital (GHC), which encompasses expertise, skills, and information related to the environment, promotes sustainable behaviors. Green relational capital (GRC), which is founded on environmentally conscious partnerships and collaborations, fosters green concepts and sustainable innovation [24]. Green structural capital (GSC), which includes green infrastructure, systems, and processes in organizations, provides the necessary foundation for successful green projects [25]. When integrated with GHRMPs, green ability (GA), green motivation (GM), and green opportunity (GOP) are elements that enhance their impact on environmentally sustainable performance. GA ensures that personnel possess environmentally friendly skills and capabilities, while GM enhances their dedication to sustainability objectives. GOP also highlights the need to provide opportunities for employees to participate in company environmental initiatives [26]. Implementing GHRMPs and developing environmentally focused intellectual capital are essential for maintaining the long-term sustainability and prosperity of a corporation [27]. This comprehensive approach highlights the interconnectedness of intellectual and human resources in creating environmentally sustainable results, giving an organization a solid basis to harmonize its operations with ecological necessities. Thus, we propose the following:

H1. *GHRMPs have a direct significant impact on GIC.*

2.2.2. Green Human Resource Management Practices and Green Innovation

To effectively address environmental concerns through environmental management solutions, it is crucial to carefully assess the organizational culture related to GIN. Hameed et al. [28] emphasize the importance of environmental performance as a decimal. The growing consciousness among employees regarding environmental concerns has resulted in a greater necessity for firms to incorporate environmental elements into their corporate social responsibility endeavors.

The environmental policies and practices of an organization promote an ecologically conscious culture. We think that significant enhancement is improbable without the backing of employees, regardless of the organization's information regulations and protocols. Insufficient green skills among workers can hinder the company's adoption of green practices [29]. Previous studies indicate that achieving substantial advancements in environmental sustainability necessitates implementing GHRMPs and cultivating a culture centered on GIN [30]. Prior studies have emphasized the importance of implementing a collaborative and innovative strategy for fostering a GIN culture and GHRM. Beliefs, actions, capabilities, personal characteristics, attitudes, and self-reflection are essential for organizational success. GIN creates environmentally friendly processes and products by utilizing green materials and eco-design principles.

High-performing organizations innovate through the utilization of sustainable resources, meeting consumer demands, and enhancing intangible assets [31]. GHRMPs significantly impact product and process innovation, with commitment leading to a higher level of innovative orientation [32]. Many past studies argue that HRM significantly and positively affects product and technological innovation. Human resource practices that focus on enhancing commitment instead of compliance enjoy excellent innovative orientation [33]. Companies that prioritize human resources utilize the AMO model to implement GHRMPs for the purpose of creating environmentally friendly products and processes. We proposed this hypothesis:

H2. *GHRMPs have a direct significant impact on GIN.*

2.2.3. Green Human Resource Management Practices and Environmental Performance

Organizations that adopt GHRMP tend to have environmentally conscientious, innovative, and efficient work environments. Additional validation is required to meet stakeholder expectations for greater environmental practices, as stated by Rizvi et al. [34], who connected environmental management strategies with improved environmental innovation and organization performance. Studies indicate that incorporating a green hiring strategy, which considers candidates' environmental perspectives, might foster a dedication to eco-friendly values. Incentives, green training, and performance management are GHRMPs that play a crucial role in enhancing EP [33]. Training programs focusing on energy efficiency, waste management, and recycling have a beneficial effect, as stated by Mousa et al. [35]. GHRM systems can enhance innovation in early-stage organizations by fostering creativity and commitment among employees in the domains of administration, processes, and products while having limited human resources [36]. GHRM initiatives excel in enhancing employee loyalty, according to Islam et al. [37], and human resource management techniques emphasizing teamwork and dedication have specific impacts on creativity within organizations. Strategically implementing eco-friendly innovations can enhance firms' financial outcomes and environmental sustainability. Employee involvement (EI) is crucial for offering opportunities to environmentally conscious individuals, particularly lower-level personnel [38]. EM activities improve EP and are encouraged to foster innovation and sustainable practices through EI projects. Thus, we formulated this hypothesis:

H3. *GHRMPs have a direct significant impact on EP.*

2.2.4. Green Intellectual Capital and Environmental Performance

Organizations achieve a competitive advantage by using their most valued resources and competencies. This study used the GIC model, which posits that a company's GIC comprises its intangible assets, skills, and relationships linked to EP and GIN [39]. The green infrastructure of an organization encompasses its non-human information repositories and its GHC, which consists of workforce attributes such as expertise and knowledge [40]. Engaging in two-way contact with significant figures in environmental management and innovation is referred to as "green relational capital" [41]. There is no broad consensus on the extent and meaning of EP. It refers to the extent to which an organization meets public expectations for ecological conservation. Businesses implementing green management strategies can save costs, enhance productivity, improve brand reputation, and gain a competitive advantage by pricing eco-friendly products higher [42]. GIC plays a crucial function in developing external partnerships and enhancing internal operations. Investing in green structural, relational, and human capital should theoretically lead to improved EP [43]. Thus, we propose the following:

H4. *GIC has a direct significant impact on EP.*

2.2.5. Green Innovation and Environmental Performance

A company's EP involves exceeding societal expectations and not just complying with rules [44]. EP involves various aspects, such as advancements in eco-friendly products and processes, sustainable business strategies, and top-notch environmentally friendly products [45]. Environmentally conscious manufacturing SMEs have prioritized GIN, emphasizing energy efficiency and pollution prevention and developing products with reduced environmental footprints [46]. Businesses promoting GIN must adhere to international environmental regulations and utilize cutting-edge technologies to ensure sustainability. GIN and sustainability are closely linked, as demonstrated by a poll conducted by Saunila et al. [47]. Ref. [48] suggests that a company can become more environmentally conscious by utilizing its internal resources and adhering to external regulations. Sustainable development, also referred to as "green innovation", involves creating new products and services to minimize the impact of human activities on the environment. This innovation is essential for an organization's environmental management strategy, as it offers social and financial advantages, enhances EP, and minimizes adverse effects [49]. According to Ullah et al. [25], GIN should be viewed as a proactive strategy to gain a competitive advantage rather than a reactive response. The study emphasizes the significance of process innovation and environmentally friendly products as essential organization assets within the AMO framework. These characteristics enhance goodwill and boost EP. Thus, we propose this hypothesis:

H5. *GIN has a direct significant impact on EP.*

2.2.6. Mediating Role of Green Intellectual Capital

The growing literature on GIC is a crucial subject of academic research, acting as a bridge between sustainable EP and GHRMPs. This topic focuses on the notion of GHC, which pertains to the ecological responsibility of a company's employees. The GA, GM, and GOP aspects of GHRMPs have a substantial impact on motivating employees to participate in ecologically responsible actions. GSC focuses on developing environmentally conscious organizational structures and procedures, while GRC highlights the significance of fostering eco-centric relationships and collaborations. Current research, such as the study by Yadiati et al. [50], highlights the significance of the eco-friendly elements of GIC in linking GHRMPs with environmentally sustainable performance. This narrative highlights the importance of organizations engaging in GIC development and utilization to enhance the efficacy of GHRM systems in achieving long-term ecological performance. Thus, we propose the following:

H6. *GIC positively mediates the relationship between GHRMPs and EP.*

2.2.7. Mediating Role of Green Innovation

GHRMPs enhance EP, foster an environmentally aware workforce, and promote new, green ideas. Yosuff et al. [51] confirmed the positive impact of green practices on corporate performance and creativity. These areas require additional investigation due to increased pressure from stakeholders on environmental management. Companies should use environmentally conscious filtering and recruiting procedures to ensure that their hiring practices align with the environmental attitudes, beliefs, and skills of potential workers, as suggested by Zhang et al. [52]. Phan et al. [53] recommend implementing green training programs to educate employees on waste reduction, energy conservation, and recycling. According to Paille et al. [1], GHRM systems or bundles have an impact on innovation in commodities, processes, and administration. GHRM systems can promote innovation, employee loyalty, and adherence to procedures, especially in startups with limited human resources. Tabrizi et al. [54] state that GHRM methods emphasize collaboration and commitment and enhance creativity by creating social networks and utilizing external resources. GIN is a crucial instrument for achieving environmental management objectives, as highlighted by Mousa et al. [35]. Organizations can enhance their performance in economics, ethics, and the environment by implementing environmentally friendly policies and using sustainable products to reduce their negative environmental impact. Our analysis utilizing the AMO shows that GHRMPs indirectly influence enterprises' sustainable development by enabling the innovation of new environmentally friendly products and processes. Thus, we propose the following:

H7. *GIN positively mediates the relationship between GHRMPs and EP.*

Building on AMO theory and insights from prior research, this study proposes the following conceptual model (Figure 1) that integrates GHRMPs, GIC, GIN, and EP.

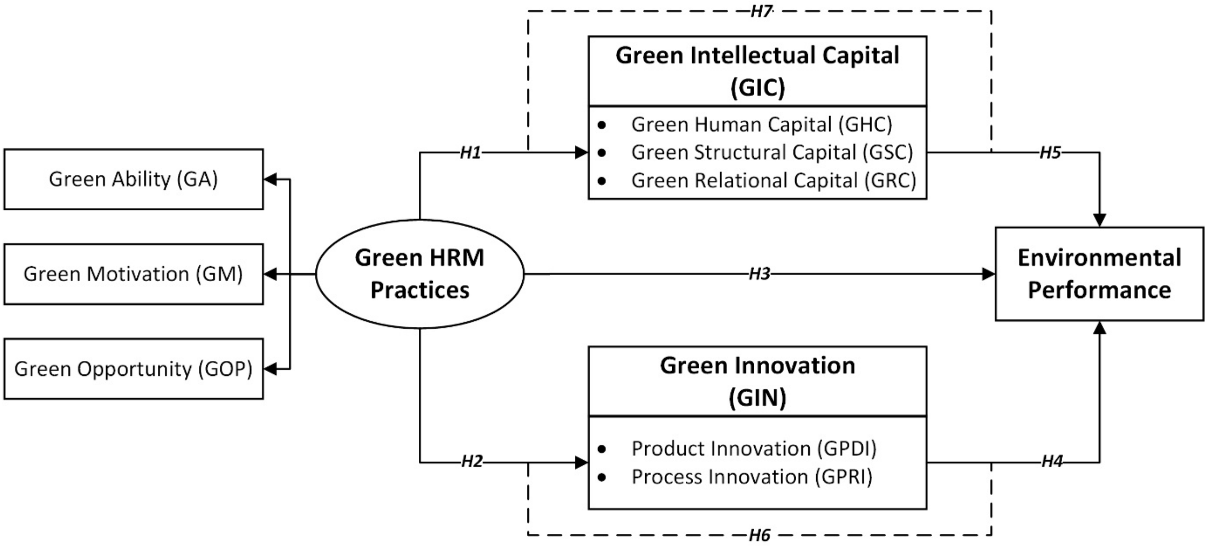


Figure 1. Conceptual model. Plain line = Direct effects; Dashed line = Mediating effects.

3. Methodology

3.1. Data Collection

For the purpose of this study, a questionnaire was used to collect information from manufacturing SMEs in Pakistan. The methodologies used for this study were survey-based, as it is a quantitative deductive study. Research was undertaken on manufacturing SMEs due to the fact that these SMEs make up 90% of all enterprises in Pakistan. It has been stated by the Small and Medium-Sized Enterprises Development Authority that this sector contributes around 40% to Pakistan's Gross Domestic Product (GDP). In addition, manufacturing SMEs provide a substantial contribution to employment, representing around 80% of non-agricultural jobs. Furthermore, the Government of Pakistan has implemented recent laws and restrictions on businesses mostly due to their apprehension around carbon emissions. To collect data from manufacturing SMEs, a convenience sample strategy was used [55]. In January 2023, we contacted senior management of manufacturing SMEs and issued 530 questionnaires with a two-month deadline for completion. In March 2023, we began collecting questionnaires, and by the end of March 2023, we had collected 448 questionnaires, with an 84.6% response rate. Following the elimination of the responses that were either ambiguous or inaccurate from the final sample, there were a total of 367 responses that were accurate and available for analysis.

The survey took approximately 4 months to complete, depending on the size and complexity of the responses from each participant. To ensure the validity and reliability of the instrument, a pilot study was conducted with 30 respondents from a subset of manufacturing SMEs prior to the main survey. The pilot study helped identify any issues with the questionnaire's clarity and allowed for adjustments to improve the overall quality of the data collected.

The sample included businesses categorized as small and medium enterprises as defined by the Small and Medium-Sized Enterprises Development Authority (SMEDA) of Pakistan. According to the SMEDA, microenterprises are defined as businesses with fewer than 10 employees and an annual revenue below PKR 2 million, small enterprises have 10–50 employees with an annual revenue of PKR 2–150 million, and medium enterprises have 51–250 employees with an annual revenue of PKR 151–800 million. Our sample predominantly consisted of small and medium enterprises, and microenterprises were not included, as they did not meet the inclusion criteria for this study. The sample consisted of businesses from various subsectors within the manufacturing industry, including textiles (35%), food processing (25%), chemicals (15%), machinery and equipment (10%), and others (15%). This categorization ensured that the sample captured the diversity within manufacturing SMEs and provided a more comprehensive understanding of their practices and perspectives.

Table 1 displays the distribution of participants according to their demographic characteristics. We classified respondents according to their gender, age, education, and length of service. There were 367 total respondents, and their responses were categorized as follows:

Table 1. Demographic characteristics.

		Frequency	**Percentage**
Gender	Male	205	55.85%
	Female	162	44.14%
Age	26–35	58	15.80%
	36–45	81	22.07%
	46–55	94	25.61%
	>55	134	36.51%
Education	Bachelor's	68	18.52%
	Master's	157	42.77%
	Doctoral degree	142	38.69%
Length of Service	Up to 1 year	79	21.52%
	2–5 years	94	25.61%
	5–10 years	107	29.15%
	More than 10 years	87	23.70%

3.2. Variable Selection

The research model (Figure 1) illustrates that all construct items were adapted from previous scales. Assessments were made on the survey items by utilizing a 5-point Likert scale ranging from 5 (strongly disagree) to 1 (strongly agree). In this investigation, we employed four items obtained from the study conducted by Roscoe et al. [56] to evaluate EP, which was designated as the dependent variable. The three components of GHRMPs (GA, GM, and GOP) were evaluated utilizing eight questions generated from prior research in accordance with the AMO framework [57]. The mediating variable, GIN, was utilized to encompass both product and process innovation. A study that was carried out by Zailani [58] was used to develop the items of these constructs. In order to gauge GIC, a total of fourteen criteria were derived by Huang et al. [59]. The detail of questions used in the survey for data collection is elaborated in Appendix B.

3.3. Ethical Approval and Informed Consent Statements

We conducted this study in accordance with the ethical standards of the institutional and/or national research committee, the 1964 Helsinki Declaration and its later amendments, or comparable ethical standards. We obtained informed consent from all individual participants included in the study. We fully informed the participants about the purpose, procedures, potential risks, and their rights, including the right to withdraw from the study at any time. We documented and securely stored the written consent.

4. Data Analysis Results

The results of the survey that were collected for this investigation were analyzed using PLS-SEM [60]. The purpose of PLS-SEM is to evaluate a collection of associations that collectively represent several equations. An in-depth examination of these analyses will be carried out in the following parts using SmartPLS4. PLS-SEM analysis comprises two constituent elements: a measurement model evaluation and a structural model evaluation [61]. The structural model generally includes components that meet the measurement model's criteria, such as sufficient indicator loading, convergent validity, composite reliability (CR), and discriminant validity. The extents of the path coefficients are examined by the structural model evaluation using the bootstrapping approach. Since the PLS-SEM method is most suited to the method proposed by Hair et al. [62], this methodology was implemented in the mediation analysis. This is the most prudent approach to examining mediating effects [63].

4.1. Assessment of Measurement Model

The measurement model's (see Figure 2) convergent validity was assessed using composite reliability (CR), Cronbach's alpha, factor loading, and average variance extracted (AVE). The purpose of evaluating a measurement model is to determine the extent to which the observed variables successfully reflect the underlying theoretical constructs and examine the model's suitability in fitting the data. To evaluate the potential presence of common method bias (CMB), Harman's Single-Factor Test was conducted using Principal Component Analysis (PCA). All observed variables were loaded into a single exploratory factor analysis without rotation. The results indicate that the first factor accounts for 32.14% of the total variance, which is below the commonly accepted threshold of 50%. This suggests that CMB is unlikely to significantly influence the results of this study. Additionally, the cumulative variance explained by the first eight components is 70.92%, further confirming that no single factor dominates the dataset. Results are presented in Appendix A.

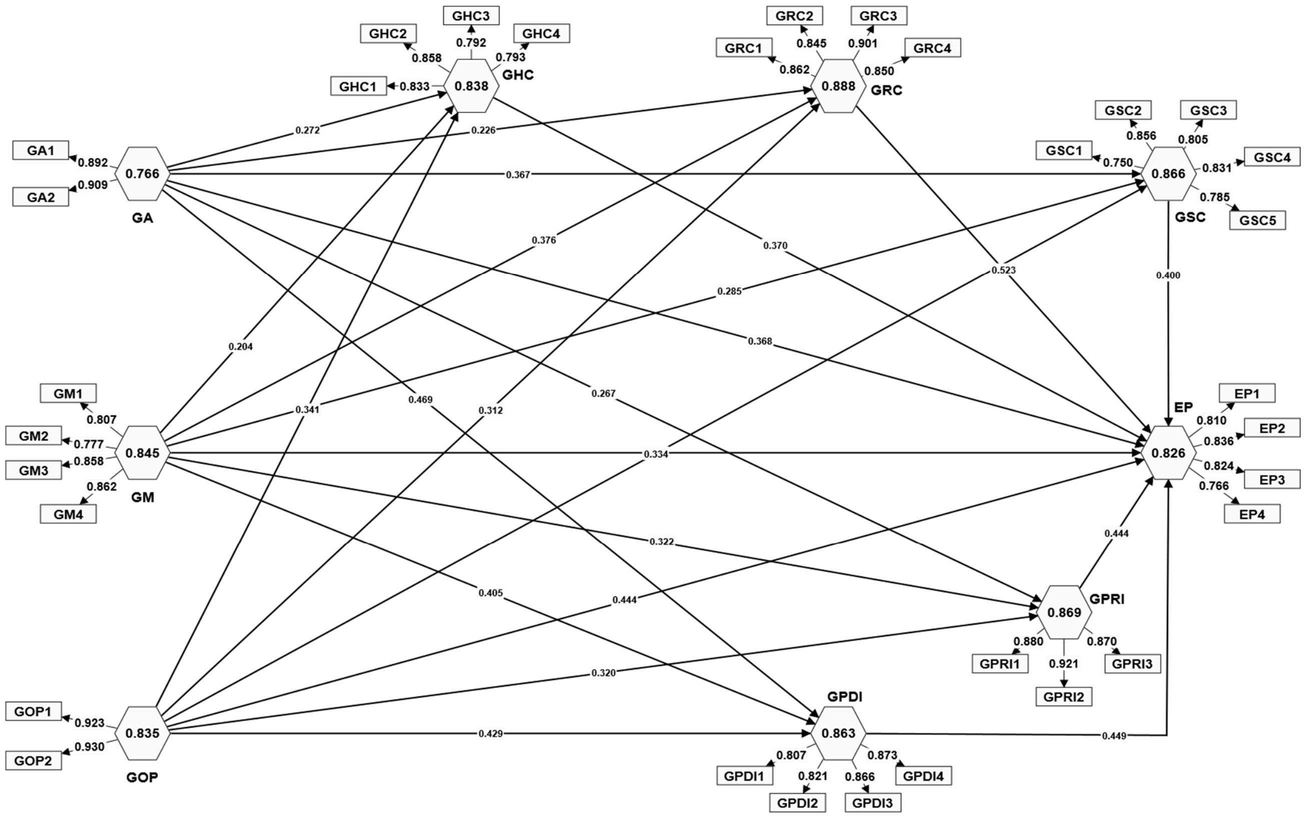


Figure 2. Measurement model evaluation results.

The recommended thresholds for asserting convergent validity, as stated by Souza et al. [64], are CR values exceeding 0.7 and AVE values exceeding 0.5. Table 2 demonstrates that the AVE values for all indicators are higher than the threshold of 0.50 and the CR is over 0.70, indicating sufficient convergent validity and internal consistency. CR scores that are equal to or greater than 0.70 are considered good, indicating strong internal consistency. Similarly, AVE scores above 0.50 confirm adequate convergent validity, suggesting that the indicators effectively capture more than 50% of the variation in a single idea. Calculating the VIF enables the detection of multicollinearity within a model. Analysts suggested that collinearity concerns regarding the findings are absent when the VIF exceeds 5 [65]. According to the results, the inner value of VIF must lie within the range of 1.421 to 1.893 for all indicators. Moreover, the results of this study indicate that there is no evidence of data collinearity, and the study's results are stable.

Table 2. Convergent validity of first-order constructs.

Variables	Items	λ	VIF	Cα	CR	AVE
Green Relational Capital	GRC1	0.862	2.237	0.888	0.889	0.748
	GRC2	0.845	2.154			
	GRC3	0.901	3.239			
	GRC4	0.850	2.476			
Green Structural Capital	GSC1	0.750	1.698	0.866	0.872	0.650
	GSC2	0.856	2.815			
	GSC3	0.805	2.274			
	GSC4	0.831	1.916			
	GSC5	0.785	1.774			

Table 2. *Cont.*

Variables	Items	λ	VIF	Cα	CR	AVE
Green Human Capital	GHC1 GHC2 GHC3 GHC4	0.833 0.858 0.792 0.793	1.858 2.331 1.993 1.699	0.838	0.850	0.672
Green Ability	GA1 GA2	0.892 0.909	1.629 1.629	0.766	0.770	0.810
Green Motivation	GM1 GM2 GM3 GM4	0.807 0.777 0.858 0.862	1.774 1.826 2.851 2.779	0.845	0.850	0.684
Green Process Innovation	GPRI1 GPRI2 GPRI3	0.880 0.921 0.870	2.421 2.926 2.006	0.869	0.873	0.793
Green Product Innovation	GPDI1 GPDI2 GPDI3 GPDI4	0.807 0.821 0.866 0.873	1.789 1.911 2.348 2.444	0.863	0.864	0.709
Green Opportunity	GOP1 GOP2	0.923 0.930	2.055 2.055	0.835	0.836	0.858
Environmental Performance	EP1 EP2 EP3 EP4	0.810 0.836 0.824 0.766	1.588 2.300 2.328 1.560	0.826	0.833	0.655

Note: λ = factor loadings; Cα = Cronbach's alpha; CR = composite reliability, AVE = average variance extracted; VIF = variance inflation factor.

Convergent validity (Tables 2 and 3) is confirmed when the average correlations between items within each dimension exceed 0.7, and all indicators strongly align with their expected underlying consistency.

Table 3. Convergent validity of second-order constructs.

Variables	Constructs	λ	Cα	CR	AVE
GHRMPs	GOP GM GA	0.856 0.730 0.825	0.726	0.732	0.648
GIC	GHC GRC GSC	0.787 0.822 0.842	0.753	0.761	0.668
GIN	GPDI GPRI	0.905 0.857	0.715	0.733	0.777

Note: λ = factor loadings; Cα = Cronbach's alpha; CR = composite reliability, AVE = average variance extracted.

This research employs the Heterotrait–Monotrait (HTMT) and Fornell–Larcker criteria to ascertain the discriminant validity [66]. In line with Fornell et al. [67], the discriminant validity of the model is indicated by the square root of the correlation with other variables, which is greater than the values on the upper correct diagonal. The discriminant validity for both first- and second-order constructs is indicated in Tables 4 and 5 by the maximum value of the variable's correlation with itself.

Table 4. Discriminant validity of first-order constructs (Fornell–Lacker criteria).

	EP	GA	GHC	GM	GOP	GPDI	GPRI	GRC	GSC
EP	0.809								
GA	0.368	0.900							
GHC	0.370	0.272	0.820						
GM	0.341	0.378	0.204	0.827					
GOP	0.444	0.614	0.341	0.415	0.926				
GPDI	0.449	0.469	0.295	0.405	0.429	0.842			
GPRI	0.444	0.267	0.211	0.322	0.320	0.557	0.890		
GRC	0.523	0.226	0.435	0.376	0.312	0.454	0.339	0.865	
GSC	0.400	0.367	0.565	0.285	0.334	0.396	0.282	0.511	0.806

Note: Diagonal values are the square roots of the AVE (average variance extracted). Under the diagonal elements are the correlations between the constructs.

Table 5. Discriminant validity of second-order constructs (Fornell–Lacker criteria).

	EP	GHRMPs	GIC	GIN
EP	0.809			
GHRMPs	0.481	0.805		
GIC	0.537	0.461	0.817	
GIN	0.507	0.527	0.471	0.881

The findings in Tables 6 and 7 indicate that for both order constructs, all HTMT ratios are less than 0.90. This further supports the claim that the classification in the present study exhibited discriminant validity.

Table 6. Discriminant validity of first-order constructs (HTMT ratio).

	EP	GA	GHC	GM	GOP	GPDI	GPRI	GRC	GSC
EP									
GA	0.456								
GHC	0.426	0.333							
GM	0.399	0.468	0.232						
GOP	0.526	0.766	0.398	0.493					
GPDI	0.518	0.573	0.347	0.476	0.506				
GPRI	0.517	0.328	0.246	0.372	0.375	0.644			
GRC	0.599	0.271	0.505	0.43	0.363	0.518	0.386		
GSC	0.453	0.44	0.66	0.331	0.383	0.453	0.317	0.578	

Note: All the values are less than 0.85, validating HTMT criteria.

Table 7. Discriminant validity of second-order constructs (HTMT ratio).

	EP	GHRMPs	GIC	GIN
EP				
GHRMPs	0.608			
GIC	0.654	0.621		
GIN	0.647	0.722	0.622	

4.2. Structural Model Assessment:

After validating the measurement model, the PLS-SEM technique was used to evaluate the structural model. The path model must be evaluated in terms of both the predictive capacity and statistical significance of the route coefficients. The current study validated and examined the model of the structure that is based on the concept [61]. For mediation analysis, we considered the criteria and suggestions [68,69].

The first stage used the coefficient of determination (R^2) and the cross-validated redundancy index (Stone–Geisser's Q2) for the predictive relevance of the structural model. Table 8 presents the R^2 and Q^2 values for GIC (0.213, 0.204), EP (0.398, 0.223), and GIN (0.278, 0.269). The ranges of R^2 between 0 and 1 with a higher value represent a higher level of predictive accuracy.

Table 8. R-square.

	R-Square	Q-Square
Green Innovation	0.278	0.269
Green Intellectual Capital	0.213	0.204
Environmental performance	0.398	0.223

Note: R-square = coefficient of determination, Q-square = predictive relevance.

Effect size measures how strongly one exogenous variable contributes to explaining a specific endogenous variable in R^2. R^2 included and excluded are the endogenous latent construct's values when a specific exogenous latent construct is included in or excluded from the research model, respectively. The details of the effect size results are presented in Table 9. The variance inflation factor (VIF) values were observed in this research to validate the model's collinearity concerns. Our study's findings demonstrate that the inner VIF values of the variable are between 1.000 and 2.767, as shown in Table 9, which indicates no collinearity problem in the data used in this study and confirms the model's robustness.

Table 9. Effect size and variance inflation factor.

	Effect Size				Variance Inflation Factor			
	EP	GHRMPs	GIC	GIN	EP	GHRMPs	GIC	GIN
EP								
GHRMPs	0.044		0.270	0.385	1.507		1.000	1.000
GIC	0.128				1.398			
GIN	0.067				1.524			

In the subsequent stage, we determined the path coefficients in the structural model assessment. To test the direct effect of the given hypotheses, β-value, t statistics, and *p* values were obtained using a bootstrapping approach with 5000 subsamples, as recommended by [61]. Figure 3 and Table 10 show that GHRMPs significantly improve GIN (β = 0.527, t = 11.308, $p < 0.001$). GHRMPs (β = 0.461, t = 9.634, $p < 0.001$) have a considerable beneficial impact on GIC. Furthermore, GHRMPs (β = 0.199, t = 4.146, $p < 0.001$), GIN (β = 0.248, t = 4.630, $p < 0.001$), and GIC (β = 0.328, t = 6.244, $p < 0.001$) improve EP. Finally, each of the hypotheses presented is validated.

Table 10. Path analysis.

Paths	β-Value	*t*-Value	Confidence Intervals [2.5–97.5%]	*p*-Value	Decision
GHRMPs→GIN	0.527 ***	11.308 ***	[0.437–0.617]	<0.001	Supported
GHRMPs→GIC	0.461 ***	9.634 ***	[0.369–0.554]	<0.001	Supported
GHRMPs→EP	0.199 ***	4.146 ***	[0.107–0.295]	<0.001	Supported
GIN→EP	0.248 ***	4.630 ***	[0.144–0.353]	<0.001	Supported
GIC→EP	0.328 ***	6.244 ***	[0.226–0.429]	<0.001	Supported

Note: Significance level: *** $p < 0.001$.

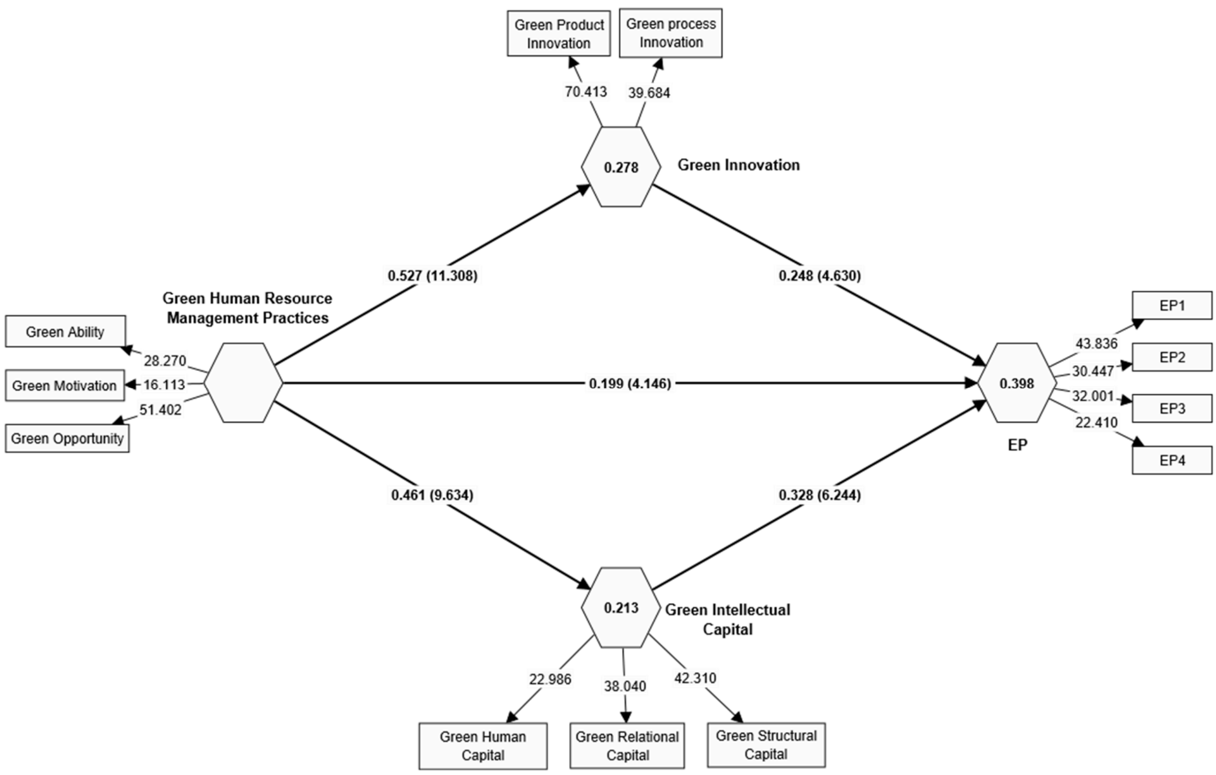


Figure 3. Structural model evaluation results.

4.3. Mediation Analysis

To analyze the particular indirect effects of GIN and GIC, as well as any potential mediating effects, we used the bootstrapping technique with 5000 iterations and confidence intervals corrected for bias at a 95% level, as recommended by [70]. In order to ascertain the importance of an indirect effect, it is essential that the confidence intervals for the 95 percent bootstrap sample do not include 0. We employed the bootstrapping percentile approach available in SmartPLS4 to conduct a direct mediation analysis and obtain estimates for the indirect effects. The results of our inquiry into the specified indirect effect, with the intention of differentiating between several mediating variables, are comprehensively presented in Table 11.

Table 11. Mediation path analysis.

Paths	β-Value	*t*-Value	Confidence Intervals [2.5–97.5%]	*p*-Value	Decision
GHRMPs→GIN→EP	0.131 ***	4.297	[0.076–0.196]	<0.001	Supported
GHRMPs→GIC→EP	0.151 ***	5.164	[0.098–0.214]	<0.001	Supported

Note: Significance level: *** $p < 0.001$.

The findings suggest that GIN and GIC influence the relationship between GHRMPs and EP. The findings confirm hypotheses H6 ($\beta = 0.131$, $p < 0.001$) and H7 ($\beta = 0.151$, $p < 0.001$).

5. Discussion

This study's theoretical framework improves our understanding of EP by elucidating the connection through a unique theoretical concept incorporating GIC and GIN as intermediaries between the relationship of GHRMPs and EP. Our research aims to contribute significantly to the current literature by highlighting the importance of GHRMPs, such as opportunity, motivation, and ability, in promoting GIN. This entails creating eco-friendly procedures and enhancing eco-friendly products, specifically targeting manufacturing SMEs in Pakistan while fostering awareness and expertise in environmental sustainability. Moreover, the external environment, including regulatory pressures, market demands, and societal values, could have a considerable influence on how GHRMPs are implemented and how GIN develops, which is important to explore further.

Our findings indicate that the implementation of GHRM practices, which include providing opportunities, incentive, and enhancing ability, has a substantial impact on promoting green innovation in Pakistan's small and medium-sized enterprises (SMEs). This green innovation encompasses both improvements in green processes and the development of green products. The study has comprehensively clarified all three hypotheses, which propose that providing green employment opportunities, cultivating employee green abilities, and stimulating employee green motivation have a considerable positive impact on green innovation, including both process innovation and product innovation. The results are consistent with the conclusions made by Roscoe et al. [56], which confirm a symbiotic relationship between green innovation and GHRMPs. The study found that GIN, encompassing both process and product aspects, significantly impacts the performance of SMEs in Pakistan. The results are aligned with the study by Asadi et al. [15] that innovation is essential for a company's competitiveness. Our research supports Mandal et al. [71]'s claims that GINs involve product development, including ecologically friendly labels, material reuse, product recovery, and the use of sustainable resources. This study suggests that GIN mediates the correlation between GHRMPs and a corporation's EP. Furthermore, mechanisms such as internal motivation, organizational culture, and leadership commitment to sustainability are important to consider when explaining how GHRMPs foster GIN.

Our research emphasizes the importance of integrating environmentally friendly innovation into manufacturing products and processes for organizations interested in implementing GHRMP concepts. GIN, either through process improvements or product innovations, is crucial for helping employees support and promote the use of environmentally friendly practices, and it contributes to enhancing strong EP. The study by [72] supports the importance of improved intellectual collaboration, a culture of GIN, and EP in attaining true and lasting environmental sustainability.

Furthermore, our study improves understanding of how various GICs impact an organization's EP, emphasizing the importance of GIC in helping a company efficiently deal with both internal and external opportunities while minimizing risks. According to AMO theory, as outlined by Yu et al. [73], this discovery is supported by the idea that challenges and limitations in the natural environment play a crucial role in fostering the development of new resources and capabilities in businesses. Our study further contributes to the understanding of how different components of GIC affect performance, therefore reinforcing the connection between GIC and green performance. However, external factors such as international environmental regulations or cross-border collaborations may influence the degree to which GIC can facilitate green performance across different markets. This finding aligns with previous studies that have connected GHRMPs with increased environmental behavior and GIC [74,75]. These findings indicate that a company's environmental performance is dependent on its GIC, which enables it to effectively address both internal and external opportunities and minimize potential threats. Managers who want to implement an environmental strategy should take into account GIC as a means of integration.

Lastly, our study's results align with the increasing studies highlighting the important significance of GHRMPs in encouraging environmentally friendly behaviors and enhancing EP [4]. Effective GHRMPs empower people by providing the resources and infrastructure needed to translate their environmental motivations and skills into impactful actions, leading to improved EP. Nevertheless, a limitation of this study is that the sample predominantly covers manufacturing SMEs in Pakistan, which may introduce representativeness biases due to the unique economic, cultural, and environmental conditions in this context. Future research could expand the sample to include SMEs from other regions or industries or explore the role of digital transformation and global supply chains in enhancing GHRMPs and GIN across different sectors.

5.1. Theoretical Contribution

Our findings have significant ramifications for the AMO theory to enhance comprehension of the dynamic connection between GHRMPs, GIN, and EP. Our study supports and advances the AMO [22], where we assert that an organization ought to develop and integrate GHRMPs that attract, retain, train, and motivate environmentally conscious employees in a bid to promote GIN and EP. Additionally, we found that using GHRMPs and GIN positively impacts a company's environmental sustainability. The results of our study indicate that implementing GHRMPs such as empowerment, performance-based incentives, and green hiring can help a company attract, retain, and support environmentally conscious individuals. This, in turn, contributes to the development of GIN in terms of services, products, and processes, ultimately leading to improved EP. Based on our analysis, an organization needs to adopt GHRMPs in order to enhance its competitive edge. Our findings indicate that organizations should implement proactive GHRMPs to foster, maintain, and attract environmentally conscious personnel. This will help improve the organization's EP and promote GIN, ultimately leading to a competitive advantage.

We are focusing our research on the unique role that GIC plays in driving enhancements in EP. Pakistani organizations should embrace environmental accounting methods to leverage long-term advantages for both society and the organization. Our research demonstrates the necessity of integrating GHRMPs with innovative strategies to enhance environmental sustainability. This enables organizations to achieve a competitive edge in a dynamic operating environment.

5.2. Practical Implications

This study also provides several practical implications for managers and policymakers. HR managers play a crucial role in integrating environmentally sustainable practices into companies. This involves executing smart recruitment, comprehensive people training, and effective performance evaluation procedures to cultivate green skills, which aid in fostering a culture of environmental responsibility among employees. Performance assessment and incentive systems are regarded as exceptional tools for recognizing and rewarding individuals who make significant contributions to environmental sustainability. In addition, these managers can create green opportunities by inviting employees to participate in creating green plans by training them and encouraging them to take up green leadership responsibilities. Organization managers can use our findings to develop a green innovation product and process culture, and this approach will offer outstanding environmental sustainability and green performance. Our research lays the groundwork for integrating environmentally friendly practices into organizational leadership to meet the needs of future managers.

Our study offers valuable empirical insights to inform top management about the influence of GHRM on both the GIN and EP of an organization. Companies should spend additional resources to improve their EP. Our findings provide a proactive strategy that organizations can employ to enhance their EP while simultaneously adhering to regulatory authorities.

6. Conclusions

In conclusion, this study provides compelling evidence of the critical role green human resource management practices play in advancing the environmental performance of manufacturing SMEs, with green intellectual capital and green innovation serving as vital mediators. Drawing on the Ability-Motivation-Opportunity theory, the research offers a novel empirical perspective on how green practices and capabilities converge to drive sustainability outcomes. By demonstrating the pathways through which GHRMPs enhance ecological efficiency, this study contributes significantly to the literature on sustainable business practices in SMEs, particularly within developing economies. The findings deliver actionable insights for managers aiming to integrate green strategies into core business functions, while also addressing broader sustainability imperatives. Future research should consider exploring cross-industry comparisons and longitudinal impacts to expand on the dynamic interplay of green practices and performance in varying contexts.

Limitations and Future Directions

Our research provides intriguing insights; however, it focuses on SMEs in Pakistan. Thus, it is advisable to use prudence when extrapolating these findings to the non-manufacturing SMEs sector. To address this limitation, subsequent research should broaden the current theoretical framework to encompass non-manufacturing SMEs, including a broader spectrum of business scenarios.

Moreover, to enhance the broader applicability of our findings, it is recommended that subsequent studies expand their geographic scope to include SMEs in both developing and developed nations. This expansion will allow for a more comprehensive knowledge of the suggested study model's validity in a variety of scenarios. Furthermore, future investigations should take a multi-stakeholder approach, going beyond management perspectives to include ideas from other relevant stakeholders. This kind of strategy will assist in gaining a deeper understanding of SMEs' dynamics, boosting the relevance and robustness of the study findings.

Additionally, we acknowledge the limitation of using a convenience sampling strategy in this study. While it provides practical feasibility, it may restrict the generalizability of the findings. Future research could employ probabilistic sampling techniques to overcome this limitation and enhance the representativeness of the sample.

Author Contributions: X.Q., methodology, validation; T.B., data curation, conceptualization; R.F.G., resources, supervision; B.S., writing and original draft preparation; A.N., formal analysis. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Business School of Hohai University (03-03-2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Common Method Bias Results

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	10.605	32.137	32.137	10.605	32.137	32.137	3.790	11.485	11.485
2	3.157	9.567	41.704	3.157	9.567	41.704	3.104	9.407	20.891
3	2.088	6.327	48.031	2.088	6.327	48.031	2.935	8.893	29.784
4	1.980	5.999	54.030	1.980	5.999	54.030	2.856	8.655	38.440
5	1.755	5.317	59.347	1.755	5.317	59.347	2.853	8.646	47.086
6	1.427	4.324	63.671	1.427	4.324	63.671	2.807	8.508	55.593
7	1.366	4.138	67.810	1.366	4.138	67.810	2.570	7.788	63.382
8	1.028	3.115	70.924	1.028	3.115	70.924	2.489	7.542	70.924
9	0.795	2.408	73.332						
10	0.710	2.151	75.484						
11	0.656	1.988	77.471						
12	0.614	1.861	79.332						
13	0.570	1.726	81.058						
14	0.516	1.563	82.621						
15	0.493	1.495	84.116						
16	0.474	1.436	85.552						
17	0.450	1.365	86.917						
18	0.429	1.299	88.216						
19	0.415	1.259	89.475						
20	0.395	1.197	90.672						
21	0.367	1.112	91.784						
22	0.332	1.006	92.790						
23	0.318	0.964	93.754						
24	0.288	0.873	94.627						
25	0.269	0.816	95.443						
26	0.259	0.786	96.229						
27	0.239	0.725	96.954						
28	0.223	0.674	97.628						
29	0.193	0.585	98.213						
30	0.184	0.558	98.771						
31	0.156	0.473	99.244						
32	0.136	0.412	99.656						
33	0.114	0.344	100.000						

Extraction Method: Principal Component Analysis.

Appendix B. Questionnaire

Questionnaire

This survey requires your feedback that will support us in our research work regarding Green Human Resource Management Practices (GHRMPs). So, you are requested to spare your 5–10 min to fill this questionnaire. The feedback shall be kept confidential and anonymous and shall be used only for academic purpose.

Section-I

Gender	☐ Male		☐ Female	
Age Group	☐ 26–35		☐ 36–45	
	☐ 46–55		☐ >55	
Education	☐ Bachelors	☐ Masters	☐ Doctoral Degree	
Length of Service	☐ up to 1 year	☐ 2–5 years	☐ 5–10 years	☐ more than 10 years

Questionnaire

Section-II

Please read the statements and show your level of agreement or disagreement with each of these statements regarding this institute. Choose neutral if you think you do not agree or disagree with the statement. **1. Strongly Disagree, 2. Disagree, 3. Neutral, 4. Agree, 5. Strongly Agree**

Sr. No.	Item	1	2	3	4	5
Green Human Resource Management Practices [76]						
Green Ability						
GA1	Environmental training is designed to enhance employee's environmental skills and knowledge.					
UGC2	Hiring only those who possess environmental values.					
Green Motivation						
GM1	Performance appraisal includes environmental incidents, responsibilities, concerns, and policy.					
GM2	Employee receives reward for environmental management.					
GM3	Employee receives reward for acquiring specific environmental competencies.					
GM4	Performance appraisal records environmental performance.					
Green Opportunity						
GO1	Employees are involved to become environmentally friendly.					
GO2	Employees to discuss environmental issues in team meetings.					

Sr. No.	Item	1	2	3	4	5
Green Intellectual Capital [4]						
Green Human Capital						
GHC1	The employees in this organization involve a positive productivity and contribution toward environmental protection.					
GHC2	The employees in this organization have an adequate competence toward environmental protection.					
GHC3	The employees of this organization provide high product and service qualities toward environmental protection.					
GHC4	The cooperative degree of teamwork toward environmental protection is performed at high levels in this organization.					
Green Structural Capital						
GSC1	This organization has a superior management system of environmental protection.					
GSC2	This organization has a high ratio of employees in environmental management to its total employees.					
GSC3	This organization makes an adequate investment in environmental protection facilities.					
GSC4	The overall operation processes toward environmental protection in this organization operate efficiently					
GSC5	This organization has formed a committee to progress on key issues in environmental protection.					

Questionnaire						
Green Relational Capital						
GRC1	This enterprise designs its products or services in compliance with the environmental desires of its employees.					
GRC2	The employees are satisfied about this enterprise's environmental protection.					
GRC3	The cooperative relationships of this enterprise with its suppliers toward environmental protection are stable.					
GRC4	The cooperative relationships of this enterprise with its employees toward environmental protection are stable.					

Sr. No.	Item	1	2	3	4	5
Green Innovation [77]						
Green Process Innovation						
GPRI1	The manufacturing processes of my company effectively reduce hazardous substances or waste.					
GPRI2	The manufacturing processes of my company effectively reduce consumption of coal, oil, electricity, or water.					
GPRI3	The manufacturing processes of my company effectively reduce use of raw materials.					
Green Product Innovation						
GPDI1	My company uses materials that produce the least pollution.					
GPDI2	My company uses materials that consumes less energy and resources.					
GPDI3	My company uses materials to design environment friendly products.					
GPDI4	My company uses materials that are easy to recycle, reuse, and decompose.					

Sr. No.	Item	1	2	3	4	5
Environmental Performance [4]						
EP1	Our organization has reduced waste.					
EP2	Our organization has reduced purchases of non-renewable materials, chemicals, and components.					
EP3	Our organization has helped enhance the reputation of our organization.					
EP4	Our organization has improved its position in the marketplace.					

References

1. Paillé, P.; Valéau, P.; Renwick, D.W. Leveraging Green Human Resource Practices to Achieve Environmental Sustainability. *J. Clean. Prod.* **2020**, *260*, 121137. [CrossRef]
2. Khan, S.A.R.; Yu, Z.; Belhadi, A.; Mardani, A. Investigating the Effects of Renewable Energy on International Trade and Environmental Quality. *J. Environ. Manag.* **2020**, *272*, 111089. [CrossRef] [PubMed]
3. Jehangir, M.; Khan, S.Z.; Lodhi, A.S.; Qureshi, M.H. The Effect of Green HRM Practices on Environmental Performance: A Moderated Mediation Model with Empirical Examination. *Adm. Manag. Sci. J.* **2024**, *2*, 125–139. [CrossRef]

4. Nisar, Q.A.; Haider, S.; Ali, F.; Jamshed, S.; Ryu, K.; Gill, S.S. Green Human Resource Management Practices and Environmental Performance in Malaysian Green Hotels: The Role of Green Intellectual Capital and pro-Environmental Behavior. *J. Clean. Prod.* **2021**, *311*, 127504. [CrossRef]
5. Jin, X.; Lei, X.; Wu, W. Can Digital Investment Improve Corporate Environmental Performance?—Empirical Evidence from China. *J. Clean. Prod.* **2023**, *414*, 137669. [CrossRef]
6. Yadegaridehkordi, E.; Foroughi, B.; Iranmanesh, M.; Nilashi, M.; Ghobakhloo, M. Determinants of Environmental, Financial, and Social Sustainable Performance of Manufacturing SMEs in Malaysia. *Sustain. Prod. Consum.* **2023**, *35*, 129–140. [CrossRef]
7. Baker, W.E.; Sinkula, J.M. Environmental Marketing Strategy and Firm Performance: Effects on New Product Performance and Market Share. *J. Acad. Mark. Sci.* **2005**, *33*, 461–475. [CrossRef]
8. Soewarno, N.; Tjahjadi, B. Measures That Matter: An Empirical Investigation of Intellectual Capital and Financial Performance of Banking Firms in Indonesia. *J. Intellect. Cap.* **2020**, *21*, 1085–1106. [CrossRef]
9. Wang, J. Building Competitive Advantage for Hospitality Companies: The Roles of Green Innovation Strategic Orientation and Green Intellectual Capital. *Int. J. Hosp. Manag.* **2022**, *102*, 103161.
10. Sahan, U.M.H.; Jaaffar, A.H.H.; Osabohien, R. Green Human Resource Management, Energy Saving Behavior and Environmental Performance: A Systematic Literature Review. *Int. J. Energy Sect. Manag.* **2024**. [CrossRef]
11. Sohu, J.M.; Mirani, M.A.; Shaikh, S.N.; Memon, U.; Bhanbhro, A.; Kherazi, F.Z. Integrating Green Human Resource Management and Big Data Analytics Capability for Sustainable Environmental Performance in SMEs. In *Examining Green Human Resources Management and Nascent Entrepreneurship*; IGI Global: Hershey, PA, USA, 2025; pp. 145–172.
12. Limijaya, A.; Hutagaol-Martowidjojo, Y.; Hartanto, E. Intellectual Capital and Firm Performance in Indonesia: The Moderating Role of Corporate Governance. *Int. J. Manag. Financ. Account.* **2021**, *13*, 159–182. [CrossRef]
13. Al-Tahitah, A.N.; Al-Mekhlafi, A.-B.A.; Omar, M.F.H.; Ateeq, A.A.; Al-Awliqi, R.M. Developing a Model Incorporating Green HRMP and Environmental Awareness for Sustainable Performance in Malaysian Logistics Companies: Conceptual Paper. *Int. J. Intellect. Hum. Resour. Manag. (IJIHRM)* **2023**, *4*, 1–6.
14. Khan, N.U.; Anwar, M.; Li, S.; Khattak, M.S. Intellectual Capital, Financial Resources, and Green Supply Chain Management as Predictors of Financial and Environmental Performance. *Environ. Sci. Pollut. Res.* **2021**, *28*, 19755–19767. [CrossRef] [PubMed]
15. Asadi, S.; Pourhashemi, S.O.; Nilashi, M.; Abdullah, R.; Samad, S.; Yadegaridehkordi, E.; Aljojo, N.; Razali, N.S. Investigating Influence of Green Innovation on Sustainability Performance: A Case on Malaysian Hotel Industry. *J. Clean. Prod.* **2020**, *258*, 120860. [CrossRef]
16. He, W.; Mushtaq, N.; Jan, L. Unlocking the Dual Black Box of GHRMP & EGOC for Sustainable Environmental Performance in Developing Economies: Can Green Workplace Behavior and Green Passion Transmit the Real Change? *Environ. Dev. Sustain.* **2024**, *26*, 16025–16055.
17. Qalati, S.A.; Siddiqui, F.; Magni, D. Senior Management's Sustainability Commitment and Environmental Performance: Revealing the Role of Green Human Resource Management Practices. *Bus. Strategy Environ.* **2024**, *33*, 8965–8977. [CrossRef]
18. Huong, P.T.; Cherian, J.; Hien, N.T.; Sial, M.S.; Samad, S.; Tuan, B.A. Environmental Management, Green Innovation, and Social–Open Innovation. *J. Open Innov. Technol. Mark. Complex.* **2021**, *7*, 89. [CrossRef]
19. Afzal, C.M.; Khan, S.N.; Baig, F.J.; Ashraf, M.U. Impact of Green Human Resource Management on Environmental Performance: The Mediating Role of Green Innovation and Environmental Strategy in Pakistan. *Rev. Appl. Manag. Soc. Sci.* **2023**, *6*, 227–242. [CrossRef]
20. Tahir, A.H.; Umer, M.; Nauman, S.; Abbass, K.; Song, H. Sustainable Development Goals and Green Human Resource Management: A Comprehensive Review of Environmental Performance. *J. Environ. Manag.* **2024**, *370*, 122495. [CrossRef] [PubMed]
21. Yulianty, P.D.; Senen, S.H. Analysis Systematic Literature Review: The Study of HRM Transformation into Digital-Based GHRM Future Research Agenda. *West. Sci. Bus. Manag.* **2023**, *1*, 553–561. [CrossRef]
22. Appelbaum, E. *Manufacturing Advantage: Why High-Performance Work Systems Pay Off*; Cornell University Press: Ithaca, NY, USA, 2000; ISBN 0801437652.
23. Messerli, P.; Murniningtyas, E.; Eloundou-Enyegue, P.; Foli, E.G.; Furman, E.; Glassman, A.; Hernández Licona, G.; Kim, E.M.; Lutz, W.; Moatti, J.-P. *Global Sustainable Development Report 2019: The Future Is Now–Science for Achieving Sustainable Development*; United Nations: New York, NY, USA, 2019.
24. Yusliza, M.Y.; Yong, J.Y.; Tanveer, M.I.; Ramayah, T.; Faezah, J.N.; Muhammad, Z. A Structural Model of the Impact of Green Intellectual Capital on Sustainable Performance. *J. Clean. Prod.* **2020**, *249*, 119334. [CrossRef]
25. Ullah, H.; Wang, Z.; Mohsin, M.; Jiang, W.; Abbas, H. Multidimensional Perspective of Green Financial Innovation between Green Intellectual Capital on Sustainable Business: The Case of Pakistan. *Environ. Sci. Pollut. Res.* **2021**, *29*, 5552–5568. [CrossRef] [PubMed]
26. Sun, X.; El Askary, A.; Meo, M.S.; Hussain, B. Green Transformational Leadership and Environmental Performance in Small and Medium Enterprises. *Econ. Res.-Ekon. Istraživanja* **2022**, *35*, 5273–5291. [CrossRef]

27. Haldorai, K.; Kim, W.G.; Garcia, R.L.F. Top Management Green Commitment and Green Intellectual Capital as Enablers of Hotel Environmental Performance: The Mediating Role of Green Human Resource Management. *Tour Manag.* **2022**, *88*, 104431. [CrossRef]
28. Hameed, Z.; Khan, I.U.; Islam, T.; Sheikh, Z.; Naeem, R.M. Do Green HRM Practices Influence Employees' Environmental Performance? *Int. J. Manpow.* **2020**, *41*, 1061–1079. [CrossRef]
29. Lee, M.T.; Raschke, R.L.; Krishen, A.S. Signaling Green! Firm ESG Signals in an Interconnected Environment That Promote Brand Valuation. *J. Bus. Res.* **2022**, *138*, 1–11. [CrossRef]
30. Mohsin, M.; Ivascu, L. Elongating Nexus Between Workplace Factors and Knowledge Hiding Behavior: Mediating Role of Job Anxiety. *Psychol. Res. Behav. Manag.* **2022**, *15*, 441–457. [CrossRef] [PubMed]
31. Rehman Khan, S.A.; Yu, Z. Assessing the Eco-Environmental Performance: An PLS-SEM Approach with Practice-Based View. *Int. J. Logist. Res. Appl.* **2021**, *24*, 303–321. [CrossRef]
32. Farza, K.; Ftiti, Z.; Hlioui, Z.; Louhichi, W.; Omri, A. Does It Pay to Go Green? The Environmental Innovation Effect on Corporate Financial Performance. *J. Environ. Manag.* **2021**, *300*, 113695. [CrossRef]
33. Hameed, Z.; Naeem, R.M.; Hassan, M.; Naeem, M.; Nazim, M.; Maqbool, A. How GHRM Is Related to Green Creativity? A Moderated Mediation Model of Green Transformational Leadership and Green Perceived Organizational Support. *Int. J. Manpow.* **2022**, *43*, 595–613. [CrossRef]
34. Rizvi, Y.S.; Garg, R. The Simultaneous Effect of Green Ability-Motivation-Opportunity and Transformational Leadership in Environment Management: The Mediating Role of Green Culture. *Benchmarking Int. J.* **2021**, *28*, 830–856. [CrossRef]
35. Mousa, S.K.; Othman, M. The Impact of Green Human Resource Management Practices on Sustainable Performance in Healthcare Organisations: A Conceptual Framework. *J. Clean. Prod.* **2020**, *243*, 118595. [CrossRef]
36. Aftab, J.; Abid, N.; Cucari, N.; Savastano, M. Green Human Resource Management and Environmental Performance: The Role of Green Innovation and Environmental Strategy in a Developing Country. *Bus. Strategy Environ.* **2023**, *32*, 1782–1798. [CrossRef]
37. Islam, M.A.; Jantan, A.H.; Yusoff, Y.M.; Chong, C.W.; Hossain, M.S. Green Human Resource Management (GHRM) Practices and Millennial Employees' Turnover Intentions in Tourism Industry in Malaysia: Moderating Role of Work Environment. *Glob. Bus. Rev.* **2023**, *24*, 642–662. [CrossRef]
38. Zameer, H.; Wang, Y.; Yasmeen, H. Reinforcing Green Competitive Advantage through Green Production, Creativity and Green Brand Image: Implications for Cleaner Production in China. *J. Clean. Prod.* **2020**, *247*, 119119. [CrossRef]
39. Syed, M.W.; Song, H.; Junaid, M. Impact of Social Media Technologies on Environmental Collaboration and Green Innovation: A Mediation–Moderation Model. *Kybernetes* **2024**, *53*, 123–151. [CrossRef]
40. Yong, J.Y.; Yusliza, M.Y.; Ramayah, T.; Fawehinmi, O. Nexus between Green Intellectual Capital and Green Human Resource Management. *J. Clean. Prod.* **2019**, *215*, 364–374. [CrossRef]
41. Wu, R.; Huo, B.; Yu, Y.; Zhang, Z. Quality and Green Management for Operational and Environmental Performance: Relational Capital in Supply Chain Management. *Int. J. Logist. Res. Appl.* **2022**, *25*, 471–492. [CrossRef]
42. Martínez-Falcó, J.; Sánchez-García, E.; Millan-Tudela, L.A.; Marco-Lajara, B. The Role of Green Agriculture and Green Supply Chain Management in the Green Intellectual Capital–Sustainable Performance Relationship: A Structural Equation Modeling Analysis Applied to the Spanish Wine Industry. *Agriculture* **2023**, *13*, 425. [CrossRef]
43. Bresciani, S.; Rehman, S.U.; Giovando, G.; Alam, G.M. The Role of Environmental Management Accounting and Environmental Knowledge Management Practices Influence on Environmental Performance: Mediated-Moderated Model. *J. Knowl. Manag.* **2023**, *27*, 896–918. [CrossRef]
44. Zameer, H.; Wang, Y.; Yasmeen, H.; Mubarak, S. Green Innovation as a Mediator in the Impact of Business Analytics and Environmental Orientation on Green Competitive Advantage. *Manag. Decis.* 2020; *ahead-of-printing*. [CrossRef]
45. Tolliver, C.; Fujii, H.; Keeley, A.R.; Managi, S. Green Innovation and Finance in Asia. *Asian Econ. Policy Rev.* **2021**, *16*, 67–87. [CrossRef]
46. Agyabeng-Mensah, Y.; Baah, C.; Afum, E. Do the Roles of Green Supply Chain Learning, Green Employee Creativity, and Green Organizational Citizenship Behavior Really Matter in Circular Supply Chain Performance? *J. Environ. Plan. Manag.* **2024**, *67*, 609–631. [CrossRef]
47. Saunila, M. Innovation Capability in SMEs: A Systematic Review of the Literature. *J. Innov. Knowl.* **2020**, *5*, 260–265. [CrossRef]
48. Bassetti, T.; Blasi, S.; Sedita, S.R. The Management of Sustainable Development: A Longitudinal Analysis of the Effects of Environmental Performance on Economic Performance. *Bus. Strategy Environ.* **2021**, *30*, 21–37. [CrossRef]
49. Singh, J.; Singh, H.; Kumar, A. Impact of Lean Practices on Organizational Sustainability through Green Supply Chain Management—an Empirical Investigation. *Int. J. Lean Six Sigma* **2020**, *11*, 1035–1068. [CrossRef]
50. Yadiati, W.; Nissa, N.; Paulus, S.; Suharman, H.; Meiryani, M. The Role of Green Intellectual Capital and Organizational Reputation in Influencing Environmental Performance. *Int. J. Energy Econ. Policy* **2019**, *9*, 261. [CrossRef]

51. Yusoff, Y.M.; Nejati, M.; Kee, D.M.H.; Amran, A. Linking Green Human Resource Management Practices to Environmental Performance in Hotel Industry. *Glob. Bus. Rev.* **2020**, *21*, 663–680. [CrossRef]
52. Zhang, Y.; Sun, J.; Yang, Z.; Wang, Y. Critical Success Factors of Green Innovation: Technology, Organization and Environment Readiness. *J. Clean. Prod.* **2020**, *264*, 121701. [CrossRef]
53. Phan, Q.; Pham, T.N.; Nguyen, L.H.L. How to Drive Brand Engagement and EWOM Intention in Social Commerce: A Competitive Strategy for the Emerging Market. *J. Compet.* **2020**, *12*, 136–155. [CrossRef]
54. Tabrizi, R.S.; Karatepe, O.M.; Rezapouraghdam, H.; Rescalvo-Martin, E.; Enea, C. Green Human Resource Management, Job Embeddedness and Their Effects on Restaurant Employees' Green Voice Behaviors. *Int. J. Contemp. Hosp. Manag.* **2023**, *35*, 3453–3480. [CrossRef]
55. Etikan, I.; Musa, S.A.; Alkassim, R.S. Comparison of Convenience Sampling and Purposive Sampling. *Am. J. Theor. Appl. Stat.* **2016**, *5*, 1–4. [CrossRef]
56. Roscoe, S.; Subramanian, N.; Jabbour, C.J.C.; Chong, T. Green Human Resource Management and the Enablers of Green Organisational Culture: Enhancing a Firm's Environmental Performance for Sustainable Development. *Bus. Strategy Environ.* **2019**, *28*, 737–749. [CrossRef]
57. Cronin, J.J.; Smith, J.S.; Gleim, M.R.; Ramirez, E.; Martinez, J.D. Green Marketing Strategies: An Examination of Stakeholders and the Opportunities They Present. *J. Acad. Mark. Sci.* **2011**, *39*, 158–174. [CrossRef]
58. Zailani, S.; Govindan, K.; Iranmanesh, M.; Shaharudin, M.R.; Chong, Y.S. Green Innovation Adoption in Automotive Supply Chain: The Malaysian Case. *J. Clean. Prod.* **2015**, *108*, 1115–1122. [CrossRef]
59. Huang, C.; Kung, F. Environmental Consciousness and Intellectual Capital Management: Evidence from Taiwan's Manufacturing Industry. *Manag. Decis.* **2011**, *49*, 1405–1425. [CrossRef]
60. Henseler, J.; Ringle, C.M.; Sarstedt, M. Using Partial Least Squares Path Modeling in Advertising Research: Basic Concepts and Recent Issues. In *Handbook of Research on International Advertising*; Edward Elgar Publishing: Cheltenham, UK, 2012; ISBN 1781001049.
61. Ringle, C.M.; Sarstedt, M.; Mitchell, R.; Gudergan, S.P. Partial Least Squares Structural Equation Modeling in HRM Research. *Int. J. Hum. Resour. Manag.* **2020**, *31*, 1617–1643. [CrossRef]
62. Hair, J.F., Jr.; Howard, M.C.; Nitzl, C. Assessing Measurement Model Quality in PLS-SEM Using Confirmatory Composite Analysis. *J. Bus. Res.* **2020**, *109*, 101–110. [CrossRef]
63. Hair, J.F.; Gabriel, M.; Patel, V. AMOS Covariance-Based Structural Equation Modeling (CB-SEM): Guidelines on Its Application as a Marketing Research Tool. *Braz. J. Mark.* **2014**, *13*. [CrossRef]
64. de Souza, A.C.; Alexandre, N.M.C.; de Brito Guirardello, E. Psychometric Properties in Instruments Evaluation of Reliability and Validity. *Epidemiol. Serv. Saude* **2017**, *26*, 649–659.
65. Kock, N. Common Method Bias in PLS-SEM: A Full Collinearity Assessment Approach. *Int. J. E-Collab. (Ijec)* **2015**, *11*, 1–10. [CrossRef]
66. Hair, J.F., Jr.; Hult, G.T.M.; Ringle, C.; Sarstedt, M. *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)*; Sage Publications: Los Angeles, CA, USA, 2016; ISBN 1483377431.
67. Fornell, C.; Larcker, D.F. Evaluating Structural Equation Models with Unobservable Variables and Measurement Error. *J. Mark. Res.* **1981**, *18*, 39–50. [CrossRef]
68. Nitzl, C.; Roldan, J.L.; Cepeda, G. Mediation Analysis in Partial Least Squares Path Modeling: Helping Researchers Discuss More Sophisticated Models. *Ind. Manag. Data Syst.* **2016**, *116*, 1849–1864. [CrossRef]
69. Preacher, K.J.; Hayes, A.F. Asymptotic and Resampling Strategies for Assessing and Comparing Indirect Effects in Multiple Mediator Models. *Behav. Res. Methods* **2008**, *40*, 879–891. [CrossRef]
70. Preacher, K.J.; Hayes, A.F. SPSS and SAS Procedures for Estimating Indirect Effects in Simple Mediation Models. *Behav. Res. Methods Instrum. Comput.* **2004**, *36*, 717–731. [CrossRef] [PubMed]
71. Mandal, A.; Pal, B. Effects of Green Innovation and Advertisement in an Imperfect Production-based Competitive Supply Chain under Two-tier Credit Facility. *Math. Methods Appl. Sci.* **2021**, *44*, 13227–13251. [CrossRef]
72. Iqbal, Q.; Ahmad, N.H.; Nasim, A.; Khan, S.A.R. A Moderated-Mediation Analysis of Psychological Empowerment: Sustainable Leadership and Sustainable Performance. *J. Clean. Prod.* **2020**, *262*, 121429. [CrossRef]
73. Yu, W.; Chavez, R.; Feng, M.; Wong, C.Y.; Fynes, B. Green Human Resource Management and Environmental Cooperation: An Ability-Motivation-Opportunity and Contingency Perspective. *Int. J. Prod. Econ.* **2020**, *219*, 224–235. [CrossRef]
74. Aboramadan, M.; Karatepe, O.M. Green Human Resource Management, Perceived Green Organizational Support and Their Effects on Hotel Employees' Behavioral Outcomes. *Int. J. Contemp. Hosp. Manag.* **2021**, *33*, 3199–3222. [CrossRef]
75. Benevene, P.; Buonomo, I. Green Human Resource Management: An Evidence-Based Systematic Literature Review. *Sustainability* **2020**, *12*, 5974. [CrossRef]

76. Kim, Y.J.; Kim, W.G.; Choi, H.-M.; Phetvaroon, K. The Effect of Green Human Resource Management on Hotel Employees' Eco-Friendly Behavior and Environmental Performance. *Int. J. Hosp. Manag.* **2019**, *76*, 83–93. [CrossRef]
77. Wang, M.; Li, Y.; Li, J.; Wang, Z. Green Process Innovation, Green Product Innovation and Its Economic Performance Improvement Paths: A Survey and Structural Model. *J. Environ. Manag.* **2021**, *297*, 113282. [CrossRef]

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
6) Fostering Education for Sustainable Development in Higher Education: A Case Study on Sustainability Competences in Research, Development and Innovation (RDI) (2024)	SUSTAINABILITY (Article From : MDPI)

27th FEBRUARY 2025
SOURCE: PERPUSTAKAAN UTM

sustainability

MDPI

Article

Fostering Education for Sustainable Development in Higher Education: A Case Study on Sustainability Competences in Research, Development and Innovation (RDI)

Tiina Muhonen *, Liisa Timonen and Kristiina Väänänen

Karelia University of Applied Sciences, 80200 Joensuu, Finland; liisa.timonen@karelia.fi (L.T.); kristiina.vaananen@karelia.fi (K.V.)
* Correspondence: tiina.muhonen@karelia.fi

Abstract: This study explores how higher education institutions (HEIs) can foster the relevance of education for sustainable development (ESD) and strategic human resource development for a holistic sustainability transformation. Sharing a case example, it discusses how sustainable and responsible research, development and innovation (RDI) competences can be recognised, described and acknowledged to support the contextualised application of ESD and human resource development in one HEI of the INVEST university alliance and its stakeholders. It compares education professionals' and stakeholders' views on current and future competence needs and investigates inter-organisational competence development practices. The methodology encompasses a qualitative and interpretive case study based on focus group interviews. The results on the current sustainable competences indicated that HEI and stakeholder respondents identified disciplinary competences as the most important competence cluster followed by systems-thinking, strategies-thinking and integration competences. Although HEIs and stakeholders jointly regard disciplinary competences as most critical for the future, they have considerably different perspectives on the megatrends influencing these needs and the overall spectrum of the required competences. This study provides methodological means for contextualising sustainability competences and enhancing stakeholder-informed competence development. The results may serve as a point of reference for aligning higher education curricula and human resource development with ESD for more sustainable higher education.

Keywords: higher education; education for sustainable development; research, development and innovation (RDI); stakeholder collaboration; competence development; human resource development

check for updates

Citation: Muhonen, T.; Timonen, L.; Väänänen, K. Fostering Education for Sustainable Development in Higher Education: A Case Study on Sustainability Competences in Research, Development and Innovation (RDI). *Sustainability* **2024**, *16*, 11134. https://doi.org/10.3390/su162411134

Academic Editor: Tarah Wright

Received: 27 September 2024
Revised: 13 December 2024
Accepted: 17 December 2024
Published: 19 December 2024
Corrected: 7 February 2025

1. Introduction

Human capacity building is regarded as a strategically crucial instrument in the discourse to combat issues arising from climate change and to foster sustainability and sustainable development [1,2]. In this discourse, higher education institutions (HEIs), in particular, have an important role both globally [3,4] and regionally through education, research and governance [5,6]. As a transformative educational practice, education for sustainable development (ESD) is outlined as a competence-based approach that focuses on finding solutions to sustainability challenges in real-life contexts [7]. As a practice, it strives to "enable and empower individuals to reflect on their own actions by taking into account their current and future social, cultural, economic and environmental impacts from both a local and a global perspective". This paper aims to contribute to this discussion within the subfield of ESD oriented toward higher education: higher education for sustainable development (HESD).

This paper examines how HESD strategies can foster adjustment to climate change by developing relevant sustainability competences. It discusses a small-scale case example of a conceptual and methodological process to strengthen the relevance of HESD. It reflects on the construction process of descriptions of research, development and innovation (RDI) competence that may benefit HESD curriculum development aligned with strategic human resource development.

This study employs a case study approach to provide contextual integrated insights into HESD curriculum development by elaborating on definitions of RDI competences relevant to sustainable development. The case context is the INVEST European university alliance [8] and one of the INVEST alliance regions, North Karelia, Finland. In this specific regional context, this study aims to validate the established sustainability competences presented in the ESD literature to strengthen the relevance of ESD in higher education.

The specific purpose of this qualitative case study is to create an RDI competence description for educationalists developing ESD curricula and organisations focusing on human resource development for sustainability transformation. To build the description, the case study examines the views of both higher education professionals and stakeholder organisation representatives on RDI competences and analyses the differences between those views. In addition, this study investigates RDI-focused competence development concerning inter-organisational practices between Karelia University of Applied Sciences (Karelia UAS) and its stakeholder organisations. The research questions include the following:

1. What are the most important sustainability competences in RDI from the perspectives of higher education and its stakeholders now and in the future?
2. How do the views of higher education experts and stakeholders on sustainability competences in RDI diverge?
3. How can sustainability competences in RDI be developed as part of the continuous development of competences through university–stakeholder cooperation?

2. Sustainability Transformation in Higher Education

2.1. Education for Sustainable Development

Higher education institutions (HEIs) are instrumental in building human capital for sustainability both globally [4] and regionally through education, research and governance [6]. Žalėnienė and Pereira [9] point out that higher education plays a significant role in forming the attitudes and mindsets of adults who will take pivotal decision-making and execution roles in advancing sustainable development and the Sustainable Development Goals (SDGs). Nevertheless, higher education has been criticised for preserving the patterns of unsustainability by continuing to reinforce unsustainable norms without critical examination [10]. Although learning is the impetus for transformation, HEIs frequently exhibit deficiencies in their learning capacity [11].

As an approach to sustainability education and learning, education for sustainable development (ESD) stands for a prominent, interdisciplinary and internationally acknowledged field of research that contributes to the identification of sustainability competences [7,12,13]. Within the context of higher education for sustainable development (HESD), ESD competence frameworks [12,14,15] provide reference points for developing sustainability competences among higher education personnel and students. In general, competence frameworks delineate the essential knowledge, skills and behaviours necessary for effective performance in each role [16].

As a reference for learning and development planning, the sustainability competence literature has defined general key sustainability competences. Wiek et al.'s [15] key competences in sustainability represent the most cited sustainability competence framework [17] which originally contains the following five key competences: systems-thinking, anticipatory, normative, strategies-thinking, collaboration and critical thinking competences. The main components of the framework have been widely confirmed [7]. The original framework has been later complemented with integrated problem-solving competences [18] and implementation, intra-personal (self-awareness) and integration competences [14].

However, research shows that the key competences have only been partially actualised [19] and inadequately operationalised into learning objectives for real-life practices in sustainability education [20]. As generalised models, they, however, have been criticised for being largely informed by academic perspectives [20,21] and oversimplifying sustainability competences [12]. Furthermore, Wilhelm et al. [20] point out that educational practitioners encounter challenges in making practical implications from generalised competence models in real-life higher education contexts. They emphasise the need for further contextualising sustainability competences. Moreover, Lambrechts et al. [22] underline that the discourses of higher education and industry have developed in distinct environments, which has led to a divergence between educational perspectives on sustainability competences and advancements in business settings.

2.2. Strategic Competence-Based Human Resource Development in Sustainability

To enhance HEIs' influence on sustainability transformation, research highlights the significance of holistically institutionalised sustainability governance [23]. Concerning governance, researchers seem to agree with the imperative of HEIs addressing sustainable development (SD) in their institutional strategies more holistically [23–26]. As drivers of this organisational development process towards sustainability, human resources, human capital, human capabilities and personnel skills seem to play a pivotal role [27]. Socio-ecological transition in HEIs entails cultivating human capital focusing especially on enhancing socio-ecological well-being by adopting innovative methods for research and education, developing distinct competencies and adhering to ethical principles [28]. To support this transition, ESD has been addressed as a viable approach for HEIs [29].

As a governance-based strategy, human resources serve as an effective way of promoting the development of personnel's sustainable competences through strategic management and the development of human capital [30,31]. As sustainability is becoming an increasingly strategic asset for organisations [32], they can gain both a competitive edge and enhance the implementation of sustainability goals by focusing on sustainability as a core value in developing the expertise of human capital [33]. The organisational change towards sustainability in HEIs can be fostered by the cultivation of ESD [29] and sustainability competences in HEI students and personnel [34–36]. It has, however, been observed that only a minority of HEI personnel have extensive expertise in sustainability [36].

Strategic human resource management in higher education can be broadly defined as the "management of people and work so that organisation's goal can be achieved within the framework of laws, strategy and personnel policy" [37]. As a strategic approach, competency-based human resource management can be employed to synchronise organisational strategic goals with personnel behaviour, i.e., skills and competences [38]. Competency-based human resource development promotes organisational learning by developing competences and skills [39]. According to Beardwell and Thompson [16], the initial learning and development planning phase is identifying learning needs. These strategically relevant competences and skills can be defined and developed, for example, through competence frameworks [32], competency mapping [38] and needs analysis [16] for the organisation or a job role.

Overall, strategic planning for sustainability in human resources in HEIs is an emerging theme and indicates that sustainable practices in human resources can enhance the overall sustainability of universities [31,40]. Sustainable human resource management involves implementing long-lasting strategies to attain financial, environmental and social objectives in sustainability both within and beyond the organisation [41]. This transformation requires a systemic transdisciplinary multistakeholder approach [42], with HEIs [43] and private organisations [44] playing crucial roles as agents of sustainable and responsible action. Stankevičiūtė and Savanevičienė [45] argue that competence development in sustainable human resource development requires a future-oriented perspective and industry–higher education cooperation. Sustainable human resource development in HEIs fosters learning and development through sustainability competences. Megatrends provide a future-oriented perspective to investigate the projections of learning and development. Thus, this study examines future projections of competence development through the analysis of the megatrends prevalent within the European Union.

Sustainability transformations in HEIs can be supported by organisational learning at individual, collective and governance levels [46]. In particular, the collaboration between HEIs and regional stakeholders in generating and transferring knowledge is viewed as a crucial element in promoting environmental, social, economic and cultural sustainable regional development [47,48]. As HEIs contribute to regional sustainable development through research, development and innovation (RDI), a focus on the development of regional RDI competences is beneficial for a variety of reasons. Firstly, since inadequate expertise is a major obstacle to the renewal of industries, regional focus allows for tailored skill development and smart specialisation which support the needs of local industries and sectors [49]. By aligning training and competence development with regional RDI priorities, the workforce becomes better equipped to drive and support sustainable innovations. Secondly, regionally relevant RDI expertise and a deep understanding of local challenges increase the adaptability to local challenges [50].

In the context of regional competence development in RDI, this study addresses the topic of supply chain sustainability, which is identified as a primary factor in promoting industrial sustainability [51]. However, sustainable policies and regulations are altering the operating environment for industry both locally and globally. Recent growing trends in the European Union are tightening supply chain sustainability via directives, such as the Corporate Sustainability Due Diligence Directive [52], and the standardisation of sustainability reporting, e.g., the European Sustainability Reporting Standard [53]. The World Economic Forum [54] assesses that over 50 per cent of global greenhouse gas emissions can be attributed to just eight supply chains in the sectors of food, construction, fashion, fast-moving consumer goods (FMCGs), electronics, automotive production, professional services and freight.

To meet the changing demands, the workforce needs to remain adaptable and equipped with relevant skills in the changing environment [1]. HEIs play a crucial role in this process by developing these field-specific competences. However, Mageto and Luke [55] regard the competence research on addressing supply chain sustainability as an emerging topic. Moreover, the body of research on supply chain sustainability presents a scarcity of engagement with higher education for sustainable development (HESD) competence research [22]. To the authors' knowledge, these competences related to supply chains have not been previously studied in the context of RDI. Thus, this study offers a regionally contextualised case study that examines sustainability competences within supply chains, specifically in the context of RDI.

To address the gaps and issues presented in the previous literature, this study aims to contribute to the existing discourse by (1) offering a regionally contextualised discussion based on a well-established sustainability competence framework in the area of RDI, (2) further clarifying the underpinnings between HESD and business competence discourses by comparing the dynamics of top–down (emanating from HEIs) versus bottom–up (originating from stakeholders) perspectives on sustainability competences and (3) enriching the emerging body of research on sustainable practices in human resource management and development in higher education.

Moving beyond theory, the next chapter outlines the step-by-step methodological approach followed by the Results and Discussion.

3. Materials and Methods

This research was conducted within the INVEST European university alliance [8] to foster institutional sustainability transformation. The work aims to present a case model for the European innovation ecosystem, bridging academia, business and society to strengthen the relevance of ESD in higher education aligned with human resource development and organisational and inter-organisational knowledge transfer. This study focuses on enhancing human resource capacity by striving to delineate the relevant sustainability competences and skills of the personnel and students involved in research, development and innovation

(RDI). The datasets were originally collected to systematically map general and specific RDI competences in sustainable supply chains onto an RDI competence matrix [56].

The initially implemented research design employed an interpretive qualitative case study with three distinct phases: scoping review, case studies and focus group interviews (FGIs). The scoping review, which was designed based on the guidelines provided by the Joanna Briggs Institute [57], identified the competences, skills and knowledge available in the scientific literature published from 2010 onwards. The second phase involved survey-based organisational case studies. Lastly, the FGIs were administered to acquire insights from the higher education professionals of INVEST organisations and their respective stakeholders.

This study deepens the initial analysis of the competence matrix [56] by further scrutinising the regional outcomes of FGIs in one of the INVEST alliance organisations, Karelia University of Applied Sciences (Karelia UAS), and its stakeholders. Karelia UAS is a multidisciplinary and internationally connected organisation that provides innovative education at both bachelor's and master's levels. It offers 24 degree programmes across seven fields of study, with six at the master's level. These fields include healthcare and social services, business, engineering, forestry, media and hospitality management. Located on two campuses near the centre of Joensuu in eastern Finland, Karelia UAS is a prominent and well-regarded educational institution, playing a vital role in regional development and RDI activities. As a university of applied sciences, it is a key factor in the regional innovation ecosystem and has a strong focus on promoting regional development and addressing the needs of the working society. For this, Karelia has been successfully validated nationally with an audit conducted by the Finnish Education Evaluation Centre (FINEEC). In its strategic choices, Karelia UAS addresses regional sustainable and responsible development. It fosters sustainable development in degree-leading education and continuous learning. Furthermore, sustainability plays a key role in research, development and innovation (RDI) initiatives.

The rationale of the INVEST alliance and Karelia UAS as a case study in this paper is multifaceted. Firstly, Karelia has a legally stated role in advancing competence development in close cooperation with regional stakeholders in North Karelia. This study directly addresses the institutional purpose of Karelia UAS by discussing competences specifically in relation to the key regional stakeholders and disclosing the perspectives of both Karelia UAS and regional stakeholders. This supports the creation of joint comprehension and development practices in competence development within the shared regional reality. Secondly, Karelia UAS has a strong strategic focus on internationalisation. Selecting the INVEST university alliance as a case study helps Karelia to align its regional functions of competence development with the aspects and needs of competence development conducted in the broader cooperation network in the INVEST university alliance. Thirdly, Karelia UAS is strategically set to promote sustainable development in regional competence development and offers a master's degree programme for sustainability management as a part of INVEST alliance cooperation. This case study specifically supports this by addressing competence development from the perspective of sustainability.

Thus, this study elaborates on the regional competence needs that Karelia UAS has as a part of the alliance. The methodology of this study encompasses a qualitative case study approach. Case study research is useful for exploring complex phenomena within their real-life context. The literature review was conducted as a scoping review, which provided the theoretical foundations for designing the case study methodology for data collection. This included designing the structure of the research instrument, preparing semi-structured focus group interviews (FGIs), and determining the criteria for selecting the FGI participants. Krueger and Casey [58] (p. 22) point out that FGIs are appropriate for study designs that aim to elucidate and compare the viewpoints of individuals belonging to different social groups carrying varying degrees of societal authority. Examples are individuals with professional roles in education or science and their stakeholders with diverse background profiles. FGIs have been previously utilised to investigate sustainability competences from the perspective of employability in working life [59].

The interview protocol (Table S1) was constructed based on the literature review results and validated through a consultation with an internal expert from Karelia UAS. In advance, the participants were sent a participation information letter to guarantee informed and consensual participation. The letter included information on (1) anonymity, confidentiality, the right to withdraw from the study and a statement granting permission for further utilisation of the data, (2) a broad outline of the literature review results and (3) the interview questions. This informed participation was meant to enhance the validity and accuracy of responses. Furthermore, permission was acquired from the participants for any further utilisation of the data.

Three virtual interview sessions were conducted for groups of 3–4 persons in Finnish: one for the personnel of Karelia UAS and two for regional stakeholders. The total number of participants was 9. Participants were selected based on a purposive sampling procedure as suggested by Creswell and Poth [60] (p. 158–159). Hence, the participant selection criteria specify the relevant characteristics of professional background and the breadth of variation according to the quadruple-helix model (see, e.g., [61]):

1. Professional background: informants must have expertise in RDI and sustainable development and supply chain management.
2. Informants must represent various stakeholder types (academia, administration, industry and civil society) as presented by the quadruple-helix model.

As this study targets specific fields of expertise in sustainable RDI, the purposive sampling criteria employed support the validity of the research. Furthermore, the participants represent many different fields of knowledge, which provides a varied number of perspectives. The participants from Karelia UAS represent teachers and RDI staff specialised in construction, energy and environmental engineering, hospitality management, tourism, and health and social services. The stakeholder participants consist of individuals affiliated with the regional development agencies, sustainable industry and regionally operating sustainable development consulting companies operating in the sectors of agriculture, engineering, construction, and circular economy and sustainable industry. Applying the purposive sampling criteria and having participants representing varied perspectives from different fields provide a comprehensive and purposeful range of viewpoints related to sustainable RDI in the sample, which enhances the validity of the content and construct. Yet, it introduces, for example, selection bias, which limits the generalisation of results.

The duration of each interview was 45–60 min. The interviews were conducted in Finnish to facilitate uninhibited participation without any linguistic barriers pertaining to the use of non-native language. To facilitate the discussions, interviewers adopted speaker roles to prompt the participants in instances of prolonged silence.

Preceding the analysis, the FGIs were recorded, transcribed, translated into English and anonymised. Content analysis was employed to identify thematic patterns in the data both inductively and deductively. During the analysis, competences that emerged in the transcripts were classified into categories based on the key competences in the sustainability framework presented by Redman and Wiek [14]. These competences comprise 7 key sustainability competences: systems-thinking, futures-thinking, values-thinking, strategies-thinking, implementation, inter-personal and intra-personal competences. These competences are complemented by disciplinary, professional and general competences [14]. The manual data analysis process was supported by generative artificial intelligence (AI) [62] to enhance and validate the researchers' decision-making processes.

Following the outline of the methodological approach employed in this study, the subsequent chapters present the findings derived from the analysis and provide insights into both contemporary and future competence needs, as well as methods for competence development.

4. Results and Discussion

4.1. Contemporary Sustainability Competences in RDI

For present competence needs, Figure 1 describes the proportional distribution of occurrences of research, development and innovation (RDI) competences across the 11 categories of key sustainability and complementary competences as outlined by Redman and Wiek [14]. The additional category 'others' includes the data items that did not align with the categories of the framework. This additional category involves competences such as general information and communication technology (ICT) skills and literacy, self-promotion skills, self-directedness and proactive attitudinal disposition at work. Previously, ICT skills and literacy have been framed, for example, as part of a 21st century skillset [63]. However, ICT has been suggested as one of the contributors to sustainable development [64]. Moreover, the ethical and sustainable use of these skills has also been suggested to have an important role in enhancing sustainability [65].

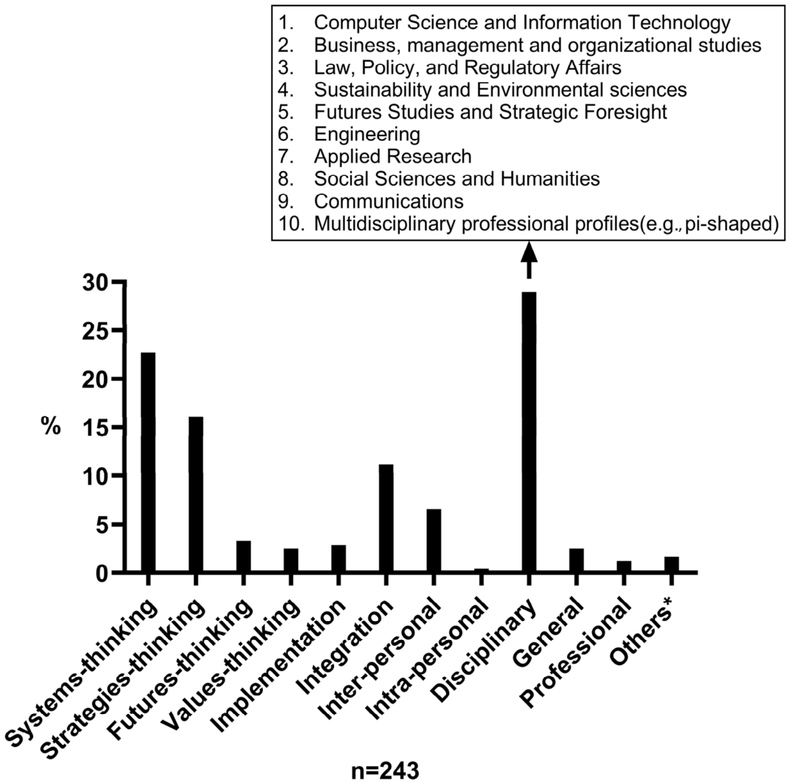


Figure 1. Proportional distribution of occurrences of key competences and complementary competences in RDI as discussed by Redman and Wiek [14]. Categorical item 'others*' includes the data that did not align with the categories of the framework.

Overall, higher education institution (HEI) and stakeholder respondents identified disciplinary competences as the most important competence cluster (29%) followed by systems-thinking (23%), strategies-thinking (16%) and integration (11%) competences (Figure 1). Broader disciplinary competence categories that emerged within the disciplinary competence cluster involve (1) computer science and information technology, (2) business, management and organisational studies, (3) law, policy and regulatory affairs, (4) sustainability and environmental sciences, (5) futures studies and strategic foresight, (6) engineering, (7) applied research, (8) social sciences and humanities, (9) communications and (10) multidisciplinary professional profiles (Table S2). It is noteworthy that these disciplinary competences were frequently detected as interlinked with key sustainability competences. Within Redman and Wiek's [13] framework, this evidence supports the idea that disciplinary competences are complementary to the key competences.

However, the results show some variation between HEI and stakeholder groups in terms of the competence categories (Figure 2). In HEI and stakeholder respondent groups, the most emphasised competence category was disciplinary (HEI: 25%; stakeholders: 30%). In HEI responses, the next highest percentages of competences were found in the categories of systems-thinking (18%) and integration (18%), followed closely by strategiesthinking (16%). In stakeholder responses, the second highest percentages were observed in the categories of systems-thinking (24%), strategies-thinking (16%) and integration (9%). Interestingly, the observed data show the fewest occurrences in both respondent groups for intra-personal competences. In this category, the low level of recognition may result from the emerging status of this competence, as stated by Redman and Wiek [14].

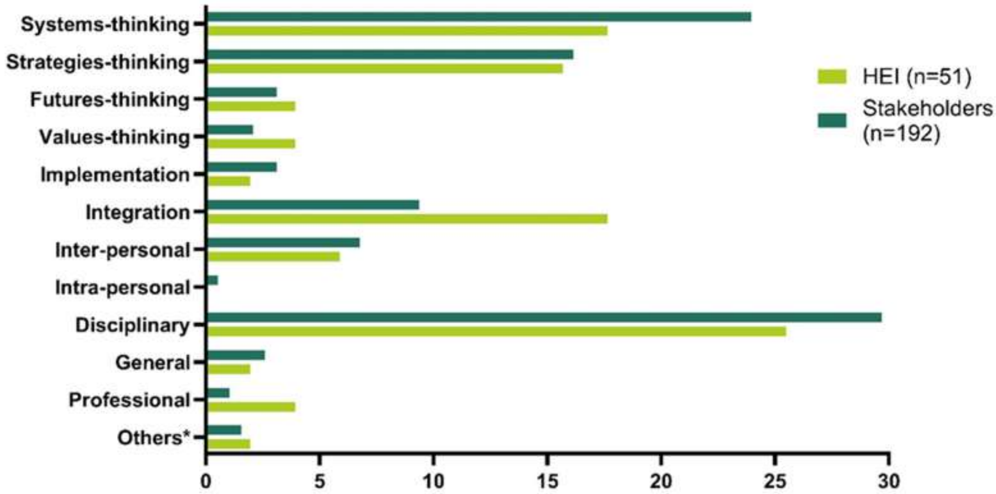


Figure 2. Proportional distribution of occurrences of key competences and complementary competences in RDI in HEI and stakeholder groups, as discussed by Redman and Wiek [14]. Categorical item 'others*' includes the data that did not align with the categories of the framework.

Moreover, within the disciplinary competence cluster, HEI and stakeholder respondents highlighted partly distinct areas of knowledge (Tables S2–S4). HEI respondents emphasised the fields related to computer science and information technology, as well as business, management and organisational studies. Examples of these fields are educational technology and business management, respectively. However, stakeholders similarly acknowledged the importance of business, management and organisational studies, but they also often underscored competence areas associated with law, policies and regulations, as well as sustainability and environmental sciences.

Both respondent groups regarded multidisciplinary, such as pi-shaped (see, e.g., [66]), professional profiles as valuable assets of an RDI professional. According to Pennington et al. [66], pi-shaped professional profiles are characterised by a deep proficiency in two disciplines. This finding is elucidated by the following stakeholder's response:

> *Well, now I have something really important to say. Or rather, it's good that you asked so I get to say it. You see, the biggest problem with the tradition of a design house is the disciplinary silos, and of course, even the schooling supports this. There's the electrical engineer. There's the mechanical engineer. There's the civil engineer, and so on. But those who can smoothly find solutions across these traditional disciplinary boundaries, that's the bottleneck. Like, if I need an electrical wire from point A to point B, I can immediately find like 100 CVs in the catalogue. But let's say I need to think about some combo solution through electricity for a water system, oh, where's that?* [67]

As solving sustainability challenges requires multidisciplinary proficiencies, the interlinkages between the sustainability and multidisciplinary professional profiles, e.g., pi-shaped professional profiles [66], of an individual or a team (working in RDI) could be studied in more depth in the future.

4.2. Megatrend-Driven Future Sustainability Competences in RDI

As support for strategic future-oriented HR planning, this section discusses the megatrend-driven future needs in RDI competences as anticipated by HEI and stakeholder respondents. Overall, 60 per cent of all key competences were detected in the categories of disciplinary (34%) and strategies-thinking (26%). Slightly less than one-third of all competences were identified in the categories of futures-thinking (10%), others (8%), inter-personal (6%) and systems-thinking (6%). In total, eight out of fourteen megatrends, as identified by the European Commission's Competence Centre on Foresight [68], were addressed by the respondents (Figure 3). These megatrends are (M1) accelerating technological change and hyperconnectivity, (M2) aggravating resource scarcity, (M3) the changing nature of work, (M4) the changing security paradigm, (M5) climate change and environmental degradation, (M6) the diversification of education and learning, (M7) growing consumption and (M8) shifting health challenges.

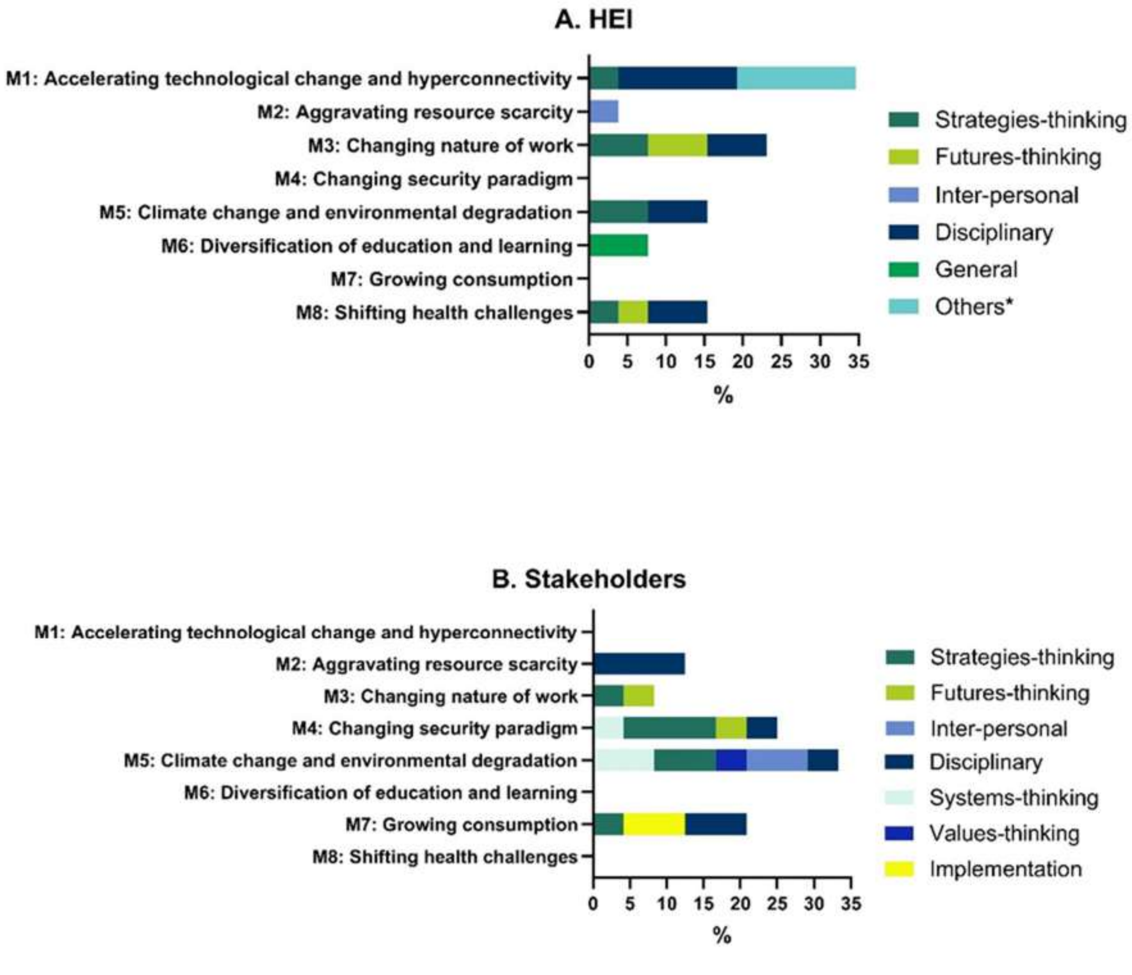


Figure 3. Proportional distribution of occurrences of key and complementary competences in RDI according to megatrends in (**A**) HEI and (**B**) stakeholder groups. Categorical item 'others*' includes the data that did not align with the categories of the framework.

For future competence needs in RDI, respondents from HEIs and stakeholder organisations seem to have notably different perspectives (Figure 3). According to HEI respondents, 88 per cent of emerging competence needs are connected to megatrends M1, M3, M5 and M8. Conversely, stakeholders attributed 79 per cent of future competence requirements to megatrends M5, M4 and M7.

HEI respondents addressed six competence categories across six megatrends, while the stakeholder group identified seven competence categories across five megatrends (Figure 3).

According to HEI responses, the four most prominent megatrends (M1, M3, M5 and M8) expected to generate the most competence needs in the future fall into the following four competence categories: disciplinary, strategies-thinking, futures-thinking and others. It is notable that in this respondent group, disciplinary competences were evident across all of these megatrends. Examples of relevant disciplinary knowledge areas in HEI responses were (1) life sciences, (2) law, policy and regulatory affairs and (3) sustainability and environmental sciences (Table S6).

Based on stakeholder responses, three megatrends (M5, M4 and M7) are projected to govern and raise competence demands in six specific areas: strategies-thinking, disciplinary, systems-thinking, inter-personal competences, implementation and values-thinking (Figure 3). In the findings showing the important status of strategic thinking in contemporary competence requirements, stakeholders also prioritise proficiency in strategic thinking in their future projections. In line with this result, Mulder [69] states that, in general, strategic expertise is crucial for advancing sustainable development.

Illustrative examples of competences in the category of strategies-thinking are adaptive strategic planning and risk awareness and assessment. For disciplinary competences, the stakeholders highlighted, for example, the following areas of knowledge: (1) law, policy and regulatory affairs, (2) sustainability and environmental sciences, (3) engineering and (4) business, management and organisational studies (Table S7). The following response from a stakeholder participant particularly highlights the role of skills related to sustainability and environmental sciences and engineering in solving problems related to the megatrend of growing consumption:

> *Overpopulation and the biodiversity loss are issues. It stems from the fact that we don't have enough food or clean water for everyone. This, in turn, creates the need for new skills and expertise, as we must develop methods to manage agriculture and other resources more efficiently, or alternatively, tap into new resources to address these needs. When we think about various regions of the world where overpopulation is a concern, we see areas where land is being cleared, trees are being burned, or forests are being cut down to obtain bio-based raw materials. This leads to forest fires, and these are all interconnected challenges. What I'm trying to say is that I see overpopulation as a major challenge, and along with it comes the need for technological advancements and improved food production systems* [67].

Some emerging competences [14], i.e., intrapersonal, received no attention from HEI and stakeholder respondents. The importance of studying and developing this novel aspect of sustainability competences further within competence-based learning has been recently addressed in the context of ESD [70].

4.3. Competence Development Methods in HEI–Stakeholder Collaboration in RDI

Existing organisational methods for competence development (Table S8) were utilised to establish relevant categories and classify the data for joint competence development between higher education institutions (HEIs) and stakeholders. These can be beneficial in education for sustainable development (ESD) pedagogy and practices.

The views of HEI and stakeholder respondents exhibited both similarities and disparities (Table 1). Both respondent groups highlighted methods for collaboration in bridging RDI and education and co-created training programmes.

Table 1. Suggestions for joint RDI competence development methods in the future according to HEI and stakeholder respondents.

RDI Competence Development Method Categories	Methods	
	HEI	**Stakeholder Organisations**
Stakeholder Collaboration for the Creation of Innovative Practices	• Recognizing stakeholder needs in HEIs and optimising the mutual benefits of RDI activities • Finding alignment with the different response rates in project work between HEIs and stakeholders	
Bridging RDI and Education	• Case study collaboration • Thesis collaboration between HEIs and stakeholders • Project- and challenge-based learning collaboration, e.g., hackathons • Creating new structures for RDI collaboration between HEIs and stakeholders	• Case study collaboration • Reducing bureaucracy between HEI and stakeholder collaboration to enhance the focus on student learning and skill development • New educational structures for integrating practical work early in studies • Reciprocal learning between students and companies through practical engagement (e.g., theses, internships) in the workplace setting
Developing Practices for Continuous Learning		• Centralizing up-to-date knowledge on sustainability (e.g., reporting) for SMEs to save resources • Needs-based stakeholder staff competence development in HEIs
Recruitment		• Co-financed internship programmes to mitigate risks and training investments for companies
Training Programmes	• Creating and co-designing new work-integrated learning models between HEIs and stakeholders with a focus on stakeholder needs data	• Stakeholder experts as HEI instructors for industry-relevant education • Enabling lecturers to participate more in collaboration with working life to gain practical and innovative insights for education

For bridging RDI and education, both groups emphasised the pivotal role of project- and challenge-based educational methods, such as case studies and hackathons. A stakeholder highlights the usefulness of case studies:

> *We've had some great experiences with case study assignments. With them, you get a theoretical framework first, but then you also get a case company and a case task, to explore what things like EU taxonomy means for this company. It sort of opens up your thinking and helps you put things into context, and also, you know, understand that not everything is necessarily so black and white; it is not just about applying theory into practice. Instead, you get new ideas about what kind of real challenges companies actually face* [67].

This discovery aligns with Lozano et al.'s [13] views, recognising case studies as an effective pedagogical strategy in ESD with the potential to enhance a wide variety of sustainability competences, such as systems-thinking. Similarly, Lambrechts and Van Petegem [71] state that the existing body of scholarly research within the field exhibits a notable inclination toward methods that carry elements of "active, student-centred and real-world learning".

In general, stakeholders regarded the integration of students into professional environments during their studies as pivotal. Furthermore, they suggested that the mitigation of bureaucracy in student-stakeholder collaboration would save time and resources for the actual development of students' expertise. In bridging RDI and education, HEI respondents underlined the need for novel interorganisational structures to facilitate collaboration.

In terms of ESD training programmes, HEI respondents recognised the further need for stakeholder-focused models in work-integrated learning. However, stakeholders expressed their willingness to participate in education as guest lecturers. For continuous learning, stakeholders posited that they would benefit from HEI-provided continuous learning opportunities customised to their needs. In the context of small and medium enterprises (SMEs), competence development could be enhanced through a centralised source providing up-to-date knowledge and insights on sustainability practices and compliance with legal sustainability requirements. Moreover, to mitigate the risks associated with student recruitment for companies, stakeholders proposed the development of co-financed internship programmes between HEIs and stakeholder organisations.

5. Conclusions, Limitations and Implications

The present research provides a regionally and professionally contextualised perspective for advancing the sustainability transition, focusing on competence-based ESD strategies aligned with human resource development within HEIs. This contributes to the theoretical discourse on how ESD can be effectively integrated into higher education curricula and human resource development. As a case study, it explores the content and methods of stakeholder-informed human capacity building in sustainable and responsible RDI at Karelia UAS by utilising a well-established sustainability competence framework [14] as a reference point. By utilizing this framework, this study offers a theoretical foundation for identifying and categorizing sustainability competences, thereby enriching the existing body of research on sustainability competences in RDI related to sustainable chains in higher education. This study provides initial findings on regionally relevant sustainable development competences and discusses the substance and methodology of both contemporary and future-oriented competences fostering sustainable development.

Conceptually, sustainability lacks a unified definition and is subject to varied interpretations and analysis schemes depending on the type of scientific discourse [72]. This point is underlined by the following stakeholder's response reflecting the ambiguity and intricacies of sustainability as a concept:

> *When we talk about sustainability, what it means to each person varies quite a bit, you know, like that. Almost all discussions should start with what it means to each person before we can then discuss how it can be developed further. So then, additional education would be needed for various parties to understand what sustainability actually entails* [67].

Thus, the existing unclarity around the term may pose challenges in interpreting and analysing the views of individuals from different social settings.

The reliance on a case study approach sets constraints for the generalisability of the results to wider populations or contexts. However, the study design and methodology offer a structured participatory approach to contextualise the broad insights provided by the key competence framework in sustainability [14] in regional realities for other HEIs who seek methodological means for making their ESD-related competence development more contextually relevant and stakeholder-informed.

As a limiting aspect of the sample, the participants represent only three out of four types of stakeholders, as depicted by the quadruple-helix model, excluding civil society representatives. To achieve a more accurate understanding of the phenomenon at hand, it is advisable to investigate this topic further with larger datasets encompassing a more comprehensive selection and balanced distribution of HEI and stakeholder representatives and reflecting more diverse stakeholder types, such as students and civil society representatives, as outlined in the quadruple-helix model.

Regarding research questions 1 and 2, HEI and stakeholder perspectives regarding current sustainability competence needs seem more aligned than their future projections of those needs. Within the sustainability key framework, both groups prioritised the current and future importance of disciplinary competences but with varying points of emphasis. For megatrend-influenced competence needs in the future, the perspectives of the respondent groups on megatrends differed considerably in terms of effective megatrends and the range of key competences. This study seems to underline Stankevičiūtė and Savanevičienė's [45] views that it is recommended to involve more stakeholder-informed and future-oriented strategic processes in terms of sustainability competences. While the key and complementary competences are inherently interlinked, a deeper analysis would reveal more about the inter-relationships between these competence areas. For example, conducting discipline-specific translation of these competences allows for a more detailed analysis of RDI competence profiles relevant to different educational and professional fields.

Following this, future research could address, for example, pi-shaped professional profiles and general information and communication technology skills and literacy contributing to sustainability. These theoretical insights contribute to the current understanding of how HEI and their stakeholders perceive and prioritise sustainability competences and draw more attention to professional profiles as contributors to sustainability.

Concerning research question 3 and joint competence development methods in RDI, the results show that both HEI and stakeholder participants highlighted the methods and practices for bridging RDI and education and collaborative training programmes. As a competence development method, case studies in particular were regarded as beneficial for advancing RDI-related sustainability expertise. As differing aspects between the groups, the stakeholders suggested tailored protocols for advancing their continuous learning in RDI and the mitigation of the financial risk associated with HEI-stakeholder cooperation, whereas HEIs underscored the processes for planning interaction between higher education and its stakeholders to ensure mutually beneficial outcomes. This study builds on Lozano et al.'s [13] perspective on case studies as an effective practical pedagogical tool for delivering sustainability competences in education and staff training.

As regional competence needs vary based on the regional economic structure, such as in Finland [73] (p. 31), there is a need for more research on the operationalisation of sustainability competences at the regional level. In the context of regional human resource development, this case study bridges the gap between HEI and industry discourses on sustainability competences relevant to sustainable supply chains, as discussed by Lambrecht et al. [22]. Also, this study offers the practical application of a well-established reference framework, Redman and Wiek's [14], for strategic human resource development processes, as well as using this framework to map relevant RDI competences and plan the regional goals and needs in sustainability. The findings and methodology of this study could be used to inform the planning of strategic human resource development processes in both HEI and stakeholder organisations in terms of co-creating curricula and training programmes for students and employees to enhance their sustainability competences. As this study examines RDI sustainability competences in the context of supply chains, it is important that other relevant contexts regarding RDI competences in sustainability are considered in future research. This study provides a participative methodology that can be used to gain a comparative understanding of the status of joint competence development between an HEI and their stakeholders for purposeful regional HR capacity building of sustainability competences.

In general, the results can serve as a reference point for aligning higher education curricula and human resource development with education for sustainable development (ESD), contributing to more sustainable practices in higher education. Also, this type of research could guide regional HEIs to address their local stakeholders' competence needs in education for sustainable development and to improve their graduates' employability in a more effective and future-oriented way. This would foster sustainability transformation in higher education.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su162411134/s1: Table S1: Focus group interview protocol; Table S2: Combined disciplinary competences in RDI in HEI and stakeholder groups; Table S3: Disciplinary competences in RDI in the HEI group; Table S4: Disciplinary competences in RDI in stakeholder groups; Table S5: Combined megatrend-driven disciplinary competences in RDI in HEI and stakeholder groups; Table S6: Megatrend-driven disciplinary competences in RDI in the HEI group; Table S7: Megatrend-driven disciplinary competences in RDI in stakeholder groups; Table S8: Existing organisational methods for RDI competence development in the HEI and its stakeholder organisations.

Author Contributions: Conceptualization, L.T. and T.M.; methodology, L.T. and T.M.; validation, L.T., T.M. and K.V.; formal analysis, L.T., T.M. and K.V.; investigation, L.T., T.M. and K.V.; data curation, T.M. and K.V.; writing—original draft preparation, L.T. and T.M.; writing—review and editing, L.T., T.M. and K.V.; visualization, L.T., T.M. and K.V.; supervision, L.T. and K.V.; project administration, K.V. and T.M.; funding acquisition, L.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's Horizon 2020 research and innovation program (Science with and for Society) under grant number 101035815 (INVEST4EXCELLENCE).

Institutional Review Board Statement: Ethical review and approval were waived for this study due to the full compliance of the study with national ethical instructions as presented by the Finnish National Board of Research Integrity (TENK).

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The original data presented in this study are openly available on Zenodo at https://doi.org/10.5281/zenodo.11395108. The RDI competence matrix is available online via theF European Commission's portal at https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5fdd5a1d2&appId=PPGMS (accessed on 17 December 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. European Commission. European Skills Agenda. Available online: https://ec.europa.eu/migrant-integration/sites/default/files/2020-07/SkillsAgenda.pdf (accessed on 31 August 2023).
2. OECD. OECD Skills Outlook 2023: Skills for a Resilient Green and Digital Transition | En | OECD. Available online: https://www.oecd.org/education/oecd-skills-outlook-e11c1c2d-en.htm (accessed on 27 May 2024).
3. Cortese, A.D. The Critical Role of Higher Education in Creating a Sustainable Future. *Plan. High. Educ.* **2003**, *31*, 15–22.
4. Haddock-Fraser, J. Higher Education for Sustainability. In *The International Encyclopedia of Higher Education Systems and Institutions*; Amaral, A., Bernasconi, A., Magalhaes, A., Kehm, B.M., Stensaker, B., Choi, E., Balbachevsky, E., Hunter, F., Goastellec, G., Mohamedbhai, G., et al., Eds.; Springer: Dordrecht, The Netherlands, 2020; ISBN 978-94-017-8904-2.
5. Radinger-Peer, V.; Stoeglehner, G. Universities as Change Agents for Sustainability—Framing the Role of Knowledge Transfer and Generation in Regional Development Processes. *J. Clean. Prod.* **2013**, *44*, 85–95. [CrossRef]
6. Sedlacek, S. The Role of Universities in Fostering Sustainable Development at the Regional Level. *J. Clean. Prod.* **2013**, *48*, 74–84. [CrossRef]
7. Rieckmann, M. Learning to Transform the World: Key Competencies in Education for Sustainable Development. In *Issues and Trends in Education for Sustainable Development*; Leicht, A., Heiss, J., Byun, W.J., Eds.; UNESCO: Paris, France, 2018; pp. 39–59.
8. INVEST. European University Alliance INVEST University Alliance's Homepage. Available online: https://www.invest-alliance.eu/ (accessed on 3 April 2024).
9. Žalėnienė, I.; Pereira, P. Higher Education For Sustainability: A Global Perspective. *Geogr. Sustain.* **2021**, *2*, 99–106. [CrossRef]
10. Singer-Brodowski, M.; Förster, R.; Eschenbacher, S.; Biberhofer, P.; Getzin, S. Facing Crises of Unsustainability: Creating and Holding Safe Enough Spaces for Transformative Learning in Higher Education for Sustainable Development. *Front. Educ.* **2022**, *7*, 787490. [CrossRef]
11. Stephens, J.C.; Graham, A.C. Toward an Empirical Research Agenda for Sustainability in Higher Education: Exploring the Transition Management Framework. *J. Clean. Prod.* **2010**, *18*, 611–618. [CrossRef]
12. Brundiers, K.; Barth, M.; Cebrián, G.; Cohen, M.; Diaz, L.; Doucette-Remington, S.; Dripps, W.; Habron, G.; Harré, N.; Jarchow, M.; et al. Key Competencies in Sustainability in Higher Education—Toward an Agreed-upon Reference Framework. *Sustain. Sci.* **2021**, *16*, 13–29. [CrossRef]

13. Lozano, R.; Merrill, M.Y.; Sammalisto, K.; Ceulemans, K.; Lozano, F.J. Connecting Competences and Pedagogical Approaches for Sustainable Development in Higher Education: A Literature Review and Framework Proposal. *Sustainability* **2017**, *9*, 1889. [CrossRef]
14. Redman, A.; Wiek, A. Competencies for Advancing Transformations Towards Sustainability. *Front. Educ.* **2021**, *6*, 785163. [CrossRef]
15. Wiek, A.; Keeler, L.; Redman, C. Key Competencies in Sustainability: A Reference Framework for Academic Program Development. *Sustain. Sci.* **2011**, *6*, 203–218. [CrossRef]
16. Beardwell, J.; Thompson, A. *Human Resource Management: A Contemporary Approach*; Pearson: London, UK, 2014; ISBN 978-1-292-00272-9.
17. Grosseck, G.; Țîru, L.G.; Bran, R.A. Education for Sustainable Development: Evolution and Perspectives: A Bibliometric Review of Research, 1992–2018. *Sustainability* **2019**, *11*, 6136. [CrossRef]
18. Wiek, A.; Bernstein, M.; Foley, R.; Cohen, M.; Forrest, N.; Kuzdas, C.; Kay, B.; Keeler, L. Operationalising Competencies in Higher Education for Sustainable Development. In *Routledge Handbook of Higher Education for Sustainable Development*; Barth, M., Michelsen, G., Rieckmann, M., Thomas, I., Eds.; Routledge: London, UK; New York, NY, USA, 2016; pp. 241–260.
19. Salovaara, J.J.; Soini, K.; Pietikäinen, J. Sustainability Science in Education: Analysis of Master's Programmes' Curricula. *Sustain. Sci.* **2020**, *15*, 901–915. [CrossRef]
20. Wilhelm, S.; Förster, R.; Zimmermann, A.B. Implementing Competence Orientation: Towards Constructively Aligned Education for Sustainable Development in University-Level Teaching-And-Learning. *Sustainability* **2019**, *11*, 1891. [CrossRef]
21. Finnveden, G.; Schneider, A. Sustainable Development in Higher Education—What Sustainability Skills Do Industry Need? *Sustainability* **2023**, *15*, 4044. [CrossRef]
22. Lambrechts, W.; Semeijn, J.; Gelderman, C.J.; Ghijsen, P.; Liedekerke, L.V. Individual Sustainability Competences in Supply Chain Management. In Proceedings of the Symposium on Learning and Innovation in Resilient Systems, Heerlen, The Netherlands, 23–24 March 2017.
23. Roos, N.; Sassen, R.; Guenther, E. Sustainability Governance toward an Organizational Sustainability Culture at German Higher Education Institutions. *Int. J. Sustain. High. Educ.* **2022**, *24*, 553–583. [CrossRef]
24. Ferrer-Balas, D.; Adachi, J.; Banas, S.; Davidson, C.I.; Hoshikoshi, A.; Mishra, A.; Motodoa, Y.; Onga, M.; Ostwald, M. An International Comparative Analysis of Sustainability Transformation across Seven Universities. *Int. J. Sustain. High. Educ.* **2008**, *9*, 295–316. [CrossRef]
25. Singer-Brodowski, M.; Etzkorn, N.; Von Seggern, J. One Transformation Path Does Not Fit All—Insights into the Diffusion Processes of Education for Sustainable Development in Different Educational Areas in Germany. *Sustainability* **2019**, *11*, 269. [CrossRef]
26. Sterling, S. Higher Education, Sustainability, and the Role of Systemic Learning. In *Higher Education and the Challenge of Sustainability*; Springer: Dordrecht, The Netherlands, 2004; pp. 49–70. ISBN 978-1-4020-2026-1.
27. Galleli, B.; Hourneaux Junior, F. Human Competences for Sustainable Strategic Management: Evidence from Brazil. *Benchmarking Int. J.* **2019**, *28*, 2835–2864. [CrossRef]
28. Wals, A.E.J.; Tassone, V.; Hampson, G.; Reams, J. Learning for Walking the Change: Eco-Social Innovation through Sustainability-Oriented Higher Education. In *Routledge Handbook of Higher Education for Sustainable Development*; Barth, M., Michelsen, G., Rieckmann, M., Thomas, I., Eds.; Routledge: London, UK, 2015; ISBN 978-1-315-85224-9.
29. Scherak, L.; Rieckmann, M. Developing ESD Competences in Higher Education Institutions—Staff Training at the University of Vechta. *Sustainability* **2020**, *12*, 10336. [CrossRef]
30. Abbas, Z.; Sarwar, S.; Rehman, M.A.; Zámečník, R.; Shoaib, M. Green HRM Promotes Higher Education Sustainability: A Mediated-Moderated Analysis. *Int. J. Manpow.* **2021**, *43*, 827–843. [CrossRef]
31. Mohiuddin, M.; Hosseini, E.; Faradonbeh, S.B.; Sabokro, M. Achieving Human Resource Management Sustainability in Universities. *Int. J. Environ. Res. Public Health* **2022**, *19*, 928. [CrossRef] [PubMed]
32. Bratton, J.; Gold, J. *Human Resource Management*, 6th ed.; Theory and Practice; Macmillan Education: London, UK, 2017; ISBN 978-1-137-58669-8.
33. Vargas-Hernández, J.G. Strategic Organizational Sustainability. *Circ. Econ. Sust.* **2021**, *1*, 457–476. [CrossRef]
34. Barth, M.; Rieckmann, M. Academic Staff Development as a Catalyst for Curriculum Change towards Education for Sustainable Development: An Output Perspective. *J. Clean. Prod.* **2012**, *26*, 28–36. [CrossRef]
35. Leal Filho, W.; Raath, S.; Lazzarini, B.; Vargas, V.R.; de Souza, L.; Anholon, R.; Quelhas, O.L.G.; Haddad, R.; Klavins, M.; Orlovic, V.L. The Role of Transformation in Learning and Education for Sustainability. *J. Clean. Prod.* **2018**, *199*, 286–295. [CrossRef]
36. Sammalisto, K.; Sundström, A.; Holm, T. Implementation of Sustainability in Universities as Perceived by Faculty and Staff—A Model from a Swedish University. *J. Clean. Prod.* **2015**, *106*, 45–54. [CrossRef]
37. Kekäle, J. Human Resource Management, Higher Education. In *Encyclopedia of International Higher Education Systems and Institutions*; Springer: Dordrecht, The Netherlands, 2018; pp. 1–7, ISBN 978-94-017-9553-1.
38. Chouhan, V.S.; Srivastava, S. Understanding Competencies and Competency Modeling—A Literature Survey. *IOSR J. Bus. Manag.* **2014**, *16*, 14–22. [CrossRef]
39. Hamlin, B.; Stewart, J. What Is HRD? A Definitional Review and Synthesis of the HRD Domain. *J. Eur. Ind. Train.* **2011**, *35*, 199–220. [CrossRef]

40. Faisal, S. Twenty-Years Journey of Sustainable Human Resource Management Research: A Bibliometric Analysis. *Adm. Sci.* **2023**, *13*, 139. [CrossRef]
41. Ehnert, I.; Parsa, S.; Roper, I.; Wagner, M.; Muller-Camen, M. Reporting on Sustainability and HRM: A Comparative Study of Sustainability Reporting Practices by the World's Largest Companies. *Int. J. Hum. Resour. Manag.* **2016**, *27*, 88–108. [CrossRef]
42. Reid, W.V.; Chen, D.; Goldfarb, L.; Hackmann, H.; Lee, Y.T.; Mokhele, K.; Ostrom, E.; Raivio, K.; Rockström, J.; Schellnhuber, H.J.; et al. Earth System Science for Global Sustainability: Grand Challenges. *Science* **2010**, *330*, 916–917. [CrossRef]
43. UNESCO. Knowledge-Driven Actions: Transforming Higher Education for Global Sustainability. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000380519.locale=en. (accessed on 11 June 2024).
44. Ekwurzel, B.; Boneham, J.; Dalton, M.W.; Heede, R.; Mera, R.J.; Allen, M.R.; Frumhoff, P.C. The Rise in Global Atmospheric CO_2, Surface Temperature, and Sea Level from Emissions Traced to Major Carbon Producers. *Clim. Change* **2017**, *144*, 579–590. [CrossRef]
45. Stankevičiūtė, Ž.; Savanevičienė, A. Designing Sustainable HRM: The Core Characteristics of Emerging Field. *Sustainability* **2018**, *10*, 4798. [CrossRef]
46. Sylvestre, P.; Wright, T. Organisational Change and Organisational Learning for Promoting Higher Education for Sustainable Development. In *Routledge Handbook of Higher Education for Sustainable Development*; Barth, M., Michelsen, G., Rieckmann, M., Thomas, I., Eds.; Routledge: London, UK, 2015; ISBN 978-1-315-85224-9.
47. Meyer, J.; Pillei, M.; Zimmermann, F.; Stöglehner, G. Customized Education as a Framework for Strengthening Collaboration between Higher Education Institutions and Regional Actors in Sustainable Development—Lessons from Albania and Kosovo. *Sustainability* **2018**, *10*, 3941. [CrossRef]
48. Trippl, M.; Sinozic, T.; Lawton Smith, H. The Role of Universities in Regional Development: Conceptual Models and Policy Institutions in the UK, Sweden and Austria. *Eur. Plan. Stud.* **2015**, *23*, 1722–1740. [CrossRef]
49. Asheim, B.; Grillitsch, M. Smart Specialisation: Sources for New Path Development in a Peripheral Manufacturing Region. In *Papers in Innovation Studies*; Lund University: Lund, Sweden, 2015; ISBN 978-82-8285-087-2.
50. Isaksen, A.; Trippl, M. Innovation in Space: The Mosaic of Regional Innovation Patterns. *Oxf. Rev. Econ. Policy* **2017**, *33*, 122–140. [CrossRef]
51. Tonelli, F.; Evans, S.; Taticchi, P. Industrial Sustainability: Challenges, Perspectives, Actions. *Int. J. Bus. Innov. Res.* **2013**, *7*, 143–163. [CrossRef]
52. European Commission. Due Diligence: MEPs Adopt Rules for Firms on Human Rights and Environment | News | European Parliament. Available online: https://www.europarl.europa.eu/news/en/press-room/20240419IPR20585/due-diligence-meps-adopt-rules-for-firms-on-human-rights-and-environment (accessed on 17 May 2024).
53. European Commission. The Commission Adopts the European Sustainability Reporting Standards—European Commission. Available online: https://finance.ec.europa.eu/news/commission-adopts-european-sustainability-reporting-standards-2023-07-31_en (accessed on 17 May 2024).
54. World Economic Forum. Net-Zero Challenge: The Supply Chain Opportunity. Available online: https://www3.weforum.org/docs/WEF_Net_Zero_Challenge_The_Supply_Chain_Opportunity_2021.pdf (accessed on 18 September 2023).
55. Mageto, J.; Luke, R. Skills Frameworks: A Focus on Supply Chains. *J. Transp. Supply Chain Manag.* **2020**, *14*, a458. [CrossRef]
56. Puhakka-Tarvainen, H.; Muhonen, T.; Timonen, L. RDI Competence Matrix. Available online: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5fdd5a1d2&appId=PPGMS (accessed on 3 April 2024).
57. Joanna Briggs Institute. Scoping Reviews—Resources | JBI. Available online: https://jbi.global/scoping-review-network/resources (accessed on 1 November 2023).
58. Krueger, R.A.; Casey, M.A. *Focus Groups: A Practical Guide for Applied Research*, 5th ed.; SAGE: Los Angeles, CA, USA, 2015; ISBN 978-1-4833-6524-4.
59. Jelonek, M.; Urbaniec, M. Development of Sustainability Competencies for the Labour Market: An Exploratory Qualitative Study. *Sustainability* **2019**, *11*, 5716. [CrossRef]
60. Creswell, J.W.; Poth, C.N. *Qualitative Inquiry & Research Design: Choosing Among Five Approaches*, 4th ed.; SAGE: Los Angeles, CA, USA, 2018; ISBN 978-1-5063-3020-4.
61. Roman, M.; Varga, H.; Cvijanovic, V.; Reid, A. Quadruple Helix Models for Sustainable Regional Innovation: Engaging and Facilitating Civil Society Participation. *Economies* **2020**, *8*, 48. [CrossRef]
62. Open AI GPT-4 (June 2024 Version). Available online: https://openai.com/gpt-4 (accessed on 3 April 2024).
63. Binkley, M.; Erstad, O.; Herman, J.; Raizen, S.; Ripley, M.; Miller-Ricci, M.; Rumble, M. Defining Twenty-First Century Skills. In *Assessment and Teaching of 21st Century Skills*; Springer: Dordrecht, The Netherlands, 2011; pp. 17–66, ISBN 978-94-007-2323-8.
64. United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs. Available online: https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981 (accessed on 16 October 2023).
65. Kavathatzopoulos, I. ICT and Sustainability: Skills and Methods for Dialogue and Policy Making. *J. Inf. Commun. Ethics Soc.* **2015**, *13*, 13–18. [CrossRef]
66. Pennington, D.; Imme, E.-U.; Freed, N.; Martin, J.; Pierce, S.A. Bridging Sustainability Science, Earth Science, and Data Science through Interdisciplinary Education. *Sustain. Sci.* **2020**, *15*, 647–661. [CrossRef]

67. Muhonen, T.; Puhakka-Tarvainen, H.; Karelia University of Applied Sciences. *TKI-Kestävyyskompetenssit Ja Niiden Kehittäminen Karelia-Ammattikorkeakoulun Ja Sidosryhmien Yhteistyössä*; Zenodo: Geneva, Switzerland, 2024.
68. European Commission. The Megatrends Hub | Knowledge for Policy. Available online: https://knowledge4policy.ec.europa.eu/foresight/tool/megatrends-hub_en (accessed on 28 February 2024).
69. Mulder, K. Strategic Competencies, Critically Important for Sustainable Development. *J. Clean. Prod.* **2014**, *78*, 243–248. [CrossRef]
70. Libertson, F. Inner Transitions in Higher Education in Sweden: Incorporating Intra-Personal Skills in Education for Sustainable Development. *Int. J. Sustain. High. Educ.* **2023**, *24*, 213–230. [CrossRef]
71. Lambrechts, W.; Van Petegem, P. The Interrelations between Competences for Sustainable Development and Research Competences. *Int. J. Sustain. High. Educ.* **2016**, *17*, 776–795. [CrossRef]
72. Ruggerio, C.A. Sustainability and Sustainable Development: A Review of Principles and Definitions. *Sci. Total Environ.* **2021**, *786*, 147481. [CrossRef]
73. Finnish Government. Competence Secures the Future. Available online: https://urn.fi/URN:ISBN:978-952-383-531-3 (accessed on 7 June 2024).

UTM Library
UNIVERSITI TEKNOLOGI MALAYSIA
SDi@JPUTM
SELECTIVE DISSEMINATION OF INFORMATION
library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
7) Integrated sustainability assessment framework for geothermal energy technologies: A literature review and a new proposal of sustainability indicators for Mexico (2024)	RENEWABLE & SUSTAINABLE ENERGY REVIEWS (Article From : ELSEVIER)

27th FEBRUARY2025
SOURCE: PERPUSTAKAAN UTM

Renewable and Sustainable Energy Reviews 192 (2024) 114231

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Integrated sustainability assessment framework for geothermal energy technologies: A literature review and a new proposal of sustainability indicators for Mexico

K. Solano-Olivares [a], E. Santoyo [b,*], E. Santoyo-Castelazo [c]

[a] Posgrado de Ingeniería (Energía), Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Priv. Xochicalco 62580, Centro, Temixco, Morelos, Mexico

[b] Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Priv. Xochicalco 62580, Centro, Temixco, Morelos, Mexico

[c] Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ciudad de México 14380, México

A R T I C L E I N F O

Keywords:
Renewable energy
Geothermal energy
Sustainable development
Climate change
Geothermal sustainability
Environmental sustainability
Socio-economic sustainability
Circular economy

A B S T R A C T

Mexico's energy agenda has the commitment to achieve a share of 35% of renewable energy in the energy portfolio by 2025. Geothermal energy is a source that may contribute to this goal due to the enormous potential, and because it constitutes a viable option for energy diversification and decarbonisation of the electricity sector. However, it is recognised that the geothermal power plants and the direct use technologies still produce some negative sustainability impacts that need to be reduced. With these purposes, an integrated sustainability assessment framework to evaluate such geothermal technologies was developed with the following goals: (i) to obtain an updated systematic literature review on sustainability assessment frameworks, and life-cycle assessment studies to quantify sustainability impacts; (ii) to generate a new set of geothermal sustainability indicators for their future application in projects of electricity generation and direct uses of Mexico; and (iii) to propose sustainable strategies to support the deployment of new geothermal projects for Mexico. As key findings of this investigation, a new integrated framework to assess the sustainability of geothermal technologies, and a new set of 36 sustainability indicators were obtained. These sustainability indicators were selected through a participatory stakeholder engagement conducted by 136 respondents from the society, government, industry and academia. These indicators were ranked and prioritised using multi-criteria decision analysis techniques by additionally considering the main physicochemical and geological features of Mexico geothermal systems, and the production technologies currently installed. With this methodology, key sustainability challenges for the geothermal industry of Mexico can be tackled.

1. Introduction

The world energy portfolio is still dominated by fossil fuels, which led to strong environmental impacts of global warming, climate change, and health [1,2]. The worldwide electricity production relies on the consumption of fossil fuels, which are responsible for ~40% of greenhouse gas (GHG) emissions [3]. To address these issues, it is necessary to increase the use of renewable energies (RE) [4]. According to the Sustainable Development Goals (SDG) of the 2030 United Nations Agenda, an energy diversification is required to guarantee a sustainable development with benefits for humanity [5,6].

Within this framework, the exploitation of geothermal resources is used in ~88 countries for electricity generation and other direct uses [7]. Geothermal energy is considered as a reliable technology for the electricity production due to the high-capacity factors (80%–95%), which enable a base-load source to be afforded [8–10]. It is considered as a good option to support the decarbonisation and diversification not only for Mexico but also for other countries [8,11–13]. Mexico is ranked in the sixth worldwide position in geothermal power generation [11,14,15]. Geothermal technologies (GET) for electricity generation and heating are referred as clean energies due to the low environmental impacts [16,17]. However, from a stricter sustainable development, such GET still exhibit negative environmental, economic and social impacts that require to be mitigated [16].

To achieve a sustainable development, integrated sustainability assessment frameworks are needed [18,19]. Geothermal sustainability

* Corresponding author.
E-mail addresses: kasol@ier.unam.mx (K. Solano-Olivares), esg@ier.unam.mx (E. Santoyo), esantoyo@tec.mx (E. Santoyo-Castelazo).

https://doi.org/10.1016/j.rser.2023.114231
Received 12 September 2023; Received in revised form 15 November 2023; Accepted 10 December 2023
Available online 20 December 2023
1364-0321/

indicators (GEOSI) are required as a baseline to reduce negative environmental, economic and social issues associated with the GET, which are typically identified from the stakeholder concerns [20]. From a holistic point of view, the consideration of these indicators may prevent or solve in advance some urgent problems of the GET, such as: (i) the major environmental issues; (ii) the acceptability of new projects by surrounding communities; (iii) the proposal of new public polices and regulations by government authorities; (iv) the technical and economic actions required by the industry to improve efficiency and profitability of the production processes; and (v) the opportunities to carry out research and innovation by the academia sector to generate new valuable knowledge.

Some previous studies on benchmarking indicators have been proposed for the evaluation of energy systems. Among these works stand out the sustainability indicators reported for: (i) national energy systems [21,22]; (ii) nuclear power [23]; (iii) RE technologies (solar thermal, solar PV, wind, hydro, geothermal, and biomass) [24–32]; (iv) hybrid RE technologies [33,34]; and (v) hybrid fossil and RE technologies [35–38]. Other type of sustainability indicators has been proposed for other industries or engineering areas such as Sala et al. [39] and Van Schoubroeck et al. [40].

Some of these frameworks were proposed by considering top-down approaches (or experts-led) [41,42]; whereas others used bottom-up approaches with a limited representation of stakeholders [18]. Among these frameworks, the concept of integrated sustainability assessment frameworks (ISAFs) stands out, where a multi-participatory work of stakeholders appears as an effective tool for the selection and valorisation of new GEOSI [22,23,28,36,40]. From an energy perspective, a sustainability model may gather opinions from different stakeholders about the clean use of natural resources, economic growth, and social progress. An ecological balance and a better human living conditions should be guaranteed with growing economy. For the development of ISAFs, some authors suggest the creation of GEOSI to cover technical, geological, environmental, economic, and social aspects [19,27]. Other authors prefer the creation of indicators by grouping the conventional pillars of sustainability (environmental, economic and social), and assuming that the technical and geological aspects are already included [34,40]. The environmental pillar usually involves the entire ecosystem by considering the resources (energy and raw materials) and the emissions to air, soil, and water [43], whereas the economic and social pillars consider technical support and human systems to involve economic (infrastructure, economic-finance) and social (human development and governance) aspects, respectively.

The creation of GEOSI for addressing major environmental, economic and social issues of geothermal projects, stakeholders composed by representative groups from the academia, government, industry, and society should be committed [44]. These stakeholders must consider multiple necessities, benefits and demands to avoid sustainability conflicts [45,46]. Unbiassed GEOSI must be selected from the use of ISAFs and robust Multi-Criteria Decision Analysis (MCDA) techniques, which enable the best prioritisation of GEOSI to be selected [30,47]. For the sustainable evaluation of GET, a limited number of indicators (technological and geological) have been proposed [48,49], whereas some other approaches have been recommended to evaluate projects through environmental, economic and social indicators [50–54]. Among these works, Shortall et al. [52–54] recommended a **G**eothermal **S**ustainability **A**ssessment **P**rotocol (GSAP) to evaluate commercial projects under a management-oriented approach using the Delphi method. Although, GSAP was specifically designed to evaluate geothermal resources of Iceland (considering technical, institutional and local cultural features) [52,53], it was also replicated to evaluate projects in New Zealand and Kenya [54].

On the other hand, Soltani et al. [55] evaluated technical and economic indicators for geothermal projects under a sustainable development framework based on environmental, governance, and social aspects, including the analysis of some key barriers.

Raos et al. [19] recently reported a revised set of sustainability criteria for the evaluation of geothermal projects based on the exploitation of **E**nhanced **G**eothermal **S**ystems (EGS). Although, this study covered the hierarchical assessment of geological settings, technical features, economic/financial aspects, and some environmental/social parameters, the environmental and social indicators were undervalued. Six criteria were scarcely defined to address the major environmental impacts (e.g., land use, noise, avoided CO_2 emissions, protected areas, potential seismicity, and conflict with other subsurface uses), whereas for social issues, a few indicators were hardly evaluated (job creation and social acceptability).

Although this world progress, further research based on new selection surveys are still needed to address and rank environmental and social sustainability indicators, which may be more representative for other developing countries where the geothermal resources are available (e.g., Mexico). The evaluation of sustainable GET requires new ISAFs for selecting GEOSI aligned with life-cycle stages of geothermal projects (i.e., exploration, construction, operation and end-of-life or decommissioning). On the other hand, the operation of dry-steam and flash-steam geothermal power plants usually produce gas emissions, where the negative environmental impacts of dry-steam plants are typically lower than those generated by flash-steam plants [55]. Binary cycle power plants which operate in a closed-loop in EGS do not produce such gas emissions. Sometimes these emissions are negligible in comparison with the pre-existing native (or fugitive) emissions which are observed in the early exploration of geothermal systems [56–58]. This is the case of the geothermal zone of Acoculco (Mexico) where large amounts of gas emissions are naturally released [57]. Such emissions may be allocated among pre-existing natural emissions and gas discharges caused by the life cycle stages. Novel research projects on geochemistry are required to quantify the pre-existing baseline emissions, which may provide some suitable arguments to obtain a better social acceptability of geothermal projects in protected ecosystems (e.g., the case of Cerritos Colorado geothermal zone of Mexico which is currently stopped by ecologists) [57]. With a wider sustainability perspective, improved Life Cycle Assessment (LCA) studies and GEOSI are still required in some countries to support geothermal projects towards the reduction of these environmental, economic and social impacts.

In the present study, a new comprehensive methodology based on an **I**ntegrated **S**ustainability **A**ssessment **F**ramework (ISAF) was proposed to evaluate GET for Mexico with the following goals: (i) to carry out an updated systematic literature review based on updated sustainability assessment frameworks and life cycle assessments for evaluating environmental, economic and social impacts; (ii) to generate a new set of geothermal sustainability indicators for their future application in projects of electricity generation and direct uses; and (iii) to propose better sustainable strategies for supporting the deployment of geothermal technologies, and a cleaner exploitation of the geothermal resources for Mexico. To select and prioritize the new GEOSI, the ISAF-GET methodology was efficiently coupled with Multi-Criteria Decision Analysis (MCDA), Multi-Group Decision Making (MGDM), Sensitivity Analysis (Sensitivity Index, *SI*) and Sustainability Importance Index (*SII*) methods. Details of all these investigation tasks are outlined in the present study.

2. Material and methods

A comprehensive work methodology was developed to carry out this investigation. By using the updated knowledge of ISAFs and LCA studies reported in the worldwide geothermal literature, an ISAF-GET was created. This methodology was conducted to propose new GEOSI for Mexico, and to be used for the future evaluation of environmental, economic and social burdens in geothermal power and heating applications. To create this ISAF-GET, a participatory process of a wide-ranging of stakeholders' inputs was conducted, and use it to compile and select the GEOSI. Fig. 1 shows a flow diagram describing the methodology used for the development of the ISAF-GET, which is composed by the following phases:

3. Theory and calculation

3.1. Phase 1: systematic literature review

Phase 1 required the compilation of articles published on ISAFs and sustainability indicators for geothermal and other energy systems, including LCA studies to evaluate GET. Articles published in peer-review journals were collected from the Web of Science® (WoS) [59] by performing the following **B**asic **W**orking **T**asks (BWT):

BWT-1 To describe the goal and scope of the present study, which are related with the proposal of a new ISAF-GET for Mexico.

BWT-2 To carry out the citation searching in the WoS using keywords and Boolean constraints to identify the most representative articles published on the related research subjects (Fig. 2).

BWT-3 To compile scientific articles published on the research subjects under evaluation (i.e., sustainability frameworks and indicators, and LCA studies for the evaluation of GET).

BWT-4 To carry out a comprehensive parametric analysis of the articles published on earlier proposals of sustainability frameworks, and sustainability indicators for geothermal and some other energy systems.

From Phase 1, a comprehensive database containing the state-of-the-art on the main research subjects was obtained.

3.2. Phase 2: compilation of sustainability indicators

The objective of this phase was to compile an updated listing of sustainability indicators commonly used to assess sustainability impacts of GET and other energy systems. Three BWT were consider for these purposes (see Fig. 1):

BWT-5 To list the most common sustainability impacts associated with GET. These impacts covered the life cycle stages for electricity generation and heating (i.e., exploration, construction, operation and end-of-life). A schematic diagram of some sustainability impacts reported by Shortall et al. [52] is shown in Fig. S1 of the supplementary material.

BWT-6 To define the sustainable development objectives most commonly associated with GET. A schematic diagram adapted for these objectives and reported by Shortall et al. [52] is shown in Fig. S2. These objectives were aligned with the SDGs to identify some aspects addressed.

BWT-7 To compile a preliminary set of GEOSI from previous studies, which were completed by using a brainstorming-method among representative stakeholders. To facilitate the handling of these indicators, an alphanumeric key was assigned to each indicator. The aim of the brainstorming-method was to identify additional sustainability indicators for Mexico that were not reported in previous geothermal studies. This method was carried out by experts on geothermal energy and advanced graduate students.

3.3. Phase 3: participatory survey research

By considering the preliminary set of GEOSI obtained in Phase 2, a **Par**ticipatory **Su**rvey **R**esearch (PASUR) was developed for Mexico. A comprehensive analysis of these indicators through a representative participation of stakeholders was conducted. PASUR was applied to gather information from technical (environmental and economic) and social opinions. One of the benefits of these surveys is to represent a diverse and hard-to-reach sample with different professional and social profiles [60]. Some important features of these surveys are the structure of data, the question relevance, the time validity, the world location, and the specific goals and challenges [61,62]. Interactive spreadsheets of responses, question phrasing and order of these questions were also defined. To perform the PASUR, three BWT were carried out (BWT-8: Global survey development [A]; BWT-9: Data compilation [B]; and BWT-10: analysis of results [C]): Fig. 3.

BWT-8 To develop the PASUR from the information compiled in Phase 2. The software SurveyMonkey® was used as a suitable platform to carry out the global survey by considering the following aspects: (i) ethical responsibility for the participation and anonymity guarantee; (ii) suitable communication instructions to fill out questionnaires; (iii) selection of sustainability pillars to be evaluated through exclusion logic rules; (iv) simplicity of question formats to collect the responses from a

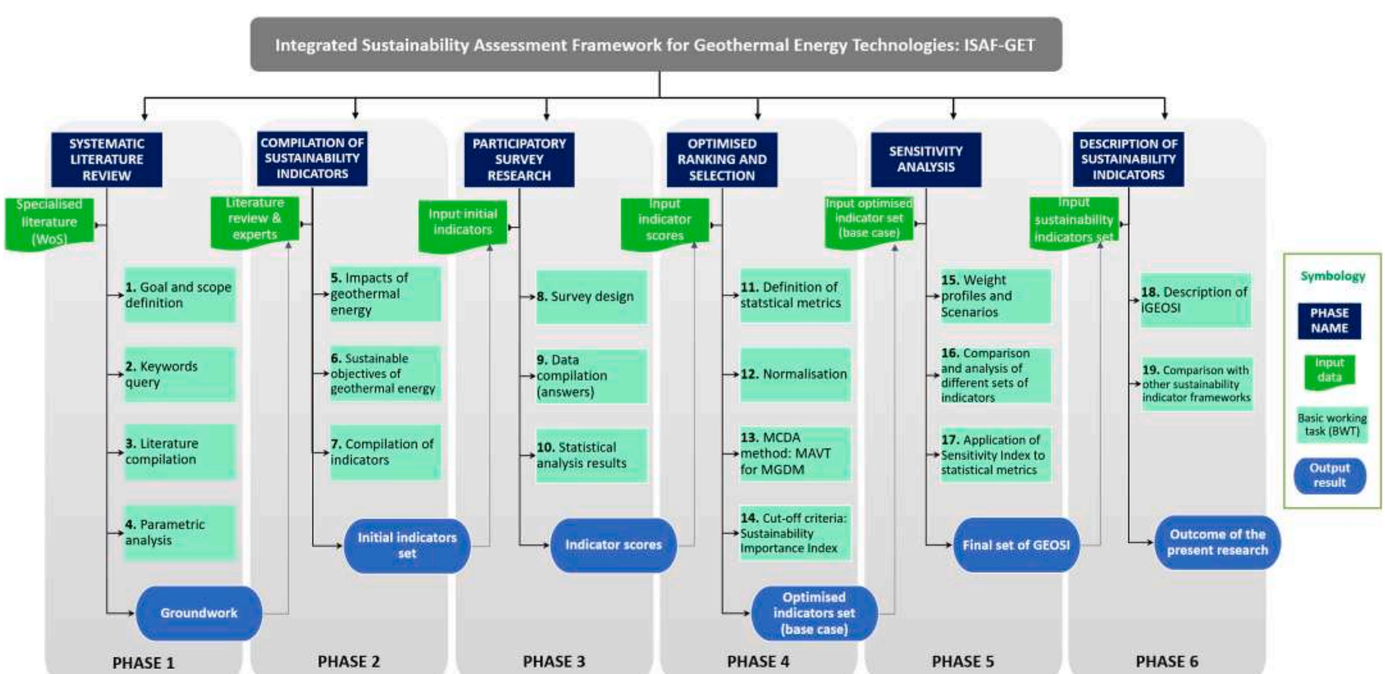


Fig. 1. Methodological flow diagram used for the development of the ISAF-GET.

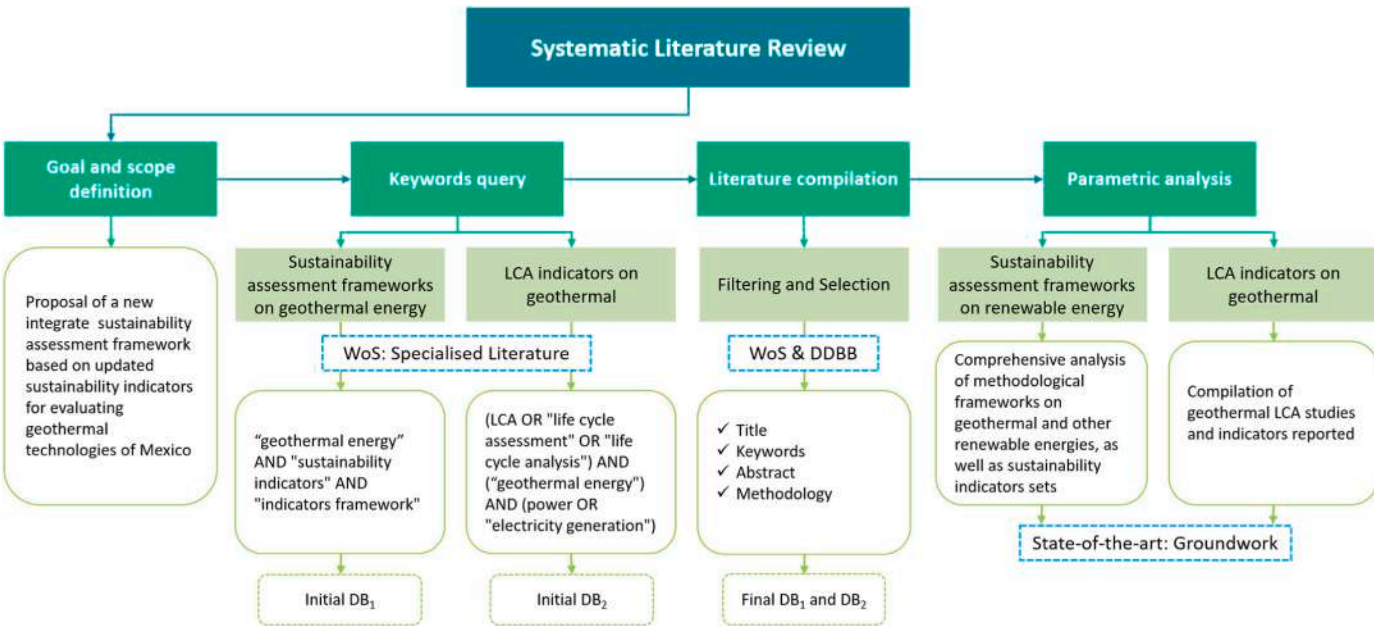


Fig. 2. Methodological flow diagram used for the comprehensive systematic literature review.

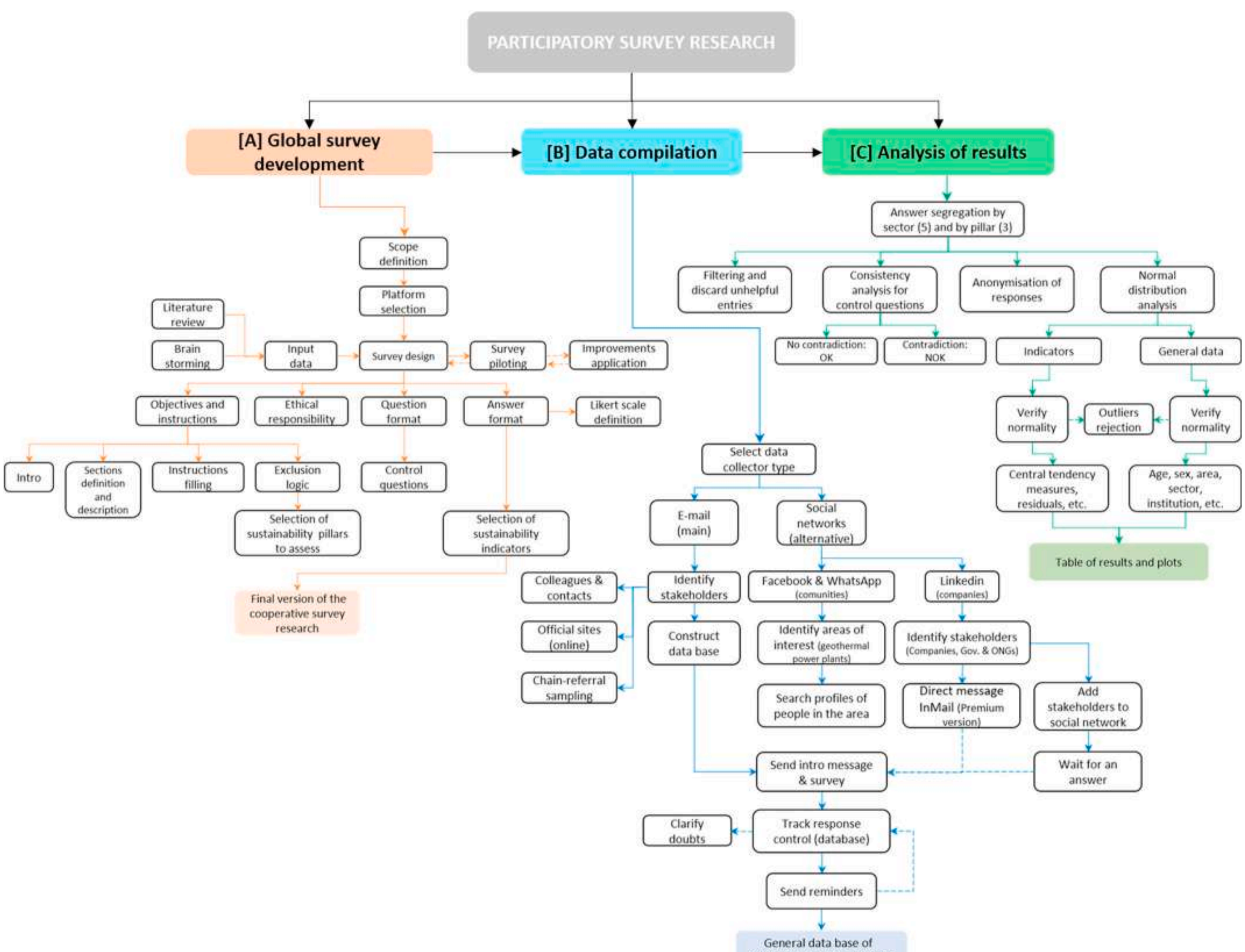


Fig. 3. Methodological flow diagram used to carry out the PASUR for geothermal projects of Mexico.

wide diversity of stakeholders; (v) control questions to verify the consistency of surveyed responses; (vi) simplicity responses through the 5-point Likert scale; and (vii) a pilot-testing survey with some stakeholders from the academia, government, industry or society sectors prior to be launched.

BWT-9 To define the collection media format for the survey's responses (i.e., web link, email, social media, website or kiosk mode). Web links and institutional emails were selected for professional contacts (e.g., LinkedIn and institutional web pages); whereas for some social networks, Facebook, Messenger and WhatsApp were used. The collection process of responses is described in Fig. 3. The "chain-referral sampling" through some selected stakeholders was also used as collection media.

BWT-10 To analyse the segregated results obtained from the PASUR per sector (academia, government, industry or society) and per sustainability pillars (environmental, economic or social): Fig. 3. This task considers the filtering and discarding of unhelpful entries such as the inconclusive or duplicated responses. Inconsistent responses found by control questions were rejected. The responses were anonymised for a further analysis of parametric and non-parametric statistics using indicator scores (e.g., *n-data*, weighted mean, geometric mean, harmonic mean, median, and the residuals: RMSE, MAE, and MAPE).

From Phase 3, sustainability indicator scores from the surveyed stakeholder's sample were collected.

3.4. Phase 4: optimised ranking and selection

To obtain the unbiassed and optimised ranking of GEOSI, a robust mathematical method based on integrated MCDA-MGDM methods was conducted. Weighting factors were used both to bulk and select the diversity of stakeholder opinions. Multiple individual responses and scores were grouped per sustainability pillar (Fig. 4). This methodology was applied as a suitable optimisation technique to solve complicated decision-making situations associated with multiple criteria found in the survey when the stakeholders differ [47,63–66]. Different technical and professional backgrounds, expertise, or cognitive habits of the stakeholders were considered to minimise a subjective analysis of these opinions. A flow diagram showing the major steps of the coupled MCDA-MGDM process is shown in Fig. 5. To perform the optimised selection and ranking of the GEOSI, the following BTW were conducted:

BWT-11 To define a suitable number of statistical metrics to be used as ranking criteria for the decision-making processes (Table S1). These metrics must be calculated from the survey responses.

BWT-12 To obtain a statistical normalisation of variables, a scale conversion of the data sample distribution was performed. The normalisation was used to avoid a bias effect on either any statistical metric or stakeholder group in the MCDA-MGDM method. The normalisation is conducted to minimise or maximize data (estimates or measurements). Dincer and Acar [67] suggested an effective normalisation for ranking electricity production options through the analysis of maximisation and minimisation cases using Eqs. (1) and (2), respectively. In this study, such equations were applied to normalise and rank statistical metrics, where the normalised results may range in a scale from 0 to 10. If a higher performance in a statistical metric was required (e.g., the statistical parameters: n-data, weighted mean, geometric mean, harmonic mean, or median), Eq. (1) was applied:

$$X'_{Max} = \frac{x_{obs} - x_{Min}}{x_{Max} - x_{Min}} \times 10 \tag{1}$$

On the other hand, if a lower performance of the statistical metric was required (e.g., in the cases of the statistical residuals: RMSE, MAE, and MAPE), Eq. (2) was applied:

$$X'_{Min} = \frac{x_{Max} - x_{obs}}{x_{Max} - x_{Min}} \times 10 \tag{2}$$

where: X' is the normalised data either for the maximisation or minimisation cases; x is the observed datum given within a dataset; and x_{Max} and x_{Min} are the largest and smallest data within the dataset, respectively.

BWT-13 To apply the MCDA-MGDM method for ranking the GEOSI by considering the pillars of sustainability [68,69]. To optimize the set

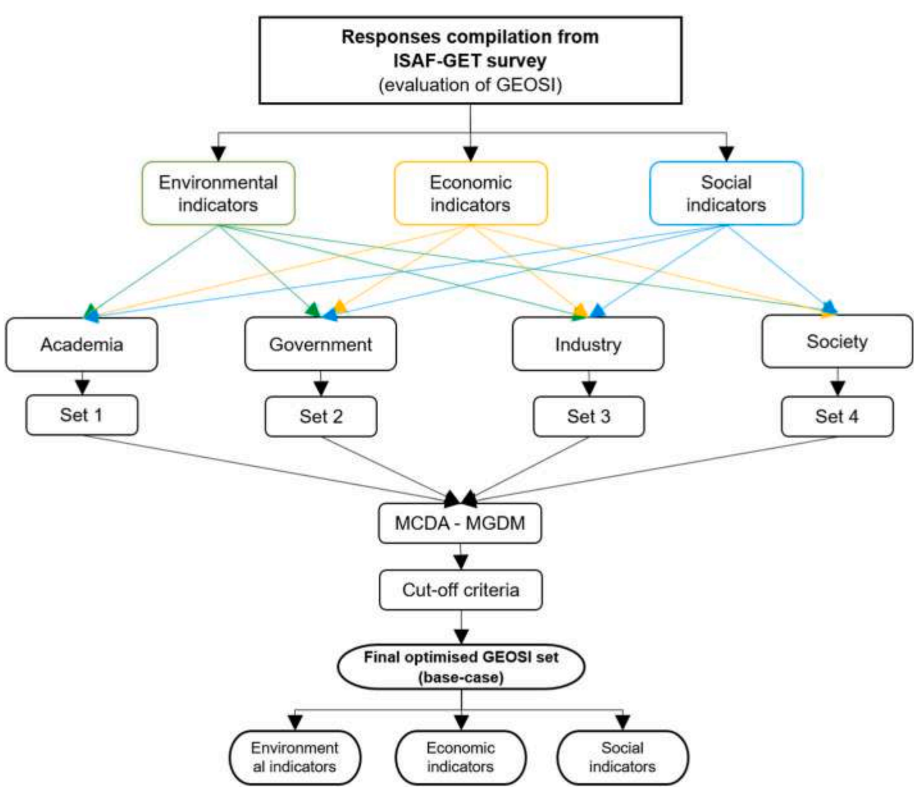


Fig. 4. Management and optimised ranking of the new GEOSI inferred from a coupled MCDA-MGDM method.

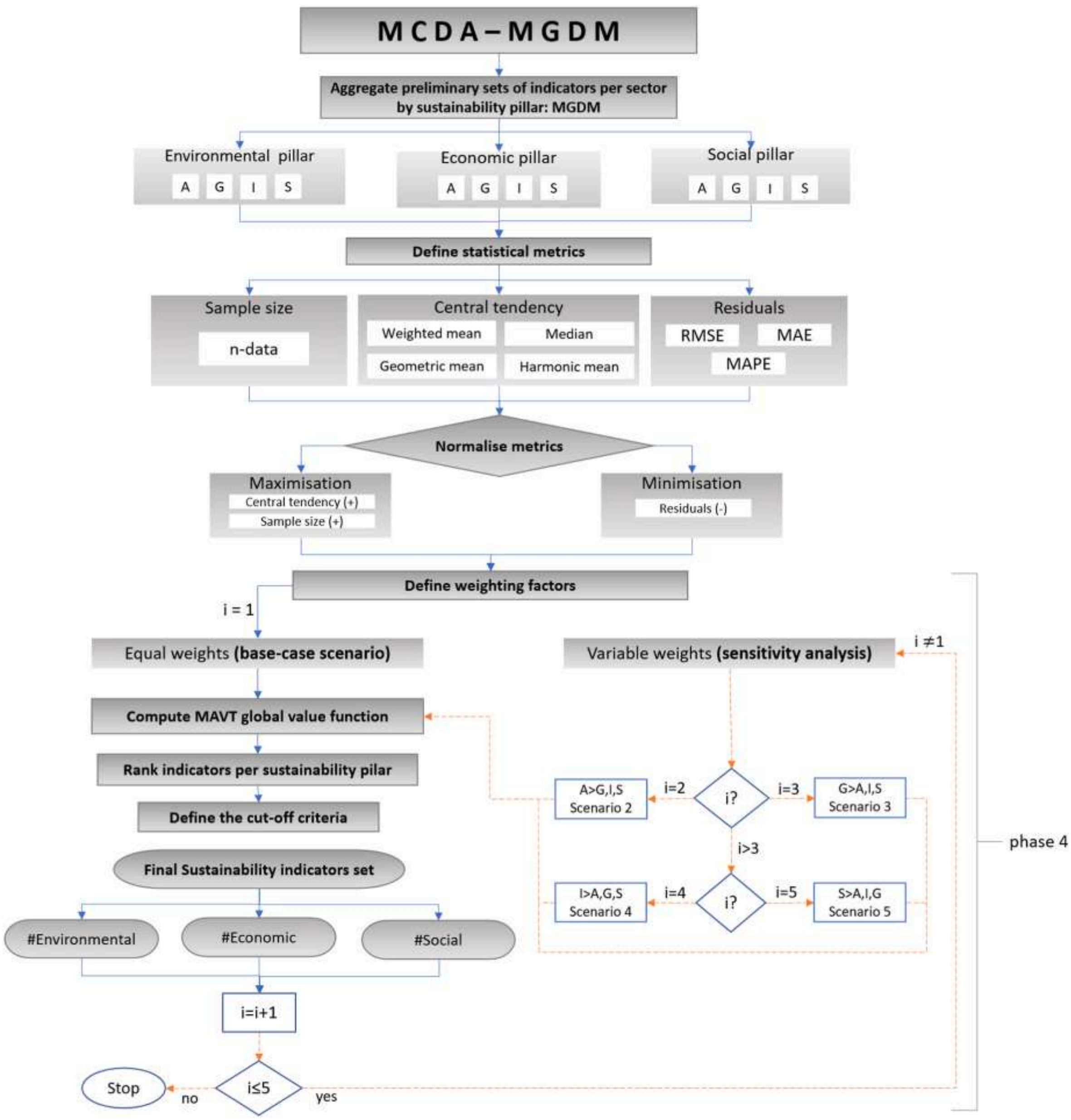


Fig. 5. Flow diagram of the numerical algorithm used by the MCDA-MGDM process to define a new set of GEOSI.

of GEOSI, the multi-attribute value theory (MAVT) method was used. MAVT provides a global value function for each indicator to calculate an overall score based on decision criteria, stakeholder "preference intensities" and weighting factors, where there are no uncertainties in the selected alternatives [70]. However, it is recognised that some inconsistencies, imprecision data and vagueness of human judgments may exist, which require to be analysed. In MAVT methods, the treatment of uncertainty is held by sensitivity analysis and/or stochastic distributions. Sensitivity analysis is considered as the most popular uncertainty handling technique for investigating the model response to different types of variation in the input information, raw data, technical parameters conveying preferences, and assumptions [70]. The goal of the MAVT was to build a deterministic additive model to correlate a normalised value of each variable to each option [71]. The highest value corresponds to the best ranked option [47,72]. The deterministic additive model was represented by Eq. (3), where the total value for any option is estimated from the weighted average value of all the criteria or attributes [70,73]:

$$V(SG) = \sum_{i=1}^{ns} w_i X_i^{'}\left(SG_{\{a,i,g,s\}}\right) \tag{3}$$

where $V(SG)$ is the normalised marginal value function for each indicator per stakeholder group (SG) in the attribute i [0, 10]; w_i is the weighting factor used by the metric and group; $X_i^{'}$ is the normalised data of criteria; and $SG_{\{a,i,g,s\}}$ are the cluster of indicators per stakeholder group (i.e., academia, industry, government, and society); and ns represents the effective number of surveyed per sector and per sustainability pillar.

BWT-14 To define the cut-off criteria for selecting the most representative indicators in the new set of GEOSI. Weighted statistical metrics were used either to avoid a bias selection or to minimise a subjective selection in the stakeholder responses. These criteria are based on the principle that the new indicators should be as condensed as possible without excluding the most important aspects evaluated in the ISAF-GET. To determine the optimised number of GEOSI, the **S**ustainability **I**mportance **I**ndex (*SII*) of the surveyed responses or scores was estimated using the equation of classification scale proposed by Saraswat and Digalwar [38]:

$$SII = \frac{\sum_{i=0}^{ns} W_i}{k \times ns} \tag{4}$$

where, ns is the effective number of surveyed per sector and per sustainability pillar, k is the maximum weight given to a single criterion ($k = 5$), and W_i is the weight given by the respondent to this criterion. The output results for this phase constitute the optimised ranking of the new GEOSI (selected), which were defined as the base-case scenario by assuming equal weighting factors (Fig. 5).

3.5. Phase 5: sensitivity analysis

The sensitivity analysis was used as a suitable technique to evaluate the impact of independent variables on a dependent variable in a deterministic model. As a sustainability decision making typically requires multiple criteria, multiple stakeholders' groups, and opinions, hierarchical scenarios and metrics with different weighting criteria to provide a broad description of the problem, and to obtain an unbiassed ranking solution were proposed. To carry out the first part of the sensitivity analysis, different weighting factors were assigned to the stakeholders' responses to evaluate alternative hierarchical scenarios, and the corresponding effects on the final ranked selection of sustainability indicators (Fig. 5). With these purposes, the preliminary set of GEOSI obtained for the base-case scenario with equal weighting factors were used as initial input data. To create four additional hierarchical scenarios for evaluating their effects on the ranked selection of GEOSI, the following BWT were executed:

BWT-15 To assign different weighting factors to the stakeholders' opinions. Five different hierarchical scenarios were obtained to highlight the importance of each stakeholder group (i.e., A: academia, G: government, I: industry, and S: society). As a global result of the Phases 4 and 5 (Fig. 5), the following scenarios were defined to carry out the ranked selection of GEOSI:

(i) A = G = I = S, given by the assumption of equal weighting factors to the four stakeholder groups (i.e., equal importance of the opinions), which was considered as the base-case scenario based on representativeness and democracy [74];
(ii) A > I, G, S, which provides a higher weighting factor for the opinion of the academia;
(iii) G > A, I, S, which provides a higher weighting factor for the opinion of the government;
(iv) I > A, G, S, which provides a higher weighting factor for the opinion of the industry; and
(v) S > A, I, G, which provides a higher weighting factor to the opinion of the society.

BWT-16 To define the optimised set of GEOSI by performing a comparison among the results obtained from the five hierarchical scenarios.

BWT-17 To perform a second part of the sensitivity analysis to determine if some of the statistical metrics used by the MCDA-MGDM method have some influence on the ranking of GEOSI. The **S**ensitivity **I**ndex (*SI*), which accounts for the difference concerning the variation of a statistical metric by using a recursive numerical procedure suggested by Qian and Mahdi [75]:

$$SI(x) = \frac{x_{Max} - x_{Min}}{x_{Max}} \tag{5}$$

Based on each hierarchical scenario, the *SI* values were calculated and analysed by using the MAVT model (Eq. (3)) to obtain the ranking of GEOSI, considering *nm-1* statistical metrics. The output results of this analysis were interpreted as a consensus and optimised set of GEOSI. If the ranking of these indicators does not significantly change with the removal of one statistical metric from the total number of these parameters, it is confirmed that the neglected statistical metric does not have any effect on the optimised ranking of indicators.

3.6. Phase 6: description of the new geothermal sustainability indicators

To describe the optimised set of GEOSI for future application in LCA studies. Burgherr et al. [76] pointed out that a sustainability indicator should be described by considering the following aspects: (i) A quantitative basis, which enables that some statistical metrics may be measured (e.g., precision: reproducibility or repeatability; and accuracy); (ii) A functional basis, which means that the indicators should be relevant, comparable, and comprehensive; and (iii) A pragmatic basis, which aims to consider some manageability in sustainability aspects. The new GEOSI should consider all the aspects shown in Fig. S3 through the following BWT:

BWT-18 To provide a full description of the GEOSI using an information structure for each sustainability indicator, and to have a better understanding among stakeholders; and

BWT-19 To compare the new set of GEOSI with other indicators previously reported for different countries.

4. Results and discussion

The main outcomes obtained per methodological phase are briefly described in the following sections, and referred to Fig. 1:

4.1. Phase 1: systematic literature review

The systematic literature review based on Sustainability Assessment Frameworks (SAFs) was used to identify sustainability indicators of worldwide energy systems, which were compiled in Table 1. LCA studies conducted to evaluate sustainability impacts of GET were also compiled in Table 2. The goal of these two databases was to identify the main SAFs and sustainability indicators that have been proposed for the evaluation of energy systems.

4.1.1. SAFs for energy systems

After analysing the literature collected from 2010 to 2022, it was found that about 20 SAFs (including this study) have been reported to evaluate different energy systems. Table 1 presents a brief description of each SAFs in terms of the energy systems, the country where the indicators were implemented, the integrating methods used to select sustainability indicators, the number of indicators per sustainability pillar, and the literature sources. A schematic description of these frameworks is shown in the supplementary Figs. S4 A-D. Some of these SAFs were proposed for covering different power technologies or energy systems (Fig. S4-A). Among these RE technologies, GET stands out as the most frequent systems where the SAFs have been proposed.

According to Table 1, the American countries stand out with a 24% where Mexico is reporting the largest number of implementation studies, followed by the Asian (20%), European (12%), and Africa and Oceania (8% each); whereas 28% do not report the geographical location (Fig. S4-B). Among these studies, the life cycle approach was the most commonly integrating method used to select sustainability indicators with a preference of nearly 55% (Fig. S4-C), followed by the Participatory Development for Stakeholder Engagement (PDSE: 40%), the multi-criteria decision analysis (MCDA: 35%); the sensitivity analysis (20), and multi-group decision analysis (MGDA: 5%). The PDSE constitutes the second integrating method more used in the SAFs, where the following methods were simultaneously used: (i) the qualitative or semi-quantitative World Cafe and Delphi techniques recommended for a remote collaboration or communication among stakeholders [51,121]; (ii) the judgement of energy experts [27] or experts' consultation [29]; (iii) the face-to-face interviews [23]; and (iv) the PASUR [38], which

Table 1
Worldwide compilation of sustainability assessment frameworks based on integrating methods and indicators for different energy systems.

ID	Sustainability Assessment Framework	Energy technology	Country	Integrating methods					Indicators per sustainability category					References
				LCA	PDSE	Sensitivity	MCDA	MGDM	# Indicators	Environmental	Economic	Social	Other categories	
1	Energy indicators for sustainable development	◆RE[1] •Fossil energy[1]	NS	–	–	–	–	–	30	10	16	4	–	IAEA [21]
2	Non-combustion renewable technologies for electricity generation	◆RE: Solar PV, Wind, Hydro, and Geothermal	Australia	✓	–	–	–	–	7	4	2	2–4	–	Evans et al. [24]
3	Hydropower Sustainability Assessment Protocol (HSAP)	◆RE: Hydro	NS[2]	✓[3]	✓	–	–	–	24[4]	5	4	5	Technical: 5 Integrated: 5	IHA [31]; Tahseen and Carney [77]; Costa et al. [32]
			Indonesia						13	4	1	1	Technical: 4 Integrated: 3	Gama [78]
			Tajikistan						15	6	2	4	Risk management: 3	Xu et al. [79]
			Indonesia						11	6	1	2	Technical: 1 Integrated: 1	Teguh and Nisaa [80]
4	Sustainability indicators for several power generation systems	◆RE: Wind, Solar, Hydrothermal and Geothermal •Fossil energy: Coal and Natural gas Alternative energy: Nuclear and Fuel cells	NS	–	–	–	–	–	7	4	2	1	–	Onat and Bayar [33]
5	Sustainability Assessment of Geothermal Projects (GSAP)	◆RE: Geothermal	Iceland	✓[3]	✓	–	–	–	25	10	9	6	–	Shortall; Shortall et al. a-c [50–54]
			New Zealand	24	10	8	6	–						
			Kenya	32	12	9	13	–						
6	Standard basic indicators for RE projects and carbon credits (CO_2, CH_4 and N_2O)	◆RE: Biomass, Wind, Hydro, and Solar	NS	–	✓	–	–	–	12	4	4	4	–	Drupp [25]
7	Sustainability indicators for assessing nuclear power plants in UK	Alternative energy: Nuclear	UK	✓	✓	–	–	–	43	11	4[5]	19	Technical: 7[5]	Stamford and Azapagic [23]
8	Sustainability indicators for assessing some renewable energy technologies in UK, specifically for commercial offices	◆RE: Solar PV	UK	–	–	–	–	–	32	5	20	2	Technical: 5	Luong et al. [28]
9	Sustainability indicators for evaluating renewable energy systems	◆RE	NS	–	–	–	–	–	10	5	3	2	–	Liu [26]
10	Hierarchical assessment of global sustainability indicators for electric power plants in México	◆RE: Hydro, Geothermal, Wind, Thermal and PV Solar power plants •Fossil energy: Coal, Heavy oil, Natural gas Alternative energy: Nuclear	Mexico	✓	–	–	✓	–	12[4]	4	4	2	Institutional: 2	Roldán et al. [35]
11	Decision-support framework for evaluating the integrated sustainability assessment of the electricity sector for Mexico	◆RE: Wind, Solar, Hydro, Geothermal, Ocean and Biomass •Fossil energy: Coal, Gas oil	Mexico	✓	–	✓	✓	–	17	10	3	4	–	Santoyo-Castelazo and Azapagic [22]

(*continued on next page*)

Table 1 (*continued*)

ID	Sustainability Assessment Framework	Energy technology	Country	Integrating methods					Indicators per sustainability category					References
				LCA	PDSE	Sensitivity	MCDA	MGDM	# Indicators	Environmental	Economic	Social	Other categories	
		Alternative energy: Nuclear												
12	Integrated life cycle sustainability assessment of the electricity sector in Turkey	◆RE[1] •Fossil energy[1]	Turkey	✓	–	✓	✓	–	20	11	3	6	–	Atilgan y Azapagic [36]
13	Framework for Integrated Sustainability Assessment (FISA) for evaluating some power generation systems in Mexico	◆RE: Solar thermal •Fossil energy: Natural gas	Mexico	✓	✓	–	–	–	18	6	6	6	–	Rodríguez-Serrano et al. [29]
14	Sustainable development indicators for the assessment of electricity production in Egypt	◆RE[1] •Fossil energy[1]	Egypt	–	–	–	–	–	13	4	3	2	Technical: 4	Shaaban and Scheffran [37]
15	Sustainability indicators for the evaluation of Concentrated Solar Power (CSP) projects	◆RE: Solar concentration	Chile	–	–	–	✓	–	10	3	3	1	Technical: 3	Simsek et al. [30]
16	Sustainability indicators for evaluating renewable energy systems	◆RE: Solar PV, Wind Alternative energy: Fuel cells (phosphoric acid and solid oxide)	NS	–	✓	–	✓	–	14	2	3	2	Resources: 4; Technical: 3	Ghenai et al. [27]
17	Life cycle-based sustainability indicators for evaluating the electricity generation using alternative and renewable energy systems	◆RE Alternative energy	Brazil	✓	–	–	–	–	28	18	6	4	–	Lassio et al. [34]
18	Empirical sustainability indicators for the assessment of energy sources in India	◆RE: Hydro, Wind, Biomass, Solar and Geothermal •Fossil energy: Coal, Gas Alternative energy: Nuclear, Fuel cell	India	–	✓	–	–	–	26	4	7	4	Technical: 5; Political: 4; Flexibility: 2	Saraswat and Digalwar [38]
19	Extended methodology for multi-criteria decision-making process for the enhanced geothermal systems	◆RE: Geothermal (EGS)	NS	✓	–	✓	✓	–	28	6	6	2	Geological setting: 7 Technology: 7	Raos et al. [19]
20	Integrated sustainability assessment framework for geothermal energy technologies (ISAF-GET) for Mexico	◆RE: Geothermal	Mexico	✓	✓	✓	✓	✓	29	11	8	10	–	Solano-Olivares et al. **[This work]**

Notes: PDSE: Participatory Development Stakeholder Engagement; NS: Countries were not specified;[1]Inferred (authors did not specify the energy sources); [2]Sustainability protocol developed for general applications, and adopted by some countries; [3]Life cycle approach developed for only one or two life cycle stages; [4]Sustainability indicators originally referred as topics; [5]Techno-economic indicators individually grouped in this work as economic and technical indicators.

Table 2
Compilation of LCA and LCC studies reported in the literature between 2010 and 2022 for the sustainable evaluation of geothermal energy technologies.

ID	Author (Year) [Ref]	Sustainability Pillar	Country	Goal of the study	Functional Unit	LCA Scope	Geothermal Uses	Geothermal Power Plant Technology	Impact Categories (Indicators)
1	Arslan and Kose; Arslan et al.; Arslan and Yetik [81–83]	Economic	Turkey	(i) To develop a multiple feasibility study for a small-scale geothermal power plant combined with heating and balneological use through a cascade system; (ii) To determine the optimum plant design	Cost per unit electricity generation	Cradle to gate	Electricity	SFS, ORC-BC	CPP, CB, PP
2	Frick et al. [84]	Environmental	Germany	To develop a comparative analysis of environmental impacts for geothermal systems	1 kWh_e 1 MJ of heat	Cradle to grave	Heat and power	EGS-BC	CED, GWP AP, EP
3	Karlsdottír et al. [85]	Environmental	Iceland	To develop standardised factors for PE and CO_2 emissions for GPP to calculate PE and CO_2 factors for geothermal-based energy production	1 MWh_e	Cradle to gate	Heat and power	DFS-CHP	CED, GWP
4	Sullivan et al. [86]	Environmental	USA	To compare LCA results from four types of geothermal plants	1 kWh delivered to the grid	Cradle to grave	Electricity	EGS-Single BC EGS-Multiple-BC Single-BC Multiple-FS	CED*, GWP[1]
5	Gerber and Maréchal [87]	Environmental	Switzerland	To compare the environmental performance for a wide range of environmental impacts	NS	Cradle to grave	Heat and power	EGS-BC[1]	GWP, HH, ECQ, non-renewable resources
6	Lacirignola and Blanc [88]	Environmental	France	To evaluate the environmental impacts from EGS	1 kWh of net energy produced	Cradle to grave	Electricity	EGS-BC	HH, ECQ, GWP, resources, seismicity risk[2]
7	Sullivan et al. [89]	Environmental	United States of America	To estimate the GHG emissions and water consumption from geothermal power technologies	1 kWh	Cradle to gate	Electricity	EGS-Single-BC, Multiple-FS, Single-BC	GWP, WC
8	Sullivan and Wang [90]	Environmental	United States of America	To estimate the operational fossil energy consumption and GHG emissions of geothermal energy systems	1 kWh	Gate to gate	Electricity	FS, DS	GWP, fossil energy use
9	Bravi and Bassosi [91]	Environmental	Italy	To evaluate the environmental impact of selected geothermal power plants	1 MWh_e	Gate to gate	Electricity	SFS	GWP, AP, HTP
10	Lacirignola et al. [92]	Environmental	France	To obtain an estimate of the life cycle GHG emissions of EGS power plants	1 kWh_e delivered to the grid	Cradle to gate	Electricity	EGS-BC	GWP
11	Ruzzenenti et al. [93]	Environmental	Italy	To evaluate the environmental impact from the use of small-size, hybrid geothermal/solar ORC plant	NS	Cradle to gate	Heat and power	Micro CHP	GWP, AP, EP, CED
12	Buonocore et al. [94]	Environmental	Italy	To evaluate the environmental impacts of a geothermal power plant	1 kWh	Cradle to gate	Electricity	DS	GWP, ADP, AP, EP, HTP, LUP, POFP, ODP
13	Marchand et al. [95]	Environmental	France	To evaluate and compare a high temperature geothermal system and other technologies for the reduction of environmental impacts	1 kWh of the net energy produced	Cradle to grave	Electricity	SFS, DFS	GWP, WC, FEP, MEP, TEP, NLT, ETP, ADP, CED Non-renewable, CED Renewable, ALO, ULO, HTP-CE, HTP-NCE, AP
14	Martín-Gamboa et al. [96]	Environmental	Spain	To determine the life cycle environmental and energy performance of a heat generation in a closed-loop GHP system and a geothermal binary-cycle power plant	1 MWh	Cradle to gate	Heat and power	BC	ADP, GWP, ODP, POFP, AP, EP, CED

(continued on next page)

Table 2 (*continued*)

ID	Author (Year) [Ref]	Sustainability Pillar	Country	Goal of the study	Functional Unit	LCA Scope	Geothermal Uses	Geothermal Power Plant Technology	Impact Categories (Indicators)
15	Karlsdottír et al. [97]	Environmental	Iceland	To evaluate the material and energy demand to build and operate a GCHP plant, including the direct emission of gases, wastewater/heat.	1 kWh_e 1 MJ of heat	Cradle to gate	Heat and power	SFS-CHP DFS-CHP	Non-impact Category[3]
16	Treyer et al. [98]	Environmental	Switzerland	To quantify the environmental burdens during the complete life cycle of deep geothermal systems	1 kWh	Cradle to grave	Electricity	EGS	GWP, ODP, TAP, FEP, MEP, HTP, POCP, PMFP, TEPT, FAETP, MAETP, IRP, ALO, ULO, NLT, WD, MRDP, ADP Fossil
17	Atilgan and Azapagic [36]	Environmental	Turkey	To estimate the life cycle environmental impacts of electricity generation from renewable power systems	1 kWh	Cradle to grave	Electricity	FS	ADP elements and fossil, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, TETP.
18	Martínez-Corona et al. [99]	Environmental Economic[4]	New Zealand	To conduct a hybrid LCA for a Wairakei Geothermal Project by using two inventories: mass requirements and monetary capital.	1 kWh*	Cradle to grave	Electricity	ORC-BC	Environmental: GWP, CED fossil, FFDP, FETP, HTP, FAETP, metal depletion, NLT, PMFP and TAP Economic: MC, CC
19	Yu et al. [100]	Environmental	The Netherlands	To compare the environmental impacts of large-scale flash GE and small-scale binary GE systems	1 MWh_e	Cradle to grave Cradle to gate	Electricity	Large-scale FS Small-scale BC (Mini-Geo)	GWP; MAET; ADP Fossil; HTP; FAETP; AD; TETP; EP; POCP; ADP; ODP
20	Hanbury and Vasquez [101]	Environmental	United States of America	To evaluate the environmental impacts of geothermal energy	1 GJ	Cradle to grave	Electricity	BC	GWP, AP, ETP, HTP, FFDP
21	Lohse [102]	Environmental	Germany	To analyse the use of finite energy carriers and selected airborne emissions of a combined geothermal power plant	1 GWh	Cradle to grave	Heat and power	BC	GWP anthropogenic
22	Pratiwi et al. [103]	Environmental	France	To quantify the GHG emissions of a combined geothermal plant	1 kWh_e 1 kWh_{th}	Cradle to grave	Heat and power	EGS	GWP
23	Parisi et al. [104]; Ferrara et al. [105]	Environmental	Italy	To assess the environmental impacts of deep geothermal energy for electricity production	1 MWh_e	Gate to gate	Electricity	FS[1]	AP, GWP, FETP, HTP-CE, HTP-NCE, PMFP, POCP, TEP
24	Paulillo et al. [106]	Environmental	Iceland	(i) To identify major hotspots in the life cycle and to evaluate the geothermal energy potential to decarbonise the heat and power generation industry	303 MJ_e 133 MJ_{th},	Cradle to grave	Heat and power	CHP-DFS	AP; GWP; FAETP; FEP; HTP-CE; HTP-NCE; PMFP; POFP; Resource depletion, MFRD
25	Tian and You [107]	Environmental	USA	To assess the life cycle environmental impacts of optimal geothermal power plants	1 kWh of heat generated	**NS**	Heat and power	NS	GWP
26	Basosi et al. [108]	Environmental	Italy	To compare the environmental performances of three power plants based on geothermal, solar, and wind energy resources	1 kWh	Gate to gate	Electricity	FS	ECQ, HH, Resources, WC, TETP, TAP, ODP, POFP, Mineral resource scarcity, MAETP, LU, IRP, HTP-CE, HTP-NCE, GWP, FEP, FAETP, Fossil resource scarcity, PMFP
27	Karlsdottír et al. [109]	Environmental	Iceland	To evaluate the environmental impacts of a geothermal power plant using double flashing technology	1 kWh	Cradle to gate	Heat and power	CHP-DFS	ADP, ADP fossil, GWP, ODP, HTP, FAETP, MAETP, TETP, POCP, CED
28	Paulillo et al. [110]	Environmental	United Kingdom	To evaluate major environmental impacts for electricity production at a UDDGP plant and compare with other energy sources	1 kWh_e	Cradle to grave	Electricity	EGS-BC	GWP, FAET, HTP-CE, HTP-NCE, PMFP, POFP

(continued on next page)

Table 2 (*continued*)

ID	Author (Year) [Ref]	Sustainability Pillar	Country	Goal of the study	Functional Unit	LCA Scope	Geothermal Uses	Geothermal Power Plant Technology	Impact Categories (Indicators)
29	Tosti et al. [111]	Environmental	Italy	To assess the potential environmental impacts for electricity generation from geothermal power plants	1 kWh	Cradle to grave	Electricity	FS	AP, GWP, FAETP, FEP, HTP-CE, HTP-NCE, IRP, LU, MAETP, MFRD, ODP, PMFP, POFP, TEP, WD
30	Yilmaz [112]	Economic	Turkey	To analyse and optimize the LCC of a geothermal energy system used for hydrogen production based on thermodynamic and economic models	NS[5]	NS	Electricity	SFS-BC*	NPV, LAC, Nsbp, Ndbp, UEC
31	Wang et al. [113]	Environmental	China	To evaluate the environmental impacts of four GPGSs by using thermodynamic and LCA methods	1 kWh	Cradle to grave	Electricity	DFS, SFS, Single ORC, Combined Flash and ORC	AP, EP, GWP
32	Chaiyat et al. [114]	Environmental	Thailand	To evaluate the environmental impacts of a CCHP prototype	1 MWh	Cradle to grave	Cooling, heating, and power	**NS**	ODP, HTP, IRP, POFP, PMFP, GWP, TETP, TAP, ALO, ULO, NLT; MAETP; MEP; FEP; WD; FFDP; MRDP
33	Colucci et al. [115]	Environmental	Iceland	To evaluate and analyse the environmental performance of a geothermal power plant	1 MWh of exergy	Cradle to grave	Heat and power	CHP-DFS	ILCD 2011— GWP; AP; PMFP, HTP-CE; HTP-NCE; FAETP; POFP; others ReCiPe 2016 — MAETP; HTP-CE; TAP; FAETP; WC; PMF; TETP; HTP-NCE; Others CML-IA — AP; POFP; MAETP; HTP; FAETP; Others
34	Menberg et al. [116]	Environmental	Germany	To evaluate consistency and differences between LCA studies on BC power plants	1 kWh	Cradle to grave	Electricity	ORC-BC	GWP, non-renewable energy, AAP, AEP
35	Sigurjonsson et al. [117]	Environmental	Iceland, France	To explore the climate change impact of deep EGS projects, and the opportunities to mitigate greenhouse gas emissions.	1 kWh	Cradle to grave	Electricity	EGS	GWP
36	Cook et al. [118]	Economic: ELCC[6]	Iceland, France	To evaluate economic costs for geothermal power ventures	NS	Cradle to grave	Electricity	EGS	CoCo, EEOO, LCOE
37	Kjeld [119]	Environmental	Iceland	To evaluate the environmental impacts of geothermal energy projects and to identify opportunities for improvements	1 kWh	Cradle to grave	Electricity	SFS	GWP total, GWP biogenic, GWP fossil, GWP LULUC, HTP-CE, HTP-NCE, AP, FAETP, ADP, ODP, POFP, FEP, MEP, TEP
38	Maione et al. [120]	Environmental	Italy	To assess the environmental performance of a heating, cooling and electric energy grid from a geothermal energy system	Energy produced by a ORC system and delivered to the grid	Cradle to grave	Heat, power and cooling	NS ORC system	GWP, ODP, IRP, POFP, PMFP, TAP, AEP, FEP, MEP, TETP, FAETP, MAETP, HTP-CE, HTP-NCE, LUP, WC, FFDP, MRDP

Notes: [1] Inferred according to context information; [2] This impact category is not included in the common LCA impact evaluation methods; [3] No impact category was reported, but the distribution of resource and material use in different stages; [4] This is not a properly explicit LCC, but it can be considered as a partial one, because it needs to complete the half of LCC stages; [5] The electricity produced by the geothermal power plant was used for the liquefaction of hydrogen in the plant, then the system FU reported was 1 L H_2; [6] Environmental Life Cycle Costs: ELCC.

Acronyms: Geothermal Power Plants (GPP); Primary Energy (PE); Geothermal Combined Heat and Power (GCHP); Geothermal Energy (GE); Cost of power plants (CPP); Cost and benefits (CB); Payback Period (PP); Materials Costs (MC); Capital Costs (CC); Net Present Value (NPV), Levelized Annual Cost (LAC), Simple Payback Period (Nsbp), Discount Payback Period (Ndbp); Unit Energy Cost (UEC); Cost Components (CoCo); Environmental Externalities of Operation (EEOO); Levelized Cost of Energy (LCOE).

Acronyms for geothermal plant technology: Hydrothermal (HT); Combined Heat and Power (CHP); Flash Steam (FS); Single Flash Steam (SFS); Double Flash Steam (DFS); Binary Cycle (BC); Binary System (BS); Enhanced Geothermal System (EGS); Dry Steam (DS); Combined Cooling Heating and Power (CCHP);

Acronyms for environmental impacts: Warming Potential (GWP), Cumulative Energy Demand (CED), Acidification Potential (AP), Eutrophication Potential (EP), Human Toxicity Potential (HTP); Abiotic Depletion Potential (ADP); Ozone Layer Depletion Potential or Stratospheric Ozone Depletion (ODP); Photochemical Oxidant Formation Potential (POFP/POCP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Marine Aquatic Ecotoxicity Potential (MAETP), Terrestrial Ecotoxicity Potential (TETP); Terrestrial Acidification Potential (TAP), Freshwater Eutrophication Potential (FEP), Marine Eutrophication Potential (MEP); Particulate Matter

Formation Potential (PMFP), Ionising Radiation Potential (IRP), Aquatic Acidification Potential (AAP), Aquatic Eutrophication Potential (AEP), Land Use (LU), Mineral, Fossil and Renewable Resource Depletion (MFRD), Terrestrial Eutrophication (TEP); Water Depletion or Water Consumption (WC/WD); Agricultural Land Occupation (ALO), Urban Land Occupation (ULO); Natural land Transformation (NLT); Fossil Fuel depletion Potential (FFDP); Mineral Resources Depletion Potential (MRDP), Human Health (HH), Ecosystem Quality (ECQ).

was successfully used in this investigation.

Regarding the MCDA, it is the most commonly used method for ranking sustainability indicators without bias. It is very usual to group these indicators using the classical sustainability pillars (i.e., environmental, economic and social): Fig. S4-D. Nevertheless, exist some authors that group these indicators in complementary sustainability categories (e.g., technical: type of resources and geological settings; and governance: institutional and political).

Regarding the sustainability indicators which have been reported in previous SAFs (Fig. 6), the number of indicators has ranged from 7 to 48 indicators (Table 1), which have been allocated into the above-mentioned categories (Fig. S4-D). There is not a standard number of sustainability indicators because it may vary depending on the sustainability pillars or complementary categories, the energy sources, and the country where the resources are located.

Lassio et al. [34] considered a larger number of environmental indicators for evaluating RE and other energy sources in Brazil, in comparison with the economic and social indicators proposed by Luong et al. [28] and Stamford and Azapagic for UK [23]. Two SAFs were applied for assessing the sustainability of hydro and geothermal energy projects (HSAP: Hydropower Sustainability Assessment Protocol; and GSAP: Geothermal Sustainability Assessment Protocol: Fig. 6), including other case studies for GET.

As a summary, among the specific SAFs reported for geothermal case studies, sustainability perspectives have been proposed by Shortall et al. [50,51], Raos et al. [19], and the present study. Shortall et al. [50,51] reported the development of the GSAP for Iceland, which closely responds to the principles of the Bellagio STAMP [122], and the version of the HSAP [123]. GSAP was developed under a systematic and management-oriented approach, which was reported in detail by Shortall [50,51] and Shortall et al. [52–54]. Because the specific data depend on the energy source, and the institutional and local cultural features, the sustainability indicators may be only valid for the country for which were developed. Some interesting aspects of the GSAP includes: (i) the involvement of stakeholders for creating sustainability indicators; (ii) the compilation of environmental impacts from energy sources (Fig. S1); and (iii) the establishment of sustainability objectives for geothermal applications (Fig. S2). This framework has been also replicated in Kenya and New Zealand [54]. Although GSAP may be considered as the first SAF for geothermal projects, it should be carefully used in other countries because their indicators were specifically recommended for Iceland geothermal sites.

A second geothermal SAF was proposed by Raos et al. [19] which was based on a multi-criteria decision-making process. This framework was proposed for EGS projects using a weighted decision matrix. This methodology considered geological, technological, economic, and

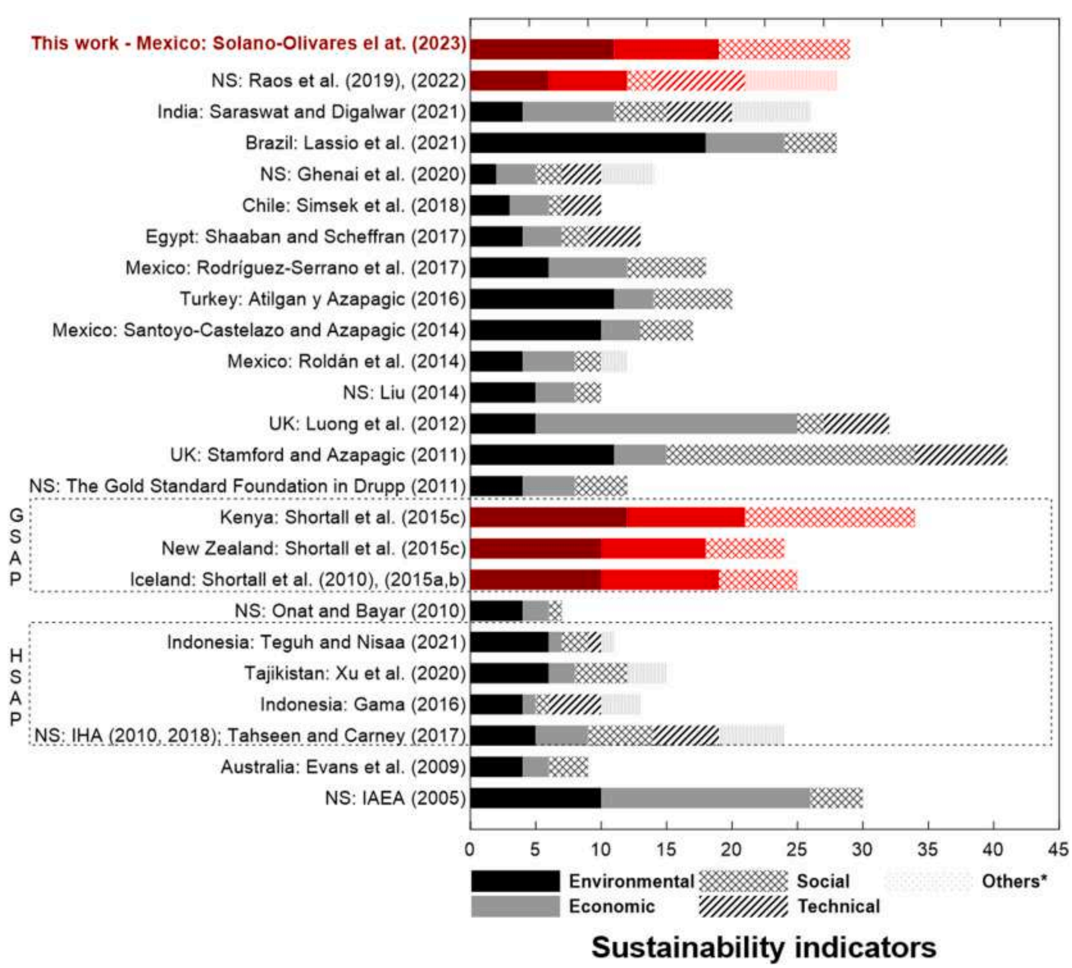


Fig. 6. Sustainability indicator frameworks proposed per category for different worldwide energy systems between 2010 and 2023. Red bars represent the GET studies.

environmental parameters to evaluate the electricity generation and heat production. The criteria considered for social concerns were limited to only two indicators (job creation and social acceptability), which may be limited due to the lack of representativeness regarding to other important social aspects, and the lack of consideration of the weighted opinion of stakeholders. Regarding these limitations, it is important to emphasise that a better sustainability scenario requires the full integration of the three sustainability pillars, including the input of stakeholders as a representative opinion from these pillars.

According to the systematic review on the two previous SAFs, it is evident the need to develop new innovated frameworks for other geothermal countries such as Mexico, where such efforts are either under development or simply do not exist. Reference methods and complete sustainability pillars are therefore needed to address future geothermal projects for other countries. To tackle these ambitious sustainability challenges, it is necessary to encourage the application of other transdisciplinary methodologies for achieving a holistic life-cycle perspective [39,40].

4.1.2. Life cycle sustainability assessment for GET

The life cycle sustainability assessment (LCSA) is the unweighted sum of the life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA), which are required for a better understanding of the interaction among environmental, economic, and social aspects. According to Li et al. [124], LCSA requires a further improvement in system boundaries, robust databases and environmental impact categories both to compare different case studies, and to obtain a better performance in the sustainability of products, processes and technologies. To address such a holistic perspective, suitable sustainability indicators are still needed for commercial geothermal projects.

4.1.2.1. LCA studies. According to the comprehensive literature review, Table 2 reports 38 LCA studies dealing with the evaluation of geothermal power plants and heat production technologies, which were published in the period 2010–2022. This compilation includes the LCA scopes, geothermal resource uses, geothermal countries, functional units, power plant or heating technologies, sustainability pillars, and impact categories. A summarized analysis of this literature is graphically presented in the supplementary Fig. S5 (A-F). From a LCSA perspective, LCA is the most commonly used methodology for the evaluation of negative environmental impacts of GET (90%) followed by LCC (10%): Fig. S5-A. Up to our knowledge, geothermal S-LCA studies have not been reported yet [118]. Social impacts have been scarcely evaluated in public acceptance or employment rate issues [124]. The world ranking of LCA studies reported per country on GET (n = 35 studies) is shown in Fig. S5-B, where Iceland and Italy are ranked in the first position with 6 articles published in peer review journals (19%); followed by France and USA with 5 publications (~14%); Germany with 3 articles (~9%), Switzerland with 2 papers (~6%), and China, New Zealand, Spain, Thailand, The Netherlands, United Kingdom and Turkey with only one study (~3%). The leadership of Iceland and Italy in LCA studies are indirectly explained due to high degree of development observed in commercial projects. Mexico, a country with an enormous geothermal potential, surprisingly does not appear in this compilation. The life cycle stages most commonly evaluated in geothermal LCA studies have been roughly classified as: (i) exploration and drilling; (ii) construction (transport pipes, geothermal power plant and machinery); (iii) operation and maintenance; and (iv) end-of-life (decommissioning) [16,124]. According to the literature review, the LCA scope/boundaries most frequently evaluated have been “cradle-to-grave” with 22 studies (~61%) followed by “cradle-to-gate” with 9 studies (~25%), “gate-to-gate” with 4 studies (~11%), and one study which does not specify the scope (~3%): Fig. S5-C. It is also important to remark that the end-of-life stage has not been evaluated in many studies.

In relation to the preferential uses of the geothermal energy, the main commercial applications rely on generation of electricity (60%), followed by combined heat and power (~34%), and combined cooling/heating and power (~6%): Fig. S5-D.

Regarding the generation of electricity, flash-steam (single- and double-flash) power plants have been the most evaluated technologies (42%), followed by binary cycle (29%), EGS (24%), and dry-steam (5%): Fig. S5-E. Other advanced energy conversion systems have not been evaluated yet (e.g., hybrid single- double- and triple-flash systems, hybrid flash-binary systems, hybrid solar-geothermal systems, hybrid fossil-geothermal systems, and hybrid back pressure system). With respect to the environmental impact categories evaluated in LCA studies, GWP stands out in 97% of the case studies, followed by AP (54%), EP and HTP (51%); and other categories such as ETP, ODP, POFP, ADP, CED and WC/WD vary between 43% and 23% (Fig. S5-F). These acronyms have been defined in the footnotes of Table 2, and are also included in the list of abbreviations as impact assessment categories.

4.1.2.2. LCC studies. Table 2 also present a few LCC case studies reported in the geothermal literature. Some economic aspects of GET have been evaluated in such studies, for example:

(i) Techno-economic reports for the selection of potential geothermal prospects for electricity generation and direct uses, and to obtain a better understanding of the interaction between economic and technical uncertainty [125,126];
(ii) Technical reports on the reduction of financial risks [125];
(iii) Reviews and improvements of concession laws for solving legal issues (e.g., land use regulation) [127]; and
(iv) Research collaborations among stakeholders for increasing the GET penetration and to prioritize financial incentives [128]; and levelized costs of electricity [129].

Some barriers have been aligned with these LCC studies, for example: (1) the costs of investment, operation, maintenance, and end-of-life; (2) the environmental externalities for operation; (3) the levelized cost of energy; (4) the net present value and payback period; and (5) the overall cost of power plants. Other LCC studies have been reported to evaluate projects on geothermal heat pumps [130–135], which were not included in this study. Although, the advances achieved in LCC, comprehensive economic assessments are still required to evaluate with accuracy the overall costs of GET for electricity generation and direct use applications.

4.1.2.3. S-LCA studies. These studies are either practically inexistent or ignored in the geothermal literature [118]. Although, the S-LCA for RE projects are gaining more attention in the last years because are crucial for a better planning and management of these technologies [136–140]. For the particular case of GET, no S-LCA approaches have been reported so far, which still represents a good opportunity to carry out such studies. The displacement of local people, land rights disputes, indigenous communities’ rights, loss of ecosystems, infrastructure, noise, and odours are social concerns that need to be addressed [141–143]. Some other social impacts of geothermal projects have been limited to qualitative descriptive aspects related to public acceptance [128,144–149]. Although, exist some trade-offs to be additionally considered such as employment and economic benefits for local population which should be considered in new commercial projects [127,143].

4.2. Phase 2: compilation of sustainability indicators

Based on the literature review, and a brainstorming technique, a preliminary set of 66 sustainability indicators was compiled (environmental: 25; economic: 17; and social: 24). These indicators are included in Table 3. From the brainstorming-method, three key indicators were

Table 3
Preliminary compilation of the sustainability indicators used in the present study.

Key	Environmental Indicator
A) Preliminary environmental indicators	
EN-01	Natural background gas emissions (measured in the early exploration stage of the geothermal system)
EN-02	Gas emissions produced by the operation of the geothermal energy technology (carbon footprint, CO_2, H_2S, GHG, radon, and others)
EN-03	Control of emission gases by technology (reduction or mitigation)
EN-04	Induced micro-seismicity
EN-05	Ozone depletion
EN-06	Solid particulate production
EN-07	Subsidence problems (ground subsidence)
EN-08	Impact to aquifers or natural water quality
EN-09	Water footprint
EN-10	Impact to land
EN-11	Agricultural land occupation
EN-12	Deforestation
EN-13	Land erosion or degradation
*	Pre-existing gas emissions from a geothermal system before the project starts (gas emission baseline)
EN-14	Solid waste generation
EN-15	Material recycling
EN-16	Fluid reinjection
EN-17	Thermal pollution
EN-18	Noise pollution (noise in the affected surrounding area, dB)
EN-19	Eutrophication (over-enrichment of nutrients in an aquatic ecosystem leading to algal blooms)
EN-20	Acidification [alteration of the chemical composition and loss of the neutralising capacity of soil and water due to the emission of acidic fluids (brine and gases) into the environment and atmosphere]
EN-21	Endangered species (fauna and flora)
EN-22	Impact to ecosystems (forests) and surrounding communities
EN-23	Odour pollution: Perception of unpleasant odour in the affected and surrounding area (ppm)
EN-24	Renewability of the geothermal resource
EN-25	Abiotic-resources depletion (fossil and mineral)
**	Solid waste management
B) Preliminary ECONOMIC indicators	
Key	**Economic Indicator**
EC-01	Gross Domestic Product (GDP)
EC-02	Internal Rate of Return (IRR)
EC-03	Investment for Research + Development + Innovation + Education
EC-04	Technical risks (supply chain, infrastructure, etc.)
EC-05	Exploration stage costs
EC-06	Infrastructure costs
EC-07	Transport costs
*	Economic growth in the country through all of assets, services and, investments value

Table 3 (*continued*)

Key	Environmental Indicator
A) Preliminary environmental indicators	
EC-08	Funds allocation for environmental protection
EC-09	Production (of the geothermal resource)
EC-10	End-uses
EC-11	Levelised energy costs
EC-12	Energy efficiency
EC-13	Exergo-economic studies
EC-14	Imports
EC-15	Strategic fuel stocks
EC-16	Direct and indirect jobs generated
EC-17	Land required for the project
**	Expenditure for waste and wastewater management, pollution mitigation, biodiversity and landscape protection, as well as for environmental protection-related research
C) Preliminary Social indicators	
Key	**Social Indicator**
SO-01	Salaries
SO-02	Housing costs
SO-03	Life expectancy
SO-04	Mortality rate
SO-05	Health (Human toxicity)
SO-06	Education and training
SO-07	Displacement or relocation of communities due to a commercial geothermal project
SO-08	Job creation
SO-09	Child labour
SO-10	Unemployment rate
SO-11	Workday
*	Economic income level of the population
SO-12	Social security
SO-13	Work-related incidents
SO-14	Occupational diseases
SO-15	Fatal occupational accidents
SO-16	Safety measures
SO-17	Respect for the preservation of cultural heritage (religion, language, customs, etc.)
SO-18	Access to the energy produced by the project
SO-19	Energy affordability (available and affordable energy for the consumer)
SO-20	Gender equity
SO-21	Legal aspects, corruption (violation of local regulations)
SO-22	Product transparency
SO-23	Acceptance of geothermal energy and its new uses
SO-24	Benefits to communities (socio-economic contributions and transport)
**	Social welfare (health, old-age pensions, disability, etc.)

NOTE: (*) and (**) means a control indicator (control question) for testing the reliability of answer respondents.

identified: (i) the analysis of the natural base-line emissions present in the early exploration of geothermal systems, where the control of these issues provides the opportunity to obtain a positive benefit for the geothermal projects and the communities that live surrounding these places; (ii) the consideration of the water footprint of the GET, which has been generally ignored in some previous studies; and (iii) the recycling of materials or installations which may be aligned with a future perspective of circular economy in the commercial projects. To properly manage all the 66 indicators, an alphanumeric code was assigned (i.e., EN-01 to EN-25: Environmental; EC-1 to EC-17: Economic; and SO-1 to SO-24: Social). Two control indicators for each pillar were considered to check the consistency of the survey responses.

4.3. Phase 3: participatory survey research

The preliminary set of 66 indicators was used as input data to carry out the PASUR. A questionnaire survey was designed for compiling the responses from different stakeholders [150]. A flow diagram describing the steps of the PASUR is shown in Fig. 7. The SurveyMonkey platform was used to design the questionnaire format and data analysis [151]. The platform of SurveyMonkey was justified as one of the top survey tools due to the simple and user-friendly interface [152]. Before to launch this survey, pilot tests were carried out with some potential participants for improving the survey efficiency.

The final structure of this survey is described in Fig. 7A, which is characterised by the following sections: (1) General presentation of the research project; (2) General description of the survey and precise instructions; (3) Registration and classification of the surveyed per sector (academia, government, industry and society); and (4) the exclusion logic module to consider the assessment of environmental, social and economic indicators using five options of the Likert scale (i.e., not relevant, neither irrelevant nor relevant, relevant, very relevant, and the response abstention): Fig. 7B. Flexibility features were also planned to consider the assessment of any indicator such as the conflict of interest, the lack of expertise, and the possibility to include new indicators in the preliminary set. The PASUR is completed by recording all the entries received, which were segregated by sustainability pillar, validated, and

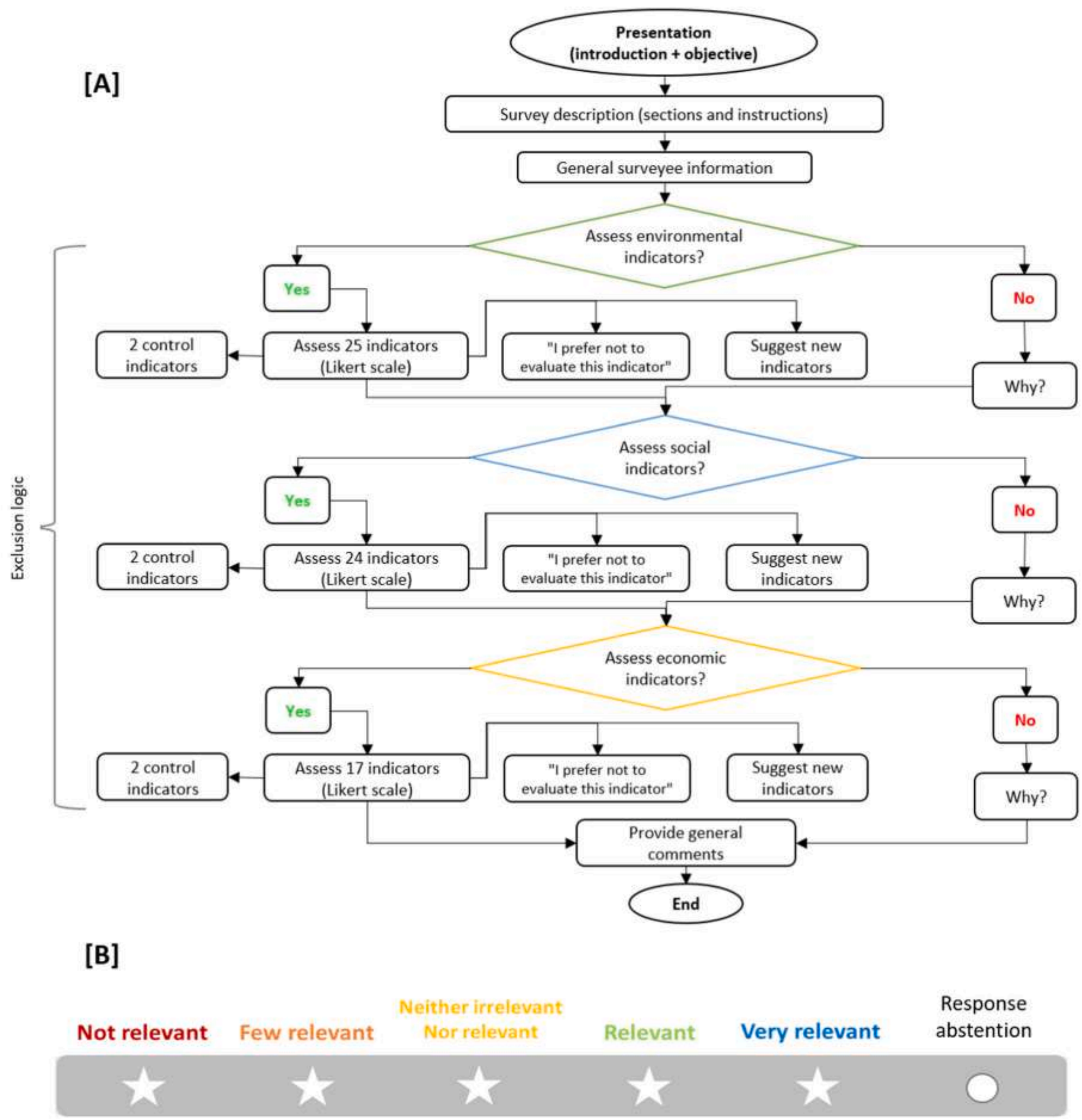


Fig. 7. Organised structure of the PASUR used for the selection of the GEOSI [A]; Likert-scale for the evaluation of the sustainability indicators [B].

analysed.

4.3.1. Basic descriptive statistics of the PASUR results

The PASUR was initially launched to statistical sample of 503 invited people, which covered different stakeholders from the academia, government, industry, and society. Representativeness, relevance and viability features were considered in these groups. The contact strategies of stakeholders used social media platforms to send the survey invitations (e.g., e-mail, LinkedIn, Facebook + Messenger, WhatsApp, and Chain referral sampling: Fig. S6-A); whereas the final effective participation accounted by sector is shown in Fig. S6-B. Institutional e-mail addresses (55%) and the chain referral sampling (30%) were the most effective communication tools used to link the academia (52%) and government (18%) sectors. LinkedIn (10%) was the professional network used to reach out the industrial sector (13%); whereas the popular social platforms of Facebook & Messenger (2%) and WhatsApp (3%) were used to link people from the social sector (16%). Important contributions to this survey came from several Mexican institutions linked with the use of geothermal resources. These sectors of stakeholders are schematically represented in the word cloud shown in the supplementary Fig. S7. A low-rate of responses was compiled with respect to the initial sample of stakeholders at the time period evaluated, which was considered as a hard-to-reach population. Rosenbaum and Lidz [153] pointed out that an effective compilation of surveyed responses typically vary from 20 to 30%. In the PASUR study, a sample of 27% of the surveyed was achieved by filling the questionnaires ($n = 136$ out of 503), which responded in an average time of 15 min. This percentage of participation was probably due to: (i) the lack of interest in the analysis of issues regarding sustainability and RE in the country; (ii) the lack of time to respond the survey; (iii) the difficulty to access any of the communication media; and (iv) the incorrect information to contact the stakeholders (e.g., wrong e-mail addresses).

To analyse the selection of indicators according to the stakeholder's preferences, the indicators were disaggregated and accounted for each sustainability pillar and per sector (Fig. S8). It was found that the academia had the highest participation in the three sustainability pillars with ~52% of the surveyed sample, followed by government (18%), society (16%) and industry (13%).

For the environmental indicators, the stakeholders' preferences of the academia varied up to a 51% of the final surveyed sample ($n = 136$, total number of effective respondents), whereas for the government, society and industry sectors, the preferences ranged up to 19%, 17%, and 13%, respectively. A similar percentage distribution was nearly observed for the economic and social indicators. Although these results may be affected by a bias towards the academia sector, such a possibility was rejected due to the application of the MCDA-MGDM methods which were used to confirm an unbiassed selection and optimised ranking of these new GEOSI (Table 3).

Some other parameters about the surveyed sample have been reported in the supplementary Fig. S9, which includes: (i) the age range of surveyed people which have the highest participation (33–37 years old: 21%), followed by neighbouring groups: 28–32 (13%) and 38–42 (11%) (Fig. S9-A). The lowest participation was found in extreme groups (i.e., 18–22 and >68 years old: 4% each); (ii) the gender participation where the men sample represented ~73% from the total, whereas the women were represented by a ~27% (Fig. S9-B); and (iii) the geographical region of the surveyed people, which mostly come from 8 regions (or 16 states) of the Mexican territory (Fig. S9-C). The highest participation of the surveyed come from the central region (CDMX: 41%), followed by the Centre and Gulf (34%) and the Western (10%) regions, where the latter one has enormous geothermal resources (Fig. S10).

4.4. Phase 4: optimised ranking and selection

After compiling the raw data results of the surveyed sample, the implementation of each indicator in the three pillars of sustainability was analysed by prioritising weighting factors. To eliminate the dependence of results on a single variable, statistical metrics were computed to carry out the unbiassed ranking of GEOSI using the MCDA-MGDM methods. Each statistical metric was calculated using the respondents' input raw data with their respective equations (Table S1).

After normalising the statistical metrics of each indicator (Eqs. (1) and (2)), and segregating the results per sector (i.e., A: academia, G: government, I: industry, and S: society), five different scenarios were analysed. A base-case scenario was defined by assigning equal weights to each surveyed sector, and applied for the unbiassed ranking of the GEOSI per pillar (i.e., EN: environmental, EC: economic, and SO: social). These numerical results per sustainability pillar are reported in Table 4 and Tables S2-A and S2-B of the supplementary material. The other four scenarios were created by weighting the importance of one particular sector over the three remaining sectors, and according to the numerical algorithm shown in Fig. 5. A complete version of these results may be obtained upon request to the authors. To define the cut-off criteria of GEOSI, the standardised responses obtained from the stakeholders were plotted in a radar graph where the importance of these indicators per sustainability pillar was represented (Fig. S11). As can be observed in this plot, the environmental indicators were systematically selected in four sectors (A, G, I, and S) as the most important sustainability pillar followed by social and economic indicators. The economic indicators were more relevant than social indicators only for the industry sector.

4.4.1. Cut-off criteria for reducing the number of GEOSI

To prioritize and reduce the number of GEOSI per pillar, the *SII* for each surveyed response was estimated by using Eq. (4). These *SII* values were analysed by studying the classification scale reported by Saraswat and Digalwar [38], which states that *SII* may range from 0.0 to 1.0. These values reveal the relative importance of variables used in the survey questionnaires. The *SII* values may be roughly classified into five categories to reflect the respondents' ratings:

1. Very important: $0.80 < \text{SII} \leq 1.00$
2. Important: $0.60 < \text{SII} \leq 0.80$
3. Preferred: $0.40 < \text{SII} \leq 0.60$
4. Less important: $0.20 < \text{SII} \leq 0.40$
5. Not important: $0.00 < \text{SII} \leq 0.20$

After using this classification scale, the *SII* were computed and reported in Table S3. From the analysis of these results and the preferential responses obtained from stakeholders (Fig. S11), it was inferred the most suitable cut-off criteria to define the optimum number of GEOSI (environmental, economic, and social). From these criteria, 36 GEOSI were selected (i.e., environmental: 11; economic: 9; and social: 16): Table 5. This total number of indicators is in good agreement with some the studies reported for the geothermal countries of Iceland (25), Kenya (32) and New Zealand (24) [54]. With respect to the life cycle impact assessment methods commonly used in LCSA studies, the well-known CML method considers between 10 and 12 environmental impact categories (i.e., ADP, GWP, ODP, HTP, FAETP, MAETP, TETP, POFP, AP, and EP), whereas for economic and social aspects, some previous works propose a limited number of economic (economic viability of geothermal power plants, comparison of renewable energies, geothermal economic impact, geothermal development risks, and policies) and social (public understanding, energy poverty, economic development-recruitment, health and safety, development of local substructure) indicators [55].

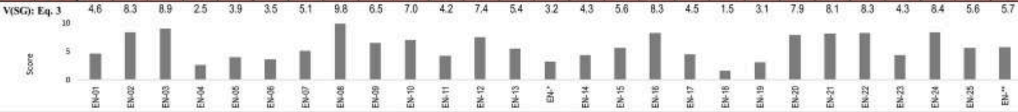
4.5. Phase 5: sensitivity analysis

As a result of first part of the sensitivity analysis, five hierarchical scenarios were created to highlight the importance of each stakeholder group after applying the algorithm shown in Fig. 5. A final ranking visualisation of the new GEOSI per sustainability pillar by considering

Table 4
Numerical results obtained for the ranking of environmental indicators from the MCDA — MGDM processes applied to the base-case scenario: assuming equal weights for the statistical metrics.

Group	ENVIRONMENTAL PILLAR Statistical metric	Optimisation	Weighting SMART Method	Weighting (%)	EN-01	EN-02	EN-03	EN-04	EN-05	EN-06	EN-07	EN-08	EN-09	EN-10	EN-11	EN-12	EN-13	EN-*	EN-14	EN-15	EN-16	EN-17	EN-18	EN-19	EN-20	EN-21	EN-22	EN-23	EN-24	EN-25	EN-**
ACADEMIA	n-data	↑	10	3.13	10.00	10.00	10.00	9.13	7.83	9.13	10.00	10.00	9.57	10.00	9.57	10.00	9.13	0.00	10.00	9.57	10.00	9.57	10.00	9.13	9.57	9.57	9.57	9.13	9.57	9.57	0.00
	Weighted mean	↑	10	3.13	1.74	8.04	8.18	0.00	3.52	2.74	3.42	10.00	7.98	5.66	2.87	6.08	4.90	2.37	4.12	5.43	8.18	3.87	0.06	4.04	7.13	7.56	7.13	3.03	7.42	3.30	5.73
	Geometric mean	↑	10	3.13	1.27	8.06	8.32	0.00	3.45	3.28	3.47	10.00	8.11	5.69	2.67	6.14	5.10	2.14	4.43	5.60	8.43	4.25	0.22	4.04	7.02	7.73	7.35	3.45	7.34	3.49	5.94
	Harmonic mean	↑	10	3.13	0.57	8.10	8.53	0.00	3.34	4.02	3.70	10.00	8.30	5.79	2.46	6.28	5.42	1.82	4.93	5.96	8.79	4.82	0.52	3.97	6.62	7.98	7.67	4.05	6.95	3.66	6.28
	Median	↑	10	3.13	0.00	10.00	10.00	0.00	0.00	0.00	0.00	10.00	10.00	10.00	0.00	10.00	0.00	0.00	0.00	10.00	10.00	0.00	0.00	0.00	10.00	10.00	10.00	0.00	10.00	0.00	5.00
	Root Mean Square Error (RMSE)	↓	10	3.13	0.88	7.86	8.53	0.00	3.11	3.75	3.16	10.00	8.18	5.40	2.24	5.90	5.12	1.79	4.54	5.40	8.95	4.52	0.22	3.81	6.76	7.89	7.62	3.75	7.26	3.53	5.94
	Mean Absolute Error (MAE)	↓	10	3.13	1.74	8.04	8.18	0.00	3.52	2.74	3.42	10.00	7.98	5.66	2.87	6.08	4.90	2.37	4.12	5.43	8.18	3.87	0.06	4.04	7.13	7.56	7.13	3.03	7.42	3.30	5.73
	Mean Absolute Percentage Error (MAPE)	↓	10	3.13	0.78	8.57	8.91	0.00	4.14	4.86	4.52	10.00	8.73	6.59	3.15	7.04	6.25	2.38	5.78	6.75	9.11	5.67	0.72	4.81	7.34	8.48	8.22	4.89	7.63	4.48	7.04
INDUSTRY	n-data	↑	10	3.13	10.00	10.00	10.00	0.00	0.00	0.00	10.00	10.00	0.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.00	10.00	10.00	10.00	10.00	10.00	0.00	10.00
	Weighted mean	↑	10	3.13	8.50	9.25	10.00	2.39	3.98	2.39	3.98	10.00	2.39	6.24	3.23	6.99	5.49	4.73	3.98	5.49	9.25	3.23	1.73	0.00	9.25	7.74	10.00	6.99	9.25	7.17	3.98
	Geometric mean	↑	10	3.13	7.71	8.65	10.00	3.64	3.44	2.41	3.19	9.37	2.00	5.66	2.84	5.90	4.32	3.96	3.96	5.29	9.27	2.31	1.37	0.00	9.43	7.55	10.00	7.17	9.27	5.89	3.47
	Harmonic mean	↑	10	3.13	5.98	8.18	10.00	4.78	2.54	2.01	2.20	8.81	1.41	4.45	2.12	4.26	2.88	2.79	4.16	4.35	9.33	1.39	0.93	0.00	9.59	7.45	10.00	7.33	9.33	4.06	2.54
	Median	↑	10	3.13	5.00	10.00	10.00	0.00	0.00	0.00	5.00	10.00	0.00	5.00	0.00	10.00	0.00	0.00	0.00	0.00	10.00	5.00	0.00	0.00	5.00	10.00	10.00	0.00	10.00	10.00	0.00
	Root Mean Square Error (RMSE)	↓	10	3.13	7.57	7.30	10.00	4.36	3.00	2.57	2.48	8.13	1.75	5.29	2.68	5.05	3.30	3.51	3.30	5.52	9.03	1.51	1.14	0.00	9.67	6.77	10.00	7.03	9.03	4.84	3.30
	Mean Absolute Error (MAE)	↓	10	3.13	8.50	9.25	10.00	2.39	3.98	2.39	3.98	10.00	2.39	6.24	3.23	6.99	5.49	4.73	3.98	5.49	9.25	3.23	1.73	0.00	9.25	7.74	10.00	6.99	9.25	7.17	3.98
	Mean Absolute Percentage Error (MAPE)	↓	10	3.13	6.76	8.63	10.00	5.62	3.22	2.60	2.83	9.12	1.87	5.29	2.73	5.09	3.62	3.52	4.99	5.19	9.51	1.85	1.26	0.00	9.71	8.04	10.00	7.94	9.51	4.89	3.22
GOVERNMENT	n-data	↑	10	3.13	8.33	10.00	10.00	8.33	8.33	8.33	9.17	9.17	8.33	9.17	10.00	10.00	9.17	0.00	10.00	10.00	9.17	9.17	10.00	8.33	8.33	10.00	10.00	9.17	9.17	10.00	0.83
	Weighted mean	↑	10	3.13	2.75	8.34	9.38	3.50	4.64	4.26	5.66	10.00	6.90	6.38	4.52	6.25	5.30	5.13	3.13	5.21	7.11	4.21	0.00	4.26	6.15	6.25	5.90	3.85	7.11	5.21	6.85
	Geometric mean	↑	10	3.13	1.96	8.16	9.50	3.24	4.59	3.86	5.57	10.00	6.63	6.37	4.31	6.02	5.09	5.15	2.80	5.05	7.20	3.94	0.00	3.38	6.06	5.77	5.56	3.41	6.93	4.89	7.15
	Harmonic mean	↑	10	3.13	0.44	7.83	9.65	2.89	4.47	3.27	5.38	10.00	6.24	6.35	3.96	5.69	4.80	5.18	2.35	4.72	7.28	3.55	0.00	1.67	5.86	5.11	5.03	2.82	6.62	4.41	7.46
	Median	↑	10	3.13	5.00	10.00	10.00	0.00	0.00	0.00	5.00	10.00	0.00	5.00	0.00	10.00	0.00	0.00	0.00	0.00	10.00	5.00	0.00	0.00	5.00	10.00	10.00	0.00	10.00	10.00	0.00
	Root Mean Square Error (RMSE)	↓	10	3.13	1.74	7.63	10.00	2.81	4.48	3.39	5.35	9.90	5.88	6.07	3.99	5.38	4.53	4.93	2.39	4.89	7.27	3.48	0.00	2.81	5.88	4.74	4.89	2.79	6.45	4.28	8.02
	Mean Absolute Error (MAE)	↓	10	3.13	2.75	8.34	9.38	3.50	4.64	4.26	5.66	10.00	6.90	6.38	4.52	6.25	5.30	5.13	3.13	5.21	7.11	4.21	0.00	4.26	6.15	6.25	5.90	3.85	7.11	5.21	6.85
	Mean Absolute Percentage Error (MAPE)	↓	10	3.13	0.61	8.35	9.75	3.64	5.32	4.06	6.21	10.00	7.00	7.10	4.80	6.50	5.65	6.02	3.02	5.57	7.91	4.36	0.00	2.21	6.66	5.96	5.88	3.55	7.34	5.26	8.05
SOCIETY	n-data	↑	10	3.13	9.33	10.00	10.00	8.67	9.33	8.67	10.00	10.00	9.33	10.00	10.00	10.00	10.00	0.00	10.00	10.00	9.33	10.00	9.33	8.00	9.33	10.00	10.00	10.00	10.00	10.00	0.67
	Weighted mean	↑	10	3.13	4.66	6.11	6.11	1.22	4.66	3.67	5.56	10.00	9.89	7.78	5.00	8.33	6.67	3.49	3.89	5.00	5.82	3.89	0.00	3.86	8.15	9.44	7.78	2.22	8.33	5.56	9.17
	Geometric mean	↑	10	3.13	4.51	6.32	6.18	1.79	4.91	3.77	5.84	10.00	9.90	7.80	5.22	8.31	6.41	2.63	3.39	4.32	5.77	3.63	0.00	3.62	8.28	9.18	7.80	2.41	8.16	5.70	9.22
	Harmonic mean	↑	10	3.13	4.27	6.55	6.27	2.41	5.20	3.95	6.14	10.00	9.91	7.83	5.47	8.28	6.00	1.61	2.77	3.47	5.75	3.35	0.00	3.33	8.43	8.89	7.83	2.54	7.98	5.87	9.28
	Median	↑	10	3.13	10.00	10.00	10.00	0.00	0.00	5.00	5.00	10.00	10.00	10.00	5.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.00	10.00	10.00	10.00	10.00	0.00	10.00	10.00	10.00
	Root Mean Square Error (RMSE)	↓	10	3.13	3.87	6.34	5.74	2.38	4.95	3.35	6.03	10.00	9.89	7.35	5.17	7.72	5.45	1.17	2.29	2.72	4.95	2.72	0.00	2.80	8.39	7.72	7.35	2.51	7.00	5.45	9.21
	Mean Absolute Error (MAE)	↓	10	3.13	4.66	6.11	6.11	1.22	4.66	3.67	5.56	10.00	9.89	7.78	5.00	8.33	6.67	3.49	3.89	5.00	5.82	3.89	0.00	3.86	8.15	9.44	7.78	2.22	8.33	5.56	9.17
	Mean Absolute Percentage Error (MAPE)	↓	10	3.13	4.90	7.09	6.84	2.90	5.82	4.57	6.71	10.00	9.93	8.23	6.08	8.61	6.59	1.99	3.30	4.06	6.35	3.94	0.00	3.91	8.74	9.12	8.23	3.05	8.36	6.46	9.43
			V(SG): Eq. 3		4.6	8.3	8.9	2.5	3.9	3.5	5.1	9.8	6.5	7.0	4.2	7.4	5.4	3.2	4.3	5.6	8.3	4.5	1.5	3.1	7.9	8.1	8.3	4.3	8.4	5.6	5.7

Indicator scoring



five case scenarios is reported in Table 6. As can be observed, the ranking and selection results of environmental, economic and social indicators obtained for the base-case scenario are nearly similar to those results provided by most of the other four scenarios.

The unique exception was the scenario 3, which exhibited minor changes regarding some environmental (EN-09: Water footprint) and economic (EC-13: Exergoeconomic) indicators. It was also observed that the environmental (EN-08: Impact to aquifers or natural water quality; and EN-03: Emission gases control), economic (EC-12: Energy efficiency; and EC-03: RDI-E), and social (SO-16: Safety measures; and SO-08: Job creation) indicators were systematically ranked in the top positions. As the results of the base-case scenario were almost systematic, it was considered as the most representative scenario for selecting and ranking the new GEOSI.

The second part of the sensitivity analysis was carried out to evaluate if some measurable variables or statistical metrics ($nm = 8$, total number of metrics) used by the MCDA-MGDM method have an influence on the final selection and ranking of GEOSI. The MCDA-MGDM method was recursively applied to all the survey responses (sustainability pillars and stakeholder' sectors: A, G, I, and S) using nm-1 statistical metrics (i.e., by neglecting one from the total number of metrics, nm), and by calculating the SI (Eq. (5)). As the average values of SI were steadily less than 0.11, it was concluded that the overall selection and ranking process was not affected by these assumptions (Table S4 A-C). These sensitivity results are in good agreement with the PROMETHEE analysis suggested by Macharis et al. [154].

4.6. Phase 6: description of sustainability indicators

A full description of the 36 GEOSI obtained from the ISAF-GET is shown in Table S5. This new set of indicators fully addresses the main environmental, economic and social issues and barriers that are currently facing not only in the Mexican geothermal industry but also the worldwide deployment of geothermal projects for electricity generation and other direct uses. Notwithstanding, it is important to remark that the application of these indicators in future LCSA studies will demand the creation of sustainability databases with private-confidential information which are sometimes difficult to access. An urgent task both to create such databases and to recommend their use for a better sustainable development of the RE technologies is required [155].

4.7. Comparison of GEOSI developed for Mexico from the ISAF-GET with other geothermal sustainability frameworks

According to the literature review, several sets of GEOSI were proposed for Iceland, New Zealand, and Kenya in projects of electricity generation and direct uses (Table S6). These indicators were compared with those selected for Mexico. Technical, production, economic, and social (cultural) aspects were considered to satisfy specific sustainability needs in these countries [50–54].

Most of these frameworks were developed within the GSAP methodology proposed by Shortall [50,51] and Shortall et al. [52–54], excepting the review reported by Soltani et al. [55], and the present study which was developed from the new ISAF-GET. Several differences arise from the chemical quality of the geothermal resources and the type of geological settings where the geothermal systems are located. It was observed that ~56% of the new GEOSI proposed for Mexico are in good agreement with those indicators recommended for Iceland, New Zealand and Kenya [54].

By considering a globalized sustainability perspective reported by Shortall et al. [54] and Soltani et al. [55], a good agreement of nearly 75% was also observed. The social pillar shows the highest number of coincidences in the selected GEOSI (13 out of 16: 81%), followed by the environmental (8 out of 11: 73%), and economic (5 out of 9: 56%) pillars. In spite of the differences observed in the economic development and cultural factors of each country, the selection results show a certain level of cross-cutting impact among the sustainability frameworks (GSAP, ISAF-GET, and the review proposed by Soltani et al. [55]). The remaining sustainability indicators of the ISAF-GET which did not overlap with the existing sets (~25%) are attributed either to local environmental, economic and social issues demanded by projects in each country or the type of geothermal systems that are being exploited.

Concerning the number of indicators selected from the ISAF-GET for Mexico also exists a good agreement with respect to those adopted in the

Table 5
Ranking of the GEOSI by considering the base-case scenario and the MCDA scores: *V(SG)* and *SII*. Score V(SG) – Eq. (3): MCDA-MGDM computing.

Environmental indicators			
Ranking	Code	V(SG)	SII
1	EN-08	9.83	0.98
2	EN-03	8.92	0.89
3	EN-24	8.38	0.84
4	EN-02	8.35	0.84
5	EN-22	8.27	0.83
6	EN-16	8.25	0.83
7	EN-21	8.12	0.81
8	EN-20	7.91	0.79
9	EN-12	7.42	0.74
10	EN-10	6.95	0.70
11	EN-09	6.48	0.65
NA	EN-**	5.73	0.57
12	EN-15	5.65	0.56
13	EN-25	5.60	0.56
14	EN-13	5.42	0.54
15	EN-07	5.13	0.51
16	EN-01	4.59	0.46
17	EN-17	4.51	0.45
18	EN-23	4.35	0.43
19	EN-14	4.33	0.43
20	EN-11	4.24	0.42
21	EN-05	3.91	0.39
22	EN-06	3.53	0.35
NA	EN-*	3.19	0.32
23	EN-19	3.13	0.31
24	EN-04	2.53	0.25
25	EN-18	1.54	0.15

Economic indicators			
Ranking	Code	V(SG)	SII
1	EC-12	9.30	0.93
2	EC-03	8.95	0.90
3	EC-09	8.88	0.89
4	EC-11	8.77	0.88
5	EC-08	8.29	0.83
6	EC-16	7.37	0.74
NA	EC-**	6.91	0.69
7	EC-02	6.60	0.66
8	EC-10	6.36	0.64
9	EC-13	6.07	0.61
10	EC-17	5.84	0.58
11	EC-06	5.77	0.58
NA	EC-*	5.20	0.52
12	EC-04	4.39	0.44
13	EC-05	4.32	0.43
14	EC-07	3.87	0.39
15	EC-15	2.78	0.28
16	EC-01	2.34	0.23
17	EC-14	1.81	0.18

Social indicators			
Ranking	Code	V(SG)	SII
1	SO-16	9.01	0.90
2	SO-08	8.36	0.84
3	SO-24	8.27	0.83
4	SO-21	8.13	0.81
5	SO-06	8.11	0.81
6	SO-23	7.99	0.80
7	SO-14	7.81	0.78
8	SO-13	7.67	0.77
9	SO-15	7.52	0.75
10	SO-05	7.50	0.75
11	SO-18	7.46	0.75
12	SO-19	7.41	0.74
13	SO-07	6.95	0.70
14	SO-12	6.92	0.69
15	SO-22	6.88	0.69
NA	SO-**	6.44	0.64
16	SO-20	6.08	0.61
NA	SO-*	5.61	0.56
17	SO-01	5.08	0.51
18	SO-17	5.01	0.50
19	SO-03	4.93	0.49
20	SO-10	4.75	0.47
21	SO-11	4.53	0.45
22	SO-04	3.42	0.34
23	SO-02	2.66	0.27
24	SO-09	2.34	0.23

same countries. This distribution can be schematically visualized in Fig. S12. The environmental pillar of previous geothermal projects has been typically analysed by up to 12 indicators, whereas the economic pillar varies between 8 and 9. It is also important to highlight that developed countries (Iceland and New Zealand) have considered only 6 social indicators, whereas developing countries (such as Kenya and Mexico) have put greater emphasis on this pillar by considering a larger number of social indicators (13 and 16, respectively). This trend is expected for Mexico because it currently faces social barriers to increase not only the installed geothermal capacity but also some other RE technologies [156]. Although the participation rate of stakeholders surveyed in the ISAF-GET was relatively low ($n = 136/503$ respondents: 27%), the total number of effective participants was significantly higher than those participations reported for other countries (Table S7). The commitment of geothermal projects with society by involving local communities should be better considered as a persistent issue of shared concern. It is therefore crucial both to address these issues, and to develop timely and suitable strategies for a larger participation of stakeholders in pursuit of optimal sustainable solutions not only for Mexico but also for other countries. It is essential to recognize that engaging with stakeholders balanced from different geographic regions still represents a big challenge to be achieved for the future [157].

4.8. Relevant sustainability barriers of Mexican geothermal projects and government policies to face out these obstacles

According to the Geothermal Technological Roadmap of Mexico [158], the geothermal industry faces the following barriers that are currently affecting its development:

4.8.1. Regulatory

The land use and the water concessions appear as main obstacles to carry out new commercial projects either for electricity generation or direct uses. Legal authorisation mechanisms are needed to unlock these projects, which may be solved by applying the new Law for Geothermal Energy proposed in Mexico [159].

4.8.2. Economic

The high initial investment costs for the projects constitute one of the big issues of the geothermal industry. New economic and financial incentives are required both to boost GET and to promote simultaneously the viability of direct use projects among other industries.

4.8.3. Social

The acceptance of the geothermal projects by the surrounding communities represents one of the main barriers that exist in Mexico, which is related to the concern of a possible damage to local natural resources and ecosystems. These obstacles should be addressed from various solutions: (i) the reduction/mitigation of the surface emissions

Table 6
Final ranking and visualisation of the GEOSI by considering five different case scenarios.

Environmental indicators				
Scenario-1	Scenario-2	Scenario-3	Scenario-4	Scenario-5
A=I=G=S	A > I, G, S	I > A, G, S	G > A, I, S	S > A, I, G
EN-08	EN-08	EN-08	EN-08	EN-08
EN-03	EN-03	EN-03	EN-03	EN-03
EN-24	EN-02	EN-22	EN-02	EN-24
EN-02	EN-16	EN-24	EN-24	EN-21
EN-22	EN-24	EN-16	EN-16	EN-22
EN-16	EN-22	EN-02	EN-22	EN-02
EN-21	EN-21	EN-21	EN-21	EN-20
EN-20	EN-20	EN-20	EN-20	EN-16
EN-12	EN-12	EN-12	EN-12	EN-12
EN-10	EN-10	EN-10	EN-10	EN-10
EN-09	EN-09	**EN-25**	EN-09	EN-09
EN-**	EN-15	EN-15	EN-**	EN-**
EN-15	EN-**	**EN-09**	EN-25	EN-25
EN-25	EN-13	EN-**	EN-15	EN-13
EN-13	EN-25	EN-13	EN-13	EN-15
EN-07	EN-07	EN-01	EN-07	EN-07
EN-01	EN-17	EN-07	EN-17	EN-01
EN-17	EN-14	EN-23	EN-11	EN-17
EN-23	EN-23	EN-14	EN-01	EN-11
EN-14	EN-01	EN-17	EN-23	EN-14
EN-11	EN-11	EN-11	EN-14	EN-05
EN-05	EN-05	EN-05	EN-05	EN-23
EN-06	EN-06	EN-*	EN-06	EN-06
EN-*	EN-19	EN-06	EN-*	EN-19
EN-19	EN-*	EN-04	EN-19	EN-*
EN-04	EN-04	EN-19	EN-04	EN-04
EN-18	EN-18	EN-18	EN-18	EN-18

Economic indicators				
Scenario-1	Scenario-2	Scenario-3	Scenario-4	Scenario-5
A=I=G=S	A > I, G, S	I > A, G, S	G > A, I, S	S > A, I, G
EC-12	EC-12	EC-09	EC-12	EC-12
EC-03	EC-03	EC-12	EC-03	EC-03
EC-09	EC-09	EC-11	EC-09	EC-11
EC-11	EC-11	EC-03	EC-08	EC-09
EC-08	EC-08	EC-08	EC-11	EC-08
EC-16	EC-16	EC-16	EC-16	EC-16
EC-**	EC-**	EC-10	EC-02	EC-**
EC-02	EC-02	EC-**	EC-**	EC-02
EC-10	EC-13	EC-02	EC-13	EC-10
EC-13	EC-10	**EC-17**	EC-10	EC-13
EC-17	EC-06	EC-06	EC-17	EC-17
EC-06	EC-17	**EC-13**	EC-*	EC-06
EC-*	EC-*	EC-*	EC-06	EC-*
EC-04	EC-04	EC-05	EC-04	EC-04
EC-05	EC-05	EC-04	EC-05	EC-05
EC-07	EC-07	EC-07	EC-07	EC-07
EC-15	EC-15	EC-15	EC-15	EC-15
EC-01	EC-01	EC-01	EC-01	EC-01
EC-14	EC-14	EC-14	EC-14	EC-14

Social indicators				
Scenario-1	Scenario-2	Scenario-3	Scenario-4	Scenario-5
A=I=G=S	A > I, G, S	I > A, G, S	G > A, I, S	S > A, I, G
SO-16	SO-16	SO-16	SO-16	SO-16
SO-08	SO-08	SO-08	SO-24	SO-06
SO-24	SO-24	SO-21	SO-08	SO-08
SO-21	SO-06	SO-23	SO-21	SO-24
SO-06	SO-21	SO-06	SO-23	SO-21
SO-23	SO-23	SO-24	SO-06	SO-13
SO-14	SO-14	SO-14	SO-18	SO-23
SO-13	SO-13	SO-15	SO-19	SO-14
SO-15	SO-18	SO-13	SO-14	SO-05
SO-05	SO-05	SO-05	SO-05	SO-15
SO-18	SO-19	SO-22	SO-15	SO-18
SO-19	SO-15	SO-18	SO-13	SO-19
SO-07	SO-07	SO-19	SO-12	SO-**
SO-12	SO-12	SO-12	SO-22	SO-07
SO-22	SO-22	SO-07	SO-07	SO-12
SO-**	SO-20	SO-**	SO-**	SO-22
SO-20	SO-**	SO-20	SO-20	SO-20
SO-*	SO-*	SO-*	SO-17	SO-*
SO-01	SO-01	SO-01	SO-*	SO-03
SO-17	SO-17	SO-17	SO-01	SO-01
SO-03	SO-03	SO-03	SO-03	SO-10
SO-10	SO-10	SO-10	SO-10	SO-17
SO-11	SO-11	SO-11	SO-11	SO-11
SO-04	SO-04	SO-04	SO-04	SO-04
SO-02	SO-02	SO-02	SO-09	SO-09
SO-09	SO-09	SO-09	SO-02	SO-02

produced by the geothermal systems in their natural state by quantifying and controlling the baseline emissions; and (ii) the access of more complete information of these projects to the communities with the goal to provide better benefits through a win-win scenario.

4.8.4. Environmental

The global impact of emissions caused by the exploitation of the geothermal resources through all the life cycle stages of their projects (i.e., early exploration, material extraction, construction, maintenance, operation, and the end-of-life). LCA studies require to be established as essential tools for geothermal projects to identify and control their major hotspots. The key results of these studies will be useful to differentiate the environmental impacts caused either by power plant emissions (i.e., negative impacts) or by natural gas baseline emissions (perceived as positive externalities), which may be controlled with the installation of sustainable geothermal plants.

4.8.5. Mexican government policies

To mitigate some barriers, energy/environmental policies have been adopted by the Mexican government. Since the Energy Reform proposed in 2013, Mexico has been one of the few countries that has established an appropriate regulatory framework for supporting the commercial geothermal projects. Among the supporting instruments of this regulation stand out the Geothermal Technology Road Map [158] and the creation of the Law for Geothermal Energy [159].

The government bodies have also modified an accompanying regulation to promote renewable energy at national scale by including: (i) the Law for Energy Transition [160]; and (ii) the General Law for Climate Change [161]. These regulation instruments intrinsically consider the promotion of non-only the deployment of geothermal projects but also the use of RE as climate change mitigation measures. To update these policy instruments, additional recommendations may emerge from this study to promote among stakeholders and decision makers, the consideration of the GEOSI both to support future sustainable geothermal projects and to provide a more competitive geothermal energy market.

4.9. Limitations of the present study

In relation to the generalised use of the ISAF-GET and GEOSI, the following limitations may be identified:

(i) The geographical location of geothermal systems. Although the GEOSI were developed for the geothermal industry of Mexico, the applicability of the ISAF-GET to generate local GEOSI may be extended to other countries, if the type of geothermal systems to be evaluated are defined by analysing their physicochemical and geological features, and prioritising the main sustainability issues to be addressed.
(ii) The representativeness of the local stakeholders. As the selected GEOSI depended on the number of representative sectors, it is expected that a larger sample of the effective participation of stakeholders may enhance a wider aggregation of diverse preferences and perspectives for a better selection of GEOSI.
(iii) The evolving nature and time validity of the GEOSI. It is accepted that the geothermal systems have a dynamic nature characterised by a production variability and socio-economic changes that require to be considered to define the validity of the GEOSI with time. Under such dynamic conditions, the environmental and socioeconomic features are continually evolving with new sustainable challenges and regulations that may appear in the future.
(iv) The use of a linear economy model for the selection of GEOSI. The linear economy model (i.e., material extraction, production, consumption and disposal) has been commonly used for the development of worldwide geothermal projects. From the LCA perspective, such projects are usually evaluated either by "cradle-to-gate" or "cradle-to-grave" scopes, which may constitute a limitation towards a better sustainable system.

With the ambitious target to achieve net zero emissions, future geothermal projects and GEOSI will require an improvement for transitioning into an improved circular economy model to consider raw materials retrieved from disposal/waste materials, and production/

utilization project more efficient, sustainable and profitable. All these LCA stages could be better characterised by a "cradle-to-cradle" scope, which still represent a big challenge for future investigations.

4.10. Future implications of the present study

Some additional tasks may be programmed as future implications of this study, which are currently under further research. To carry out such actions, the construction of geothermal sustainability indexes (GeoSIndx) appears as a key task by applying conceptual methodologies similar to those proposed by Braat [162] and Wu & Wu [163]. In agreement with these methodologies, GeoSIndx could be generated as highly aggregated indexes for aligning in a simple way with crucial environmental and human (socioeconomical) hotspots to achieve a sustainable exploitation of geothermal resources (e.g., global ecological footprint, human development index, material flows accounting, among others). These indexes may provide a picture of the system performance, which may be obtained from the GEOSI by following the sequential tasks represented in Fig. 8 (left pyramid). From this information, future implications may create strong links and actions among the society, government, industry and academia (Fig. 8, right pyramid), resulting in a much better sustainable development of the projects.

For the society, it is expected that a more complete information should flow to the communities, which may help to obtain a better acceptance of geothermal projects that are currently under conflicting situations. For the government, improved public polices and regulations may emerge as a new contribution of the sustainability category of governance [164]. For the industry, stronger connections or synergies with the other sectors may be obtained to improve the efficiency and reengineering to maximize resource utilization, and increase the production profitability. Finally, for the academia, a valuable knowledge of the sustainable development of GET may be achieved by applying comprehensive LCSA (LCA, SLCA and LCC) and circular economy studies.

5. Conclusions

Geothermal energy is currently contributing to the diversification of the energy matrix and the decarbonisation of the Mexican electricity sector. An urgent task to provide GEOSI for endorsing a cleaner energy option is therefore required. To move rapidly towards a RE transition accompanied by a sustainable development pathway, decision-making strategies supported by stakeholders must be considered. Geothermal industry still requires sustainability indicators and methods to take decisions for supporting the sustainable development of future commercial projects. Most of the GEOSI applied in some countries (for electricity generation or direct uses) are strongly criticized due to an unbalanced representation of the sustainability, where environmental and economic aspects are usually overemphasised whereas social issues are undervalued or simply ignored.

To address these issues with a wider sustainability perspective, a transdisciplinary methodology based on a systematic literature review and a new ISAF-GET was developed in this investigation. A ranked selection of GEOSI to evaluate GET for Mexico was successfully achieved. Using the ISAF-GET through an iterative PASUR, 36 out of 66 GEOSI were selected (11 environmental, 9 economic, and 16 social). These indicators were optimally ranked using MCDA-MGDM techniques.

The selection of these GEOSI was performed by considering the existing geothermal zones of Mexico, the different types of technology, and the opinion of transdisciplinary stakeholders. The iterative survey was based on a resilient engagement of stakeholders which were effectively grouped in four sectors (academia, government, industry, and society). All these sectors look for supporting the sustainable development of geothermal projects, and the deployment of commercial technologies for Mexico. It is expected that the present integrated methodology addresses the main environmental, economic and social issues and barriers of the Mexican geothermal industry. The new conceptual ISAF-GET should be applied in the future from a better life cycle perspective to analyse the major life cycle stages (i.e., full exploration, construction, operation and end-of-life). To avoid a wrong allocation of environmental burdens to the operation stage of these projects, the evaluation of baseline gas emissions in the early exploration is urgently required as a key aspect for future LCA studies.

On the other hand, social sustainability indicators, which have been usually ignored in many geothermal projects, still present a strong debate regarding what impacts or performance measures should be considered. As the impacts on social communities are interrelated to the specific location where the geothermal resources are available, it becomes necessary to consider these issues for breaking obstacles that exist in new exploration and exploitation programmes of Mexico. The current social barriers need to be broken to prevent future social conflicts and to offer a win-win scenario for a better deployment of these GET. Regarding these aspects, 16 social indicators were identified from the ISAF-GET methodology to satisfy the actual society needs. Some of these indicators (SO-05, SO-08, SO-14, SO-15, SO-16, SO-21, and SO-22) have not been previously linked with social aspects in geothermal projects of other countries. A significant incentive to include social sustainability indicators into LCSA studies of geothermal projects for Mexico still

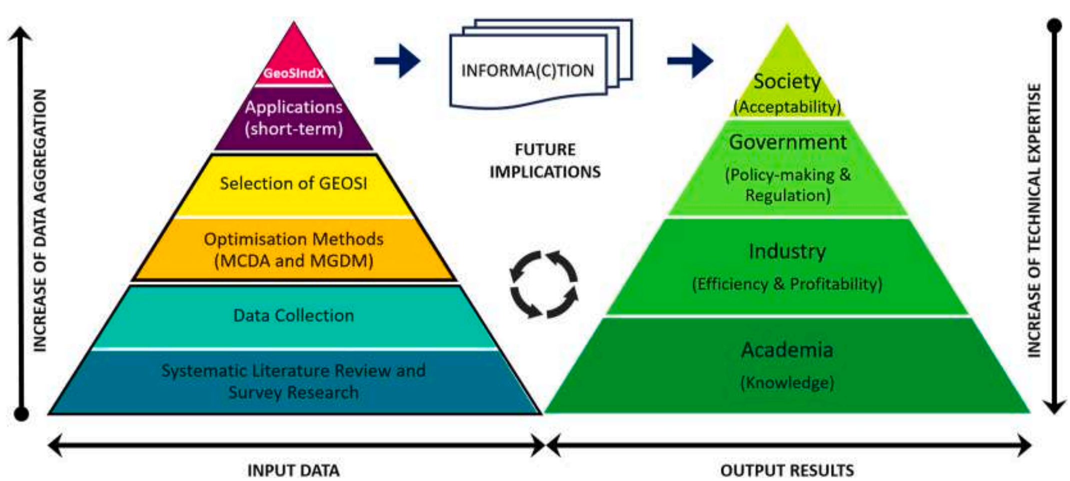


Fig. 8. Common relationships among the literature review, data collection, indicators (GEOSI), indexes (GeoSIndx), and information required for sustainability actions in future geothermal projects through a close interaction among sustainability measures, producers and potential users (modified and improved after Braat [162].

represent a big challenge to address their aggregation and normalisation. All the GEOSI developed in this work may be reliably used: (i) to apply LCSA for quantifying environmental, economic and social impacts; (ii) to improve the technical performance of these GET for mitigating or reducing environmental impacts, and increasing the overall efficiency of the power plants and heating processes; and (iii) to support the decision- and policy-making actions for the sustainable harnessing the geothermal resources in Mexico.

Further research work is still needed for completing the future implications reported in this study, and to overcome the barriers that currently affect the geothermal industry of Mexico. Finally, we also may conclude that the present integrated ISAF-GET methodology could be extended to the assessment of other energy systems or RE technologies.

CRediT author statement

K. Solano-Olivares: Investigation, Data curation, Resources, Formal analysis, Visualisation, Writing - Original Draft. **E. Santoyo:** Investigation, Conceptualization, Methodology, Resources, Supervision, Validation, Writing – Review & Editing. **E. Santoyo-Castelazo:** Investigation, Conceptualization, Validation, Software, Writing – Review & Editing.

Funding information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The first author wants to thank to CONACyT and the Engineering Graduate Program (Energy) of the UNAM for the scholarships and support awarded. Special thanks to M.Sc. M. Guevara and M.T.I. E.O. García-Mandujano for providing support in the purchase of the SurveyMonkey software, the compilation of information, and the processing of bibliometric data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.114231.

References

[1] Solano-Olivares K, Romero RJ, Santoyo E, Herrera I, Galindo–Luna YR, Rodríguez–Martínez A, Santoyo-Castelazo E. Life cycle assessment of a solar absorption air-conditioning system. J Clean Prod 2019;240:118206. https://doi.org/10.1016/j.jclepro.2019.118206.

[2] Statistical BP. Review of world energy. 70th ed. 2021. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf. [Accessed 28 February 2023].

[3] Lombardi P, Gruenig M. Low-carbon energy security from a European perspective. Academic Press; 2016.

[4] García-Gusano D, Iribarren D, Garraín D. Prospective analysis of energy security: a practical life-cycle approach focused on renewable power generation and oriented towards policy-makers. Appl Energy 2017;190:891–901. https://doi.org/10.1016/j.apenergy.2017.01.011.

[5] Rohit RV, Kiplangat DC, Veena R, Jose R, Pradeepkumar AP, Kumar KS. Tracing the evolution and charting the future of geothermal energy research and development. Renew Sustain Energy Rev 2023;184:113531. https://doi.org/10.1016/j.rser.2023.113531. 2023.

[6] Santoyo-Castelazo E, Solano-Olivares K, Martínez E, García EO, Santoyo E. Life cycle assessment for a grid-connected multi-crystalline silicon photovoltaic system of 3 kWp: a case study for Mexico. J Clean Prod 2021;316:128314. https://doi.org/10.1016/j.jclepro.2021.128314.

[7] Lund JW, Toth AN. Direct utilization of geothermal energy 2020 worldwide review. Geothermics 2021;90:101915. https://doi.org/10.1016/j.geothermics.2020.101915.

[8] International Energy Agency, IEA. Mexico energy Outlook. 2016. www.worldenergyoutlook.org/mexico. [Accessed 1 December 2021].

[9] International Renewable Energy Agency. IRENA. Geothermal power: technology brief. 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Aug/IRENA_Geothermal_Power_2017.pdf. [Accessed 1 December 2021].

[10] Kabeyi MJB, Olanrewaju OA. Geothermal wellhead technology power plants in grid electricity generation: a review. Energy Strategy Rev 2022;39:100735. https://doi.org/10.1016/j.esr.2021.100735.

[11] Collard N, Peiffer L, Taran Y. Heat and fluid flow dynamics of a stratovolcano: the Tacaná Volcanic Complex, Mexico-Guatemala. J Volcanol Geoth Res 2020;400:106916. https://doi.org/10.1016/j.jvolgeores.2020.106916.

[12] Ball PJ. A review of geothermal technologies and their role in reducing greenhouse gas emissions in the USA. J Energy Resour Technol 2021;143(1). https://doi.org/10.1115/1.4048187.

[13] Buira D, Tovilla J, Farbes J, Jones R, Haley B, Gastelum D. A whole-economy deep decarbonization pathway for Mexico. Energy Strategy Rev 2021;33:100578. https://doi.org/10.1016/j.esr.2020.100578.

[14] Gutiérrez-Negrín LC, Canchola Félix I, Romo-Jones JM, Quijano-León JL. Geothermal energy in Mexico: update and perspectives. Proceedings, proceedings world geothermal congress. 2020. https://pangea.stanford.edu/ERE/db/WGC/Abstract.php?PaperID=4367.

[15] ThinkGeoEnergy. Top 10 geothermal countries 2020 installed power generation capacity. https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2020-installed-power-generation-capacity-mwe/. [Accessed 1 December 2021].

[16] Tomasini-Montenegro C, Santoyo-Castelazo E, Gujba H, Romero RJ, Santoyo E. Life cycle assessment of geothermal power generation technologies: an updated review. Appl Therm Eng 2017;114:1119–36. https://doi.org/10.1016/j.applthermaleng.2016.10.074.

[17] de Jesus Fernandez A, Watson J. Mexico's renewable energy innovation system: geothermal and solar photovoltaics case study. Environ Innov Soc Transit 2022;43:200–19. https://doi.org/10.1016/j.eist.2022.04.004.

[18] Turcu C. Re-thinking sustainability indicators: local perspectives of urban sustainability. J Environ Plann Manag 2013;56(5):695–719. https://doi.org/10.1080/09640568.2012.698984.

[19] Raos S, Hranić J, Rajšl I, Bär K. An extended methodology for multi-criteria decision-making process focused on enhanced geothermal systems. Energy Convers Manag 2022;258:115253. https://doi.org/10.1016/j.enconman.2022.115253.

[20] Banacloche S, Cadarso MA, Monsalve F, Lechon Y. Assessment of the sustainability of Mexico green investments in the road to Paris. Energy Pol 2020;141:111458. https://doi.org/10.1016/j.enpol.2020.111458.

[21] IAEA (International Atomic Energy Agency). Energy indicators for sustainable development: guidelines and methodologies. Report. 2005. p. 171. https://www-pub.iaea.org/mtcd/publications/pdf/pub1222_web.pdf. [Accessed 28 January 2023].

[22] Santoyo-Castelazo E, Azapagic A. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. J Clean Prod 2014;80:119–38. https://doi.org/10.1016/j.jclepro.2014.05.061.

[23] Stamford L, Azapagic A. Sustainability indicators for the assessment of nuclear power. Energy 2011;36(10):6037–57. https://doi.org/10.1016/j.energy.2011.08.011.

[24] Evans A, Strezov V, Evans TJ. Assessment of sustainability indicators for renewable energy technologies. Renew Sustain Energy Rev 2009;13(5):1082–8. https://doi.org/10.1016/j.rser.2008.03.008.

[25] Drupp MA. Does the Gold Standard label hold its promise in delivering higher Sustainable Development benefits? A multi-criteria comparison of CDM projects. Energy Pol 2011;39(3):1213–27. https://doi.org/10.1016/j.enpol.2010.11.049.

[26] Liu G. Development of a general sustainability indicator for renewable energy systems: a review. Renew Sustain Energy Rev 2014;31:611–21. https://doi.org/10.1016/j.rser.2013.12.038.

[27] Ghenai C, Albawab M, Bettayeb M. Sustainability indicators for renewable energy systems using multi-criteria decision-making model and extended SWARA/ARAS hybrid method. Renew Energy 2020;146:580–97. https://doi.org/10.1016/j.renene.2019.06.157.

[28] Luong S, Liu K, Robey J. Sustainability assessment framework for renewable energy technology. Technologies for Sustainable Built Environment Centre; 2012. p. 1–8.

[29] Rodríguez-Serrano I, Caldés N, de la Rúa C, Lechón Y. Assessing the three sustainability pillars through the framework for integrated sustainability assessment (FISA): case study of a solar thermal electricity project in Mexico. J Clean Prod 2017;14:1127–43. https://doi.org/10.1016/j.jclepro.2017.02.179.

[30] Simsek Y, Watts D, Escobar R. Sustainability evaluation of concentrated solar power (CSP) projects under clean development mechanism (CDM) by using multi criteria decision method (MCDM). Renew Sustain Energy Rev 2018;93:421–38. https://doi.org/10.1016/j.rser.2018.04.090.

[31] IHA (International Hydropower Association). Hydropower sustainability assessment protocol. Report. International Hydropower Association; 2018. p. 232. ISBN: 978-0-9566228-1-5.
[32] Costa J, Kilajian A, Kadyrzhanova A. Hydropower sustainability assessment. Reference module in earth systems and environmental sciences. Elsevier; 2021. https://doi.org/10.1016/B978-0-12-819727-1.00061-3.
[33] Onat N, Bayar H. The sustainability indicators of power production systems. Renew Sustain Energy Rev 2010;14(9):3108–15. https://doi.org/10.1016/j.rser.2010.07.022.
[34] Lassio JG, Magrini A, Branco D. Life cycle-based sustainability indicators for electricity generation: a systematic review and a proposal for assessments in Brazil. J Clean Prod 2021:127568. https://doi.org/10.1016/j.jclepro.2021.127568.
[35] Roldán MC, Martínez M, Peña R. Scenarios for a hierarchical assessment of the global sustainability of electric power plants in México. Renew Sustain Energy Rev 2014;33:154–60. https://doi.org/10.1016/j.rser.2014.02.007.
[36] Atilgan B, Azapagic A. An integrated life cycle sustainability assessment of electricity generation in Turkey. Energy Pol 2016;93:168–86. https://doi.org/10.1016/j.enpol.2016.02.055.
[37] Shaaban M, Scheffran J. Selection of sustainable development indicators for the assessment of electricity production in Egypt. Sustain Energy Technol Assessments 2017;22:65–73. https://doi.org/10.1016/j.seta.2017.07.003.
[38] Saraswat SK, Digalwar AK. Empirical investigation and validation of sustainability indicators for the assessment of energy sources in India. Renew Sustain Energy Rev 2021;145:111156. https://doi.org/10.1016/j.rser.2021.111156.
[39] Sala S, Ciuffo B, Nijkamp P. A systemic framework for sustainability assessment. Ecol Econ 2015;119:314–25. https://doi.org/10.1016/j.ecolecon.2015.09.015.
[40] Van Schoubroeck S, Springael J, Van Dael M, Malina R, Van Passel S. Sustainability indicators for biobased chemicals: a Delphi study using Multi-Criteria Decision Analysis. Resour Conserv Recycl 2019;144:198–208. https://doi.org/10.1016/j.resconrec.2018.12.024.
[41] Morse S, Fraser ED. Making 'dirty'nations look clean? The nation state and the problem of selecting and weighting indices as tools for measuring progress towards sustainability. Geoforum 2005;36(5):625–40. https://doi.org/10.1016/j.geoforum.2004.10.005.
[42] Banacloche S, Lechon Y, Rodríguez-Martínez A. Carbon capture penetration in Mexico's 2050 horizon: a sustainability assessment of Mexican CCS policy. Int J Greenh Gas Control 2022;115:103603. https://doi.org/10.1016/j.ijggc.2022.103603.
[43] Bossel H. Indicators for sustainable development: theory, method, applications. Winnipeg: International Institute for Sustainable Development; 1999. p. 138. https://epe.lac-bac.gc.ca/100/200/300/iisd/measurement_assessment/indicators/balatonreport.pdf. [Accessed 1 March 2023].
[44] Reed MS, Fraser ED, Dougill AJ. An adaptive learning process for developing and applying sustainability indicators with local communities. Ecol Econ 2006;59(4):406–18. https://doi.org/10.1016/j.ecolecon.2005.11.008.
[45] Azapagic A, Perdan S. An integrated sustainability decision-support framework Part I: problem structuring. Int J Sustain Dev World Ecol 2005;12(2):98–111. https://doi.org/10.1080/13504500509469622.
[46] Azapagic A, Perdan S. An integrated sustainability decision-support framework Part II: problem analysis. Int J Sustain Dev World Ecol 2005;12(2):112–31. https://doi.org/10.1080/13504500509469623.
[47] Acevedo-Anicasio A, Santoyo E, Pérez-Zárate D, Pandarinath K, Guevara M, GaS_GeoT Díaz-González L. A computer program for an effective use of newly improved gas geothermometers in predicting reliable geothermal reservoir temperatures. Geotherm Energy 2021;9(1):1–41. https://doi.org/10.1186/s40517-020-00182-9.
[48] Bjarnadóttir R. Sustainability evaluation of geothermal systems in Iceland. Indicators for sustainable production. 2010. p. 88. Doctoral dissertation, https://geothermalcommunities.geonardo.com/assets/elearning/1.28.thesis_fixed.pdf.
[49] Monterrosa M. Sustainability analysis of the Berlin geothermal field, El Salvador. Proceedings of SIMS 2012, the 53rd Scandinavian Simulation and Modelling Society Conference Reykjavik, Iceland. 2012. 001251218.
[50] Shortall R. A sustainability assessment protocol for geothermal utilization. University of Iceland; 2010. p. 310. M.Sc. Dissertation.
[51] Shortall R. A Sustainability assessment framework for geothermal energy developments. University of Iceland; 2015. p. 204. PhD dissertation.
[52] Shortall R, Davidsdottir B, Axelsson G. Geothermal energy for sustainable development: a review of sustainability impacts and assessment frameworks. Renew Sustain Energy Rev 2015;44:391–406. https://doi.org/10.1016/j.rser.2014.12.020.
[53] Shortall R, Davidsdottir B, Axelsson G. Development of a sustainability assessment framework for geothermal energy projects. Energy Sustain Dev 2015;27:28–45. https://doi.org/10.1016/j.esd.2015.02.004.
[54] Shortall R, Davidsdottir B, Axelsson G. A sustainability assessment framework for geothermal energy projects: development in Iceland, New Zealand and Kenya. Renew Sustain Energy Rev 2015;50:372–407. https://doi.org/10.1016/j.rser.2015.04.175.
[55] Soltani M, Kashkooli FM, Souri M, Rafiei B, Jabarifar M, Gharali K, Nathwani JS. Environmental, economic, and social impacts of geothermal energy systems. Renew Sustain Energy Rev 2021;140:110750. https://doi.org/10.1016/j.rser.2021.110750.
[56] ENEL. Deep Carbon project: geothermal energy can be officially classified as a sustainable resource. https://sway.office.com/Dkz9dbiNIDuGlbp3. [Accessed 20 April 2022].
[57] Santoyo E, Acevedo-Anicasio A, Pérez-Zarate D, Guevara M. Evaluation of artificial neural networks and eddy covariance measurements for modelling the CO_2 flux dynamics in the Acoculco geothermal caldera (Mexico). Int J Environ Sustain Dev 2018;9:298–302. https://doi.org/10.18178/ijesd.2018.9.10.1117.
[58] Chandrasekharam D, Ranjith Pathegama G. CO_2 emissions from renewables: solar pv, hydrothermal and EGS sources. Geomech Geophys Geo-Energy 2022;6(1):1–17. https://doi.org/10.1007/s40948-019-00135-y.
[59] Depren SK, Kartal MT, Çelikdemir NÇ, Depren Ö. Energy consumption and environmental degradation nexus: a systematic review and meta-analysis of fossil fuel and renewable energy consumption. Ecol Inf 2022;70:101747. https://doi.org/10.1016/j.ecoinf.2022.101747.
[60] Jusselme T, Rey E, Andersen M. Surveying the environmental life-cycle performance assessments: practice and context at early building design stages. Sustain Cities Soc 2020;52:101879. https://doi.org/10.1016/j.scs.2019.101879.
[61] Harkness Janet A. In: Edith D de Leeuw, Hox Joop, Dillman Don, editors. Comparative survey research: goals and challenges. International handbook of survey methodology; 2012. p. 56–77. https://doi.org/10.4324/9780203843123.
[62] De Vaus D. Survey research. Research methods for postgraduates. 2016. p. 202–13.
[63] Roy B. Two conceptions of decision aiding. Int J Multicriteria Decis Mak 2010;1(1):74–9. https://doi.org/10.1504/IJMCDM.2010.033687.
[64] Qiu J, Li L. A new approach for multiple attribute group decision making with interval-valued intuitionistic fuzzy information. Appl Soft Comput 2017;61:111–21. https://doi.org/10.1016/j.asoc.2017.07.008.
[65] Fu C, Chang W, Xue M, Yang S. Multiple criteria group decision making with belief distributions and distributed preference relations. Eur J Oper Res 2019;273(2):623–33. https://doi.org/10.1016/j.ejor.2018.08.012.
[66] Cinelli M, Spada M, Kim W, Zhang Y, Burgherr P. MCDA Index Tool: an interactive software to develop indices and rankings. Environ Syst Decis 2020:1–28. https://doi.org/10.1007/s10669-020-09784-x.
[67] Dincer I, Acar C. A review on clean energy solutions for better sustainability. Int J Energy Res 2015;39(5):585–606. https://doi.org/10.1002/er.3329.
[68] Schuwirth N, Reichert P, Lienert J. Methodological aspects of multi-criteria decision analysis for policy support: a case study on pharmaceutical removal from hospital wastewater. Eur J Oper Res 2012;220:472–83. https://doi.org/10.1016/j.ejor.2012.01.055.
[69] Reichert P, Langhans SD, Lienert J, Schuwirth N. The conceptual foundation of environmental decision support. J Environ Manag 2015;154:316–32. https://doi:10.1016/j.jenvman.2015.01.053.
[70] Henggeler Antunes C, Oliveira Henriques C. In: Greco S, Ehrgott M, Figueira JR, editors. Multi-objective optimization and multi-criteria analysis models and methods for problems in the energy sector (Chapter 25). Multiple criteria decision analysis - state of the art surveys. second ed.; 2016. p. 233 International Series in Operations Research & Management Science https://link.springer.com/chapter/10.1007/978-1-4939-3094-4_25; 1067-1167.
[71] van Herwijnen M. Multi− attribute value theory (MAVT). Amsterdam, The Netherlands: Vrije-Universiteit; 2010. http://www.ivm.vu.nl/en/Images/MCA1_tcm234-161527.pdf. [Accessed 1 December 2021].
[72] Santoyo-Castelazo E. Sustainability assessment of electricity options for Mexico: current situation and future scenarios. 2011. The University of Manchester (United Kingdom), https://core.ac.uk/download/pdf/40016472.pdf. [Accessed 1 December 2021].
[73] Hostmann M, Bernauer T, Mosler HJ, Reichert P, Truffer B. Multi-attribute value theory as a framework for conflict resolution in river rehabilitation. J Multi-Criteria Decis Anal 2005;13(2–3):91–102. https://doi:10.1002/mcda.375.
[74] Saarikoski H, Mustajoki J, Barton DN, Geneletti D, Langemeyer J, Gomez-Baggethun E, Marttunen M, Antunes P, Keune H, Santos R. Multi-Criteria Decision Analysis and Cost-Benefit Analysis: Comparing alternative frameworks for integrated valuation of ecosystem services. Ecosyst Serv 2016;22:238–49. https://doi.org/10.1016/j.ecoser.2016.10.014.
[75] Qian G, Mahdi A. Sensitivity analysis methods in the biomedical sciences. Math Biosci 2020;323:108306. https://doi.org/10.1016/j.mbs.2020.108306.
[76] Burgherr P, Hirschberg S, Brukmajster D, Hampel J. Survey of criteria and indicators. New energy externalities developments for sustainability (NEEDS). Deliverable D 2005;1:2002–6.
[77] Tahseen S, Karney BW. Reviewing and critiquing published approaches to the sustainability assessment of hydropower. Renew Sustain Energy Rev 2017;67:225–34. https://doi.org/10.1016/j.rser.2016.09.031.
[78] Gama FY. Sustainability assessment of Ir. H. Juanda hydropower reservoir using hydropower sustainability assessment protocol (HSAP). Repository IHE Delft Institute for Water Education; 2016. https://doi.org/10.25831/k44p-eg56.
[79] Xu Z, Niu Y, Liang Y, Li Z, Iftikhor A. The integrated hydropower sustainability assessment in Tajikistan: a case study of Rogun hydropower plant. Adv Civ Eng 2020:1–18. https://doi.org/10.1155/2020/8894072.
[80] Teguh NA, Nisaa AF. Hydropower sustainability assessment protocol (HSAP) implementation in Indonesia: a mini-review. J Infrastruc Facil Asset Manag 2021;3(1). https://doi.org/10.12962/jifam.v3i1.13463.
[81] Arslan O, Kose R. Exergoeconomic optimisation of integrated geothermal system in Simav, Kutahya. Energy Convers Manag 2010;51(4):663–76. https://doi.org/10.1016/j.enconman.2009.11.010.
[82] Arslan O, Ozgur MA, Kose R. Electricity generation ability of the Simav geothermal field: a technoeconomic approach. Energy Sources: Recovery Util

Environ Eff 2012;34(12):1130–44. https://doi.org/10.1080/15567031003773254.
[83] Arslan O, Yetik O. ANN modeling of an ORC-binary geothermal power plant: Simav case study. Energy Sources: Recovery Util Environ Eff 2014;36(4):418–28. https://doi.org/10.1080/15567036.2010.542437.
[84] Frick S, Kaltschmitt M, Schröder G. Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. Energy 2010;35(5):2281–94. https://doi.org/10.1016/j.energy.2010.02.016.
[85] Karlsdottir MR, Palsson OP, Palsson H. LCA of combined heat and power production at Hellisheiði geothermal power plant with focus on primary energy efficiency. The 12th International Symposium on district heating and cooling. Estonia: Tallinn; 2010.
[86] Sullivan JL, Clark CE, Han JW, Wang MQ. Life cycle analysis results of geothermal systems in comparison to other power systems. Technical Report of the Energy Systems Division, Argonne National Laboratory, Argonne/ESD/10-5. 2010. p. 72. https://doi.org/10.2172/993694.
[87] Gerber L, Maréchal F. Environomic optimal configurations of geothermal energy conversion systems: application to the future construction of Enhanced Geothermal Systems in Switzerland. Energy 2012;45(1):908–23. https://doi.org/10.1016/j.energy.2012.06.068.
[88] Lacirignola M, Blanc I. Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment. Renew Energy 2013;50:901–14. https://doi.org/10.1016/j.renene.2012.08.005.
[89] Sullivan JL, Clark CE, Han J, Harto C, Wang M. Cumulative energy, emissions, and water consumption for geothermal electric power production. J Renew Sustain Energy 2013;5:023127. https://doi.org/10.1063/1.4798315. 23 p.
[90] Sullivan JL, Wang MQ. Life cycle greenhouse gas emissions from geothermal electricity production. J Renew Sustain Energy 2013;5(6):063122. https://doi.org/10.1063/1.4841235.
[91] Bravi M, Basosi R. Environmental impact of electricity from selected geothermal power plants in Italy. J Clean Prod 2014;66:301–8. https://doi.org/10.1016/j.jclepro.2013.11.015.
[92] Lacirignola M, Meany BH, Padey P, Blanc I. A simplified model for the estimation of life-cycle greenhouse gas emissions of enhanced geothermal systems. Geotherm Energy 2014;2(1):8. https://doi.org/10.1186/s40517-014-0008-y.
[93] Ruzzenenti F, Bravi M, Tempesti D, Salvatici E, Manfrida G, Basosi R. Evaluation of the environmental sustainability of a micro CHP system fueled by low-temperature geothermal and solar energy. Energy Convers Manag 2014;78:611–6. https://doi.org/10.1016/j.enconman.2013.11.025.
[94] Buonocore E, Vanoli L, Carotenuto A, Ulgiati S. Integrating life cycle assessment and emergy synthesis for the evaluation of a dry steam geothermal power plant in Italy. Energy 2015;86:476–87. https://doi.org/10.1016/j.energy.2015.04.048.
[95] Marchand M, Blanc I, Marquand A, Beylot A, Bezelgues-Courtade S, Traineau H. s. Life cycle assessment of high temperature geothermal energy system. Proc. World geothermal congress. 2015. Melbourne, Australia. ISBN 978-1-877040-02-3. <hal-01146355>.
[96] Martín-Gamboa M, Iribarren D, Dufour J. On the environmental suitability of high-and low-enthalpy geothermal systems. Geothermics 2015;53:27–37. https://doi.org/10.1016/j.geothermics.2014.03.012.
[97] Karlsdóttir MR, Pálsson ÓP, Pálsson H, Maya-Drysdale L. Life cycle inventory of a flash geothermal combined heat and power plant located in Iceland. Int J Life Cycle Assess 2015;20(4):503–19. https://doi.org/10.1007/s11367-014-0842-y.
[98] Treyer K, Oshikawa H, Bauer C, Miotti M. Energy from the earth, WP4: environment. Zürich: vdf Hochschulverlag. ISBN 978-3-7281-3655-8, https://doi.org/10.3218/3655-8; 2015.
[99] Martínez-Corona JI, Gibon T, Hertwich EG, Parra-Saldívar R. Hybrid life cycle assessment of a geothermal plant: from physical to monetary inventory accounting. J Clean Prod 2017;142:2509–23. https://doi.org/10.1016/j.jclepro.2016.11.024.
[100] Yu T, Looijen JM, van der Meer FD, Willemsen N. A life cycle assessment-based comparison of large & small scale geo-thermal electricity production systems. Proceedings of the 5th Indonesia International Geothermal Convention & Exhibition (IIGCE), Jakarta, Indonesia. 2017. Msc. Thesis, https://webapps.itc.utwente.nl/librarywww/papers_2017/msc/nrm/tyu.pdf. [Accessed 1 December 2021].
[101] Hanbury O, Vasquez VR. Life cycle analysis of geothermal energy for power and transportation: a stochastic approach. Renew Energy 2018;115:371–81. https://doi.org/10.1016/j.renene.2017.08.053.
[102] Lohse C. Environmental impact by hydrogeothermal energy generation in low-enthalpy regions. Renew Energy 2018;128:509–19. https://doi.org/10.1016/j.renene.2017.06.030.
[103] Pratiwi A, Ravier G, Genter A. Life-cycle climate-change impact assessment of enhanced geothermal system plants in the Upper Rhine Valley. Geothermics 2018;75:26–39. https://doi.org/10.1016/j.geothermics.2018.03.012.
[104] Parisi ML, Ferrara N, Torsello L, Basosi R. Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants. J Clean Prod 2019;234:881–94. https://doi.org/10.1016/j.jclepro.2019.06.222.
[105] Ferrara N, Basosi R, Parisi ML. Data analysis of atmospheric emission from geothermal power plants in Italy. Data Brief 2019;25:104339. https://doi.org/10.1016/j.dib.2019.104339.
[106] Paulillo A, Striolo A, Lettieri P. The environmental impacts and the carbon intensity of geothermal energy: a case study on the Hellisheiði plant. Environ Int 2019;133:105226. https://doi.org/10.1016/j.envint.2019.105226.
[107] Tian X, You F. Carbon-neutral hybrid energy systems with deep water source cooling, biomass heating, and geothermal heat and power. Appl Energy 2019;250:413–32. https://doi.org/10.1016/j.apenergy.2019.04.172.
[108] Basosi R, Bonciani R, Frosali D, Manfrida G, Parisi ML, Sansone F. Life cycle analysis of a geothermal power plant: comparison of the environmental performance with other renewable energy systems. Sustainability 2020;12(7):2786. https://doi.org/10.3390/su12072786.
[109] Karlsdottir MR, Heinonen J, Palsson H, Palsson OP. Life cycle assessment of a geothermal combined heat and power plant based on high temperature utilization. Geothermics 2020;84:101727. https://doi.org/10.1016/j.geothermics.2019.101727.
[110] Paulillo A, Cotton L, Law R, Striolo A, Lettieri P. Geothermal energy in the UK: the life-cycle environmental impacts of electricity production from the United Downs Deep Geothermal Power project. J Clean Prod 2020;249:119410. https://doi.org/10.1016/j.jclepro.2019.119410.
[111] Tosti L, Ferrara N, Basosi R, Parisi ML. Complete data inventory of a geothermal power plant for robust cradle-to-grave life cycle assessment results. Energies 2020;13(11):2839. https://doi.org/10.3390/en13112839.
[112] Yilmaz C. Life cycle cost assessment of a geothermal power assisted hydrogen energy system. Geothermics 2020;83:101737. https://doi.org/10.1016/j.geothermics.2019.101737.
[113] Wang Y, Du Y, Wang J, Zhao J, Deng S, Yin H. Comparative life cycle assessment of geothermal power generation systems in China. Resour Conserv Recycl 2020;155(1):04670. https://doi.org/10.1016/j.resconrec.2019.104670.
[114] Chaiyat N, Lerdjaturanon W, Ondokmai P. Life cycle assessment of a combined cooling heating and power generation system. Case Stud Chem Environ Eng 2021;4:100134. https://doi.org/10.1016/j.cscee.2021.100134.
[115] Colucci V, Manfrida G, Mendecka B, Talluri L, Zuffi C. LCA and exergo-environmental evaluation of a combined heat and power double-flash geothermal power plant. Sustainability 2021;13(4):1935. https://doi.org/10.3390/su13041935.
[116] Menberg K, Heberle F, Bott C, Brüggemann D, Bayer P. Environmental performance of a geothermal power plant using a hydrothermal resource in the Southern German Molasse Basin. Renew Energy 2021;167:20–31. https://doi.org/10.1016/j.renene.2020.11.028.
[117] Sigurjónsson HÆ, Cook D, Davíðsdóttir B, Bogason SG. A life-cycle analysis of deep enhanced geothermal systems–The case studies of Reykjanes, Iceland and Vendenheim, France. Renew Energy 2021;177:1076–86. https://doi.org/10.1016/j.renene.2021.06.013.
[118] Cook D, Sigurjónsson HÆ, Davíðsdóttir B, Bogason SG. An environmental life cycle cost assessment of the costs of deep enhanced geothermal systems–The case studies of Reykjanes, Iceland and Vendenheim, France. Geothermics 2022;103:102425. https://doi.org/10.1016/j.geothermics.2022.102425.
[119] Kjeld A, Bjarnadottir HJ, Olafsdottir R. Life cycle assessment of the Theistareykir geothermal power plant in Iceland. Geothermics 2022;105:102530. https://doi.org/10.1016/j.geothermics.2022.102530.
[120] Maione A, Massarotti N, Santagata R, Vanoli L. Environmental assessment of a heating, cooling and electric energy grid from a geothermal source in Southern Italy. J Clean Prod 2022;375:134198. https://doi.org/10.1016/j.jclepro.2022.134198.
[121] Jolly A, Caulfield LS, Sojka B, Iafrati S, Rees J, Massie R. Café Delphi: Hybridising 'World cafe' and 'Delphi techniques' for successful remote academic collaboration. Soc Sci Humanit Open 2021;3(1):100095. https://doi.org/10.1016/j.ssaho.2020.100095.
[122] Hardi P, Zdan T. Assessing sustainable development: principles in practice. International Institute for Sustainable Development; 1997. p. 175. Report, https://www.iisd.org/library/assessing-sustainable-development-principles-practice. [Accessed 1 December 2021].
[123] IHA (International Hydropower Association). Hydropower sustainability assessment protocol. International Hydropower Association; 2006.
[124] Li J, Tarpani RRZ, Stamford L, Gallego-Schmid A. Life cycle sustainability assessment and circularity of geothermal power plants. Sustain Prod Consum 2023;35:141–56. https://doi.org/10.1016/j.spc.2022.10.027.
[125] Daniilidis A, Alpsoy B, Herber R. Impact of technical and economic uncertainties on the economic performance of a deep geothermal heat system. Renew Energy 2017;114:805–16. https://doi.org/10.1016/j.renene.2017.07.090.
[126] Moya D, Paredes J, Kaparaju P. Technical, financial, economic and environmental pre-feasibility study of geothermal power plants by RETScreen–Ecuador's case study. Renew Sustain Energy Rev 2018;92:628–37. https://doi.org/10.1016/j.rser.2018.04.027.
[127] Mariita NO. The impact of large-scale renewable energy development on the poor: environmental and socio-economic impact of a geothermal power plant on a poor rural community in Kenya. Energy Pol 2002;30(11–12):1119–28. https://doi.org/10.1016/S0301-4215(02)00063-0.
[128] Tsagarakis KP. Shallow geothermal energy under the microscope: social, economic, and institutional aspects. Renew Energy 2020;147:2801–8. https://doi.org/10.1016/j.renene.2019.01.004.
[129] Sanchez-Alfaro P, Sielfeld G, Van Campen B, Dobson P, Fuentes V, Reed A, Palma-Behnke R, Morata D. Geothermal barriers, policies and economics in Chile–Lessons for the Andes. Renew Sustain Energy Rev 2015;51:1390–401. https://doi.org/10.1016/j.rser.2015.07.001.
[130] Ozgener O, Hepbasli A. An economical analysis on a solar greenhouse integrated solar assisted geothermal heat pump system. J Energy Resour Technol 2006;128(1):28–34. https://doi.org/10.1115/1.2126984.
[131] Tao YX, Zhu Y. Analysis of energy, environmental and life cycle cost reduction potential of ground source heat pump (GSHP) in hot and humid climate. Technical Report. United States, https://doi.org/10.2172/1039050; 2012.
[132] Zhu Y, Tao Y, Rayegan R. A comparison of deterministic and probabilistic life cycle cost analyses of ground source heat pump (GSHP) applications in hot and

humid climate. Energy Build 2012;55:312–21. https://doi.org/10.1016/j.enbuild.2012.08.039.
[133] Zhu Y, Rayegan R, Tao YX. Case study of ground-source heat pump applications in hot and humid climates. J Architect Eng 2015;21(1). https://doi.org/10.1061/(ASCE)AE.1943-5568.0000155.
[134] Chiasson A. Life-cycle cost study of a geothermal heat pump system bia office building. Winnebago, NE: Midwest Research Institute (Geo-Heat Center, Oregon Institute of Technology); 2006. p. 13. https://www.oit.edu/docs/default-source/geoheat-centerdocuments/toa/winnebago-life-cycle-cost-analysis-report.pdf?sfvrsn=6. [Accessed 1 December 2021]. 2006.
[135] Kim YJ, Woo NS, Jang SC, Choi JJ. Feasibility study of a hybrid renewable energy system with geothermal and solar heat sources for residential buildings in South Korea. J Mech Sci Technol 2013;27(8):2513–21. https://doi.org/10.1007/s12206-013-0634-5.
[136] Tseng YC, Lee YM, Liao SJ. An integrated assessment framework of offshore wind power projects applying equator principles and social life cycle assessment. Sustainability 2017;9(10):1822. https://doi.org/10.3390/su9101822.
[137] Lobsiger-Kägi E, López L, Kuehn T, Roth R, Carabias V, Zipper C. Social life cycle assessment: specific approach and case study for Switzerland. Sustainability 2018;10(12):4382. https://doi.org/10.3390/su10124382.
[138] Schlör H, Venghaus S, Zapp P, Marx J, Schreiber A, Hake JF. The energy-mineral-society nexus–A social LCA model. Appl Energy 2018;228:999–1008. https://doi.org/10.1016/j.apenergy.2018.06.048.
[139] Fortier MOP, Teron L, Reames TG, Munardy DT, Sullivan BM. Introduction to evaluating energy justice across the life cycle: a social life cycle assessment approach. Appl Energy 2019;236:211–9. https://doi.org/10.1016/j.apenergy.2018.11.022.
[140] Takeda S, Keeley AR, Sakurai S, Managi S, Norris CB. Are renewables as friendly to humans as to the environment?: a social life cycle assessment of renewable electricity. Sustainability 2019;11(5):1370. https://doi.org/10.3390/su11051370.
[141] Lesser JA. Estimating the economic impacts of geothermal resource development. Geothermics 1994;23(1):43–59. https://doi.org/10.1016/0375-6505(94)90045-0.
[142] Kubota H, Hondo H, Hienuki S, Kaieda H. Determining barriers to developing geothermal power generation in Japan: Societal acceptance by stakeholders involved in hot springs. Energy Pol 2013;61:1079–87. https://doi.org/10.1016/j.enpol.2013.05.084.
[143] Manzella A, Bonciani R, Allansdottir A, Botteghi S, Donato A, Giamberini S, Lenzi A, Paci M, Pellizzone A, Scrocca D. Environmental and social aspects of geothermal energy in Italy. Geothermics 2018;72:232–48. https://doi.org/10.1016/j.geothermics.2017.11.015.
[144] Borzoni M, Rizzi F, Frey M. Geothermal power in Italy: a social multicriteria evaluation. Renew Energy 2014;69:60–73. https://doi.org/10.1016/j.renene.2014.03.026.
[145] Pellizzone A, Allansdottir A, De Franco R, Muttoni G, Manzella A. Exploring public engagement with geothermal energy in southern Italy: a case study. Energy Pol 2015;85:1–11. https://doi.org/10.1016/j.enpol.2015.05.002.
[146] Pellizzone A, Allansdottir A, De Franco R, Muttoni G, Manzella A. Geothermal energy and the public: a case study on deliberative citizens' engagement in central Italy. Energy Pol 2017;101:561–70. https://doi.org/10.1016/j.enpol.2016.11.013.
[147] Çetiner ZS, Ertekin C, Gültay B. Initial assessment of public perception and acceptance of geothermal energy applications in Canakkale, NW Turkey. Energy Proc 2016;97:194–201. https://doi.org/10.1016/j.egypro.2016.10.052.
[148] Vargas-Payera S. Understanding social acceptance of geothermal energy: case study for Araucanía region, Chile. Geothermics 2018;72:138–44. https://doi.org/10.1016/j.geothermics.2017.10.014.
[149] Yasukawa K, Kubota H, Soma N, Noda T. Integration of natural and social environment in the implementation of geothermal projects. Geothermics 2018;73:111–23. https://doi.org/10.1016/j.geothermics.2017.09.011.
[150] Regmi PR, Waithaka E, Paudyal A, Simkhada P, van Teijlingen E. Guide to the design and application of online questionnaire surveys. Nepal J Epidemiol 2016;6(4):640. 10.3126%2Fnje.v6i4.17258.
[151] Nagalakhmi LR, Trivedi MJ. Utilization of online survey tools for academic research: a practical approach to survey monkey. Int J Sci Res Publ 2015;4(3):21–8.
[152] Abd Halim M, Foozy CFM, Rahmi I, Mustapha A. A review of live survey application: SurveyMonkey and SurveyGizmo. Int J Inform Visualization 2018;2(4–2):309–12. https://doi.org/10.30630/joiv.2.4-2.170.
[153] Rosenbaum J, Lidz CW. Maximizing the results of internet surveys. Psychiatry Inf Brief 2007;4(2):1. https://doi.org/10.7191/pib.1017.
[154] Macharis C, Mareschal B, Waaub JP, Milan L. PROMETHEE–GDSS revisited: applications so far and new developments. Int J Multicriteria Decis Mak 2015;5(1–2):129–51. https://doi.org/10.1504/IJMCDM.2015.067941.
[155] Waas T, Hugé J, Block T, Wright T, Benitez-Capistros F, Verbruggen A. Sustainability assessment and indicators: tools in a decision-making strategy for sustainable development. Sustainability 2014;6(9):5512–34. https://doi.org/10.3390/su6095512.
[156] Lokey E. Barriers to clean development mechanism renewable energy projects in Mexico. Renew Energy 2009;34(3):504–8. https://doi.org/10.1016/j.renene.2008.06.004.
[157] Hutchins MJ, Richter JS, Henry ML, Sutherland JW. Development of indicators for the social dimension of sustainability in a US business context. J Clean Prod 2019;212:687–97. https://doi.org/10.1016/j.jclepro.2018.11.199.
[158] Secretaría de Energía SENER. Geothermal Technology Road Map (In Spanish: "Mapa de Ruta Tecnológica en Geotermia"), Secretaría de Energía, Gobierno de México. https://www.gob.mx/cms/uploads/attachment/file/279714/MRTGEO_SENER_V_20_Oct_Rev_2-OPT.pdf. [Accessed 10 November 2023].
[159] Oficial de la Federación Diario. Law for geothermal energy (in Spanish: "Ley de Energía geotérmica"). Nueva Ley publicada en el Diario Oficial de la Federación, DOF 11-08-2014, Cámara de Diputados del H. Congreso de la Unión, Estados Unidos Mexicanos. 2014. 11 de agosto de 2014, 22 pp. https://www.diputados.gob.mx/LeyesBiblio/pdf/LEG_110814.pdf. [Accessed 10 November 2023].
[160] Oficial de la Federación Diario. Law for energy transition (in Spanish: "Ley de Transición Energética"). Nueva Ley publicada en el Diario Oficial de la Federación, DOF 24-12-2015, Cámara de Diputados del H. Congreso de la Unión, Estados Unidos Mexicanos. 2015. 24 de diciembre de 2015, 40 pp. https://www.diputados.gob.mx/LeyesBiblio/pdf/LTE.pdf. [Accessed 10 November 2023].
[161] Oficial de la Federación Diario. General law for climate change (in Spanish: "Ley general de Cambio Climático"). Nueva Ley publicada en el Diario Oficial de la Federación, Ultima Reforma, DOF 11-05-2022, Cámara de Diputados del H. Congreso de la Unión, Estados Unidos Mexicanos, 6 de junio de 2012. 2012. p. 66. https://www.diputados.gob.mx/LeyesBiblio/pdf/LGCC.pdf. [Accessed 10 November 2023].
[162] Braat L. In: Kuik O, Verbruggen H, editors. The predictive meaning of sustainability indicators. In search of indicators of sustainable development. Dordrecht: Kluwer Academic Publishers; 1991. p. 57–70.
[163] Wu J, Wu T. In: Madu Christian N, Kuei C, editors. Sustainability indicators and indices. Handbook of sustainable management. London: Imperial College Press; 2012. p. 65–86.
[164] Vallarta-Serrano SI, Santoyo-Castelazo E, Santoyo E, García-Mandujano EO, Vázquez-Sánchez H. Integrated sustainability assessment framework of industry 4.0 from an energy systems thinking perspective: bibliometric analysis and systematic literature review. Energies 2023;16(14):5440.

List of Abbreviations

BWT: Basic Working Tasks
CML: Centrum voor Milieukunde Leiden
EN: Environmental
EC: Economic
EGS: Enhanced Geothermal Systems
GHG: Greenhouse Gas
GEOSI: Geothermal Sustainability Indicators
GET: Geothermal Technologies
GSAP: Geothermal Sustainability Assessment Protocol
HSAP: Hydropower Sustainability Assessment Protocol
ISAF: Integrated Sustainability Assessment Framework
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCSA: Life Cycle Sustainability Assessment
MAE: Mean Absolute Error
MAPE: Mean Absolute Percentage Error
MAVT: Multi-attribute Value Theory
MCDA: Multi-Criteria Decision Analysis
MGDM: Multi-Group Decision Making
PASUR: Participatory Survey Research
PDSE: Participatory Development for Stakeholder Engagement
RE: Renewable Energy
RMSE: Root Mean Square Error
SAF: Sustainability Assessment Framework
SDG: Sustainable Development Goals
SI: Sensitivity Index
SII: Sustainability Importance Index
S-LCA: Social Life Cycle Assessment
SO: Social

Impact Assessment Categories

AP: Acidification Potential
ADP: Abiotic Depletion Potential
CED: Cumulative Energy Demand
EP: Eutrophication Potential
FAETP: Freshwater Aquatic Ecotoxicity Potential
GWP: Global Warming Potential
HTP: Human Toxicity Potential
MAETP: Marine Aquatic Ecotoxicity Potential
MEP: Marine Eutrophication Potential
ODP: Ozone Depletion Potential
PMFP: Particulate Matter Formation Potential
POFP: Photochemical Oxidant Formation Potential
TETP: Terrestrial Ecotoxicity
WD: Water Depletion
WC: Water Consumption

Nomenclature

X': Normalised data; X'_{Max} and X'_{Min} corresponds to maximisation and minimisation cases

x_{obs}: Datum within a data set
x_{Max}: Largest datum within a set
x_{Min}: Smallest datum within a set
$V(SG)$: Normalised marginal value function in [0, 10] for each indicator per stakeholder group (SG) in attribute i
nm: Number of statistical metrics
ns: Effective number of surveyed per sector and per sustainability pillar
w_i: Weighting factor used by the statistical metric and groups
$\overline{X}_i$: Normalised data of criteria
$SG_{\{a,i,g,s\}}$: Indicators cluster by stakeholder group (academia, industry, government, and society)
k: Maximum weight given to a single criterion (k = 5)
W_i: Weight given by the respondent to the statistical metrics

More info

SDi@JPUTM

SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
8) The Sustainable Integration of AI in Higher Education: Analyzing ChatGPT Acceptance Factors Through an Extended UTAUT2 Framework in Peruvian Universities (2024)	SUSTAINABILITY (Article From : MDPI)

27th FEBRUARY 2025
SOURCE: PERPUSTAKAAN UTM

sustainability

MDPI

Article

The Sustainable Integration of AI in Higher Education: Analyzing ChatGPT Acceptance Factors Through an Extended UTAUT2 Framework in Peruvian Universities

Marco Agustín Arbulú Ballesteros [1,*], Benicio Gonzalo Acosta Enríquez [2], Emma Verónica Ramos Farroñán [3], Hugo Daniel García Juárez [3], Luis Edgardo Cruz Salinas [3], Julio Ernesto Blas Sánchez [1], Julie Catherine Arbulú Castillo [3], Gladys Sandi Licapa-Redolfo [4] and Gary Christiam Farfán Chilicaus [3]

[1] Ingeniería de Sistemas—Campus Virtual, Escuela de Contabilidad—Campus Chiclayo, Universidad Tecnológica del Perú, Chiclayo 14011, Peru; c15383@utp.edu.pe
[2] Departamento de Ciencias Psicológicas, Universidad Nacional de Trujillo, Trujillo 13001, Peru; t528100220@unitru.edu.pe
[3] Instituto de Investigación en Ciencias y Tecnología, Universidad César Vallejo, Campus Chepén-Chiclayo, Trujillo 13001, Peru; eramosf@ucv.edu.pe (E.V.R.F.); hgarcia@ucv.edu.pe (H.D.G.J.); lcruzs@ucv.edu.pe (L.E.C.S.); jarbuluca26@ucvvirtual.edu.pe (J.C.A.C.); gfarfanch@ucvvirtual.edu.pe (G.C.F.C.)
[4] Grupo de Investigación en Ecología Evolutiva, Protección de Cultivos, Remediación Ambiental, y Biotecnología (EPROBIO), Universidad Privada del Norte, Trujillo 13006, Peru; gladys.licapa@upn.edu.pe
* Correspondence: c14069@utp.edu.pe; Tel.: +51-991413001

Abstract: ChatGPT, a large language model AI, has the potential to transform higher education by providing students with personalized learning support, assisting in writing tasks, and enhancing their level of engagement. This study examines the factors influencing the acceptance of ChatGPT among university students in Peru, following the extended UTAUT2 model with the addition of a construct called knowledge sharing (KS). A total of 772 students from seven universities in Lambayeque and La Libertad participated in an online survey, providing insights into their perceptions and experiences with using ChatGPT for academic purposes. The results from the structural equation model showed that effort expectancy, behavioral intention, and knowledge sharing positively influenced the actual use of ChatGPT. Furthermore, effort expectancy and performance expectancy were found to be determinants of the behavioral intention to use ChatGPT. The study also revealed that performance expectancy and behavioral intention serve as sequential mediating variables regarding the effect of effort expectancy on actual use. These findings suggest a positive adoption of ChatGPT among students, driven by individual and contextual factors, and highlight the importance of managing effort and performance expectations appropriately. This study represents a significant advancement in understanding the acceptance of ChatGPT in higher education and provides valuable guidance for practical implementation efforts, ensuring that this powerful AI tool is effectively leveraged to support student learning and success.

Keywords: ChatGPT; UTAUT2; artificial intelligence; educational technology; higher education; undergraduate students

check for updates

Citation: Arbulú Ballesteros, M.A.; Acosta Enríquez, B.G.; Ramos Farroñán, E.V.; García Juárez, H.D.; Cruz Salinas, L.E.; Blas Sánchez, J.E.; Arbulú Castillo, J.C.; Licapa-Redolfo, G.S.; Farfán Chilicaus, G.C. The Sustainable Integration of AI in Higher Education: Analyzing ChatGPT Acceptance Factors Through an Extended UTAUT2 Framework in Peruvian Universities. *Sustainability* **2024**, *16*, 10707. https://doi.org/10.3390/su162310707

Academic Editor: Antonio P. Gutierrez de Blume

Received: 14 November 2024
Revised: 29 November 2024
Accepted: 3 December 2024
Published: 6 December 2024

1. Introduction

1.1. Current Status of ChatGPT in Higher Education

The adoption of ChatGPT-4o in higher education is part of a broader trend of incorporating advanced technologies into educational settings, requiring a careful assessment of students' behavioral intention to use and actual use of these tools [1]. Since its launch in November 2022, ChatGPT has seen massive acceptance and usage by university students. Statistically, a study conducted in Karachi, Pakistan, revealed that 76.2% of participants were aware of ChatGPT, even though 51.4% did not frequently use it [2]. ChatGPT has been noted for its ability to generate natural language, offering potential applications in learning, research, and academic communication [3]. However, the integration of such technologies into higher education raises fundamental questions about students' readiness to adopt them, barriers to their effective use, and differences in technological acceptance among various student populations [4].

Studies have shown the mixed effects of ChatGPT in the teaching–learning process in higher education, with both potential benefits and significant challenges [5,6]. It can enhance the educational experience and provide immersive, dynamic, and personalized learning environments, potentially increasing student engagement [7,8]. Furthermore, it is considered a student-driven innovation with the potential to empower them and enhance their educational experiences and resources [8]. Studies have shown varying attitudes toward the use and implementation of ChatGPT in their academic activities, as shown in the study by [9], where 73.2% of participants agreed on ChatGPT's potential to facilitate the learning process. However, there are concerns about the negative impact of ChatGPT, particularly on higher-order thinking skills and students' intellectual growth [10,11]. According to [2], 50.1% of participants believed that using ChatGPT could diminish their cognitive ability, whereas 40.0% expressed no concern about privacy and security issues. Issues related to integrity, accuracy, reliability, information bias, and privacy need to be considered when employing AI in education [7,12]. Nevertheless, a survey among students revealed that although many are familiar with ChatGPT, they do not routinely use it for academic purposes and are skeptical of its positive effects on learning [11]. Students also expressed the need for clearer guidelines and better training on how and where the tool can be used for learning activities [11].

On the other hand, the global issue is characterized by several aspects: There is variability in students' familiarity and comfort with AI technologies such as ChatGPT, which can influence their willingness to use these tools in their learning [13]. For example, the perception of the utility and efficacy of ChatGPT in educational contexts is a critical factor that may vary according to academic discipline and teaching method [14]. Additionally, concerns about data privacy, academic integrity, and overreliance on technology emerge as significant barriers to ChatGPT acceptance [15]. The technological infrastructure and access to digital resources are unequal globally, which could result in an uneven adoption of these tools across different regions and socioeconomic strata [16].

1.2. International Perspectives on ChatGPT Adoption

In the United States, with an advanced educational system and a high degree of technological adoption, the issue centers on integrating ChatGPT as a complementary tool in learning [17]. Challenges include concerns about academic integrity, given the potential for the misuse of AI in producing academic work, and the need to develop critical skills to distinguish between AI-generated information and traditional academic sources [18]. In Japan, a country known for its rapid adoption of technology, the generally positive cultural attitude toward AI and automation facilitates its acceptance but also raises questions about technological dependency and the need to maintain essential human skills in education [19]. In Germany, with its emphasis on technical and professional education, there is a particular interest in applying ChatGPT in the technical and scientific fields [20]. However, there is caution regarding data privacy and security, which are critical aspects of European regulation.

With a rapidly expanding educational system and an emerging tech sector, India faces the challenge of the digital divide [21]. However, in urban areas and among populations with better access to resources, the acceptance of ChatGPT may be high; in more rural and less developed regions, limited access to technology and digital infrastructure represents significant obstacles [22]. In Nigeria, the adoption of ChatGPT in higher education faces unique challenges related to technological infrastructure, internet connectivity stability, and the availability of digitized educational resources. Additionally, there is a gap in technical skills and familiarity with AI tools, requiring a focus on training and developing digital skills among students and teachers. Consequently, the issue of ChatGPT acceptance in these five countries highlights how differences in technological infrastructure, privacy regulations, cultural attitudes toward AI, and challenges in academic integrity and access equity uniquely shape the integration and use of this technology in higher education.

The integration of ChatGPT in higher education presents unique characteristics that deserve careful examination through established theoretical frameworks. As demonstrated by [23–25], the UTAUT2 model provides a robust framework for understanding how students adopt and use ChatGPT in academic settings. These studies have shown that the relationship between effort expectancy and actual use takes on particular importance in educational contexts, where ease of use directly influences adoption patterns. Furthermore, research by [5,6] has revealed that the successful implementation of ChatGPT in higher education depends not only on technological factors but also on institutional support and clear guidelines. This aligns with UTAUT2's emphasis on facilitating conditions as a key determinant of technology adoption. The findings from [23,26,27] demonstrate that performance expectancy plays a crucial role in students' decisions to incorporate ChatGPT into their learning processes, particularly when they perceive clear benefits for their academic performance. Recent studies [7,10,11] have also highlighted how the educational application of ChatGPT differs from other technological tools, requiring the specific consideration of factors such as academic integrity, learning effectiveness, and ethical use. These considerations extend the traditional UTAUT2 framework by incorporating elements unique to AI-powered educational tools.

1.3. ChatGPT Implementation in Peru

In the context of Peru, the issue of the acceptance and use of ChatGPT by higher-education students presents unique challenges and opportunities, reflecting the country's socioeconomic, cultural, and technological characteristics [28]. One of the most significant challenges is the existing digital divide in the country [29]. Although there is relatively high access to technology and internet connectivity in urban areas such as Lima, this access is limited in more rural and remote regions [30]. This difference directly impacts the possibility of using tools such as ChatGPT, limiting its use to a more privileged segment of the student population [31]. The technological infrastructure of Peruvian educational institutions varies considerably, while some private universities and research centers have advanced technological resources, and many public institutions face limitations in terms of hardware and software, which may restrict the effective integration of AI-based solutions into their curricula and teaching methods [32].

The familiarity and comfort of students and teachers with emerging technologies such as ChatGPT are not uniform. There is a need to foster a culture of innovation and technological adaptability in the education system, as well as to develop digital competencies in both students and teachers [33]. Consequently, the implementation of balanced strategies that integrate these technologies in a way that complements and enriches the educational process, rather than replacing fundamental aspects, is necessary [34]. Education policies in Peru related to advanced technology in education are still in development [35]. Creating regulations that ensure the ethical and responsible use of AI while promoting innovation and digital inclusion is essential for the successful integration of tools such as ChatGPT into higher education [36].

1.4. Research Gap and Study Objectives

While numerous studies have investigated acceptance and attitudes toward ChatGPT, there is a notable paucity of research on the behavioral intention to use and the actual use of this tool [37]. Moreover, there is a deficiency in the recent literature on the adoption of ChatGPT within higher education [26,38]. This study aims to fill this gap by examining how performance expectations and effort expectancy affect both the behavioral intention to use and the actual use of ChatGPT. Additionally, the literature has not yet explored how the dissemination of knowledge about ChatGPT among students impacts its actual use. Therefore, this study adds to the discourse by analyzing the moderating effect of knowledge sharing on the intention to use and the actual use of ChatGPT.

While existing research has established UTAUT2's validity for studying technology adoption, its application to AI-powered educational tools like ChatGPT presents unique opportunities and challenges. Previous studies [23,26,27] have primarily focused on general acceptance patterns, but there remains a critical need to understand how the model's constructs specifically operate in the context of AI-enhanced learning environments. This study addresses this gap by examining not only the direct relationships between UTAUT2 constructs but also their unique manifestations in ChatGPT-enabled educational settings.

Specifically, this study aims to address the following research objectives:

1. To examine how effort expectancy and performance expectancy specifically influence ChatGPT adoption among Peruvian university students, considering the unique technological infrastructure and digital literacy levels in the Lambayeque and La Libertad regions.
2. To analyze the role of knowledge-sharing practices within Peruvian academic communities in mediating the relationship between behavioral intention and actual use of ChatGPT.
3. To identify the most significant barriers and facilitators to ChatGPT adoption in Peruvian universities, particularly focusing on:
    - Infrastructure availability and internet connectivity;
    - The digital competency levels of students;
    - Academic policies regarding AI tool usage;
    - Cultural attitudes toward AI adoption in education.
4. To determine how the relationship between effort expectancy and actual use is moderated by:
    - Students' prior experience with AI tools;
    - Access to technological resources;
    - Academic discipline (Business vs. Engineering).

These refined objectives reflect the specific context of Peruvian higher education and acknowledge the unique challenges and opportunities present in regional universities. By focusing on these specific aspects, this study aims to provide actionable insights for university administrators developing AI integration policies, faculty members implementing ChatGPT in their courses, educational technology planners addressing infrastructure needs, and policymakers working on digital education initiatives in Peru.

1.5. Study Significance and Contributions

This study presents several unique aspects that contribute to a deeper understanding of the acceptance and use of ChatGPT by university students. It employs the extended UTAUT2 model with the addition of the knowledge-sharing (KS) construct, allowing for an exploration of how knowledge exchange among students influences the acceptance and actual use of ChatGPT. Additionally, it focuses on university students from the Lambayeque and La Libertad regions in Peru, providing a specific contextual perspective on how geographical and cultural factors may affect the adoption of ChatGPT.

One of the main contributions of this study is its analysis of the mediating role of KS in the relationships between performance expectancy (PE) and the actual use of ChatGPT and between effort expectancy (EE) and the actual use of ChatGPT. These analyses shed light on how knowledge sharing among students can influence the relationship between individual perceptions of ChatGPT and its actual use.

Furthermore, this study extensively explores the interactions between the constructs of the UTAUT2 model and KS, evaluating the moderating role of KS in the relationships between EE, PE, behavioral intention (BI), and the actual use (AU) of ChatGPT. These interactions provide a more nuanced understanding of how individual and contextual factors mutually influence the adoption of ChatGPT.

This study also stands out for its focus on the long-term impact and sustainability of ChatGPT use in higher education. This finding underscores the need for the continuous evaluation of the adaptation and evolution of ChatGPT in response to changing educational needs and challenges, as well as the implications of increased reliance on artificial intelligence in education. Finally, this study addresses ethical considerations and academic integrity issues related to the adoption of ChatGPT in higher education. These findings emphasize the importance of developing and implementing clear policies for the appropriate use of ChatGPT and fostering a culture of transparency and respect for academic norms.

The primary objective of this study was to analyze the factors influencing the acceptance and use of ChatGPT by university students in Peru. Specifically, it aims to examine how individual and contextual factors, such as effort expectancy, performance expectancy, and knowledge sharing, affect the adoption of this artificial intelligence tool in the realm of higher education. Additionally, this study sought to explore the mediating role of performance expectancy and behavioral intention in the relationship between effort expectancy and the actual use of ChatGPT. Furthermore, it investigates the moderating effect of knowledge sharing on the relationships between the constructs of the UTAUT2 model and the actual use of ChatGPT.

Moreover, although ChatGPT has gained popularity among university students, it is crucial to investigate usage intention to better understand the factors driving its adoption and continuous use in the educational context. Despite ChatGPT's growing popularity, its effective integration into higher education necessitates a deep understanding of students' perceptions, attitudes, and motivations for using it. Investigating usage intention also helps identify the key factors influencing students' decisions to adopt and use ChatGPT for academic purposes. This is particularly relevant given that the use of ChatGPT in higher education presents both opportunities and challenges, such as issues related to academic integrity, information accuracy, and overreliance on technology.

1.6. Practical and Social Implications

Socially, the justification for the study lies in its ability to address and understand the needs, expectations, and concerns of higher-education students regarding the adoption of new technologies. Given that education plays a crucial role in social and personal development, understanding how AI tools such as ChatGPT are perceived and used can offer insights for enhancing teaching and learning processes. This study has the potential to provide a framework for the development of educational policies and technological implementation strategies that are inclusive and sensitive to the diverse socioeconomic and cultural realities of students.

The practical implications include the proper management of student expectations, the provision of training and support, the development of clear policies, the integration of technology into the curriculum, investment in infrastructure, and continuous evaluation. By addressing these aspects, universities can effectively leverage the potential of ChatGPT to enhance learning, foster student engagement, and prepare students for success in an increasingly technology-driven world. Ultimately, this study lays the groundwork for the strategic implementation of ChatGPT in higher education, ensuring that this powerful AI tool is effectively utilized to support student learning and success.

Finally, the study is justified from an economic perspective, as it explores ChatGPT's potential to influence the efficiency and effectiveness of higher education. The adoption of AI tools can lead to the optimization of resources, both in terms of time and costs, for educational institutions and students. Moreover, by preparing students for an increasingly technological and automated job market, this study can provide guidance on how to integrate AI-related skills into education, thereby increasing the employability and economic competitiveness of graduates.

Furthermore, the environmental implications of ChatGPT adoption in education warrant consideration. The deployment of large language models like ChatGPT raises important questions about energy consumption and computational resource requirements.

While AI tools can potentially reduce traditional resource usage through the digitalization of educational materials and reduced physical transportation needs, they also present environmental challenges through increased energy consumption in data centers and computing infrastructure. Educational institutions must balance the benefits of AI adoption with sustainable practices and energy-efficient implementation strategies. This includes considering the carbon footprint of AI model training and deployment, as well as exploring ways to optimize resource utilization while maintaining educational effectiveness. Understanding these environmental aspects is crucial for developing sustainable long-term strategies for AI integration in higher education.

1.7. General Implications of ChatGPT

The generative pretrained transformer (ChatGPT) was launched to the public in November 2022 [39–42]. It quickly gained global popularity, reaching 100 million users by January [40]. Additionally, ChatGPT is estimated to have had a profound impact across various fields, such as nursing, education, and interdisciplinary research [41,43,44]. This language system has diverse applications, ranging from customer service systems to virtual assistants and chatbots [45].

In the educational domain, ChatGPT has been shown to positively impact the teaching–learning process, but proper teacher training is critical for successful implementation [5]. The potential of ChatGPT in education is apparent, with studies highlighting its benefits and challenges in educational settings [26,27,46–49].

It can enhance educational experience, but reliance on ChatGPT may lead to a decline in higher-order thinking skills among students [10]. Students are familiar with ChatGPT, but they require better guidelines and training on its use in learning activities [11]. ChatGPT has been used to generate medical and scientific articles, interpret complex datasets, and provide quick access to medical information [50]. It is noted for its ability to express ideas clearly and frame general contexts comprehensibly, but limitations in temporal scope and the need for expert corrections are cited as weaknesses and threats [50].

A study on the general population's knowledge, attitudes, and practices toward ChatGPT revealed that most participants were familiar with ChatGPT and believed in its capacity to understand and respond to user queries, but some expressed concerns about potential negative effects on cognitive abilities when relying too heavily on ChatGPT [2].

Additionally, ChatGPT can provide personalized assistance to university students via models such as UTAUT2 to investigate the factors influencing usage intention and actual use [23,24,26,27]. Ref. [51] also highlighted the role of knowledge sharing in the use of chatbots. However, the present study focuses on university students from Lambayeque and La Libertad in Peru and analyses the mediating role of knowledge sharing in the relationships between performance expectancy, effort expectancy, and the actual use of ChatGPT. Additionally, it extensively explores the interactions between the constructs of the UTAUT2 model and knowledge sharing, evaluating the moderating role of the latter in the relationships between effort expectancy, performance expectancy, behavioral intention, and the actual use of ChatGPT. This provides a more nuanced understanding of how individual and contextual factors mutually influence the adoption of this technology.

1.8. Use of ChatGPT in Higher Education

Since its launch, ChatGPT has gained significant attention among university students, with research showing both benefits and challenges in its academic applications [52]. Research indicates that ChatGPT can contribute to improving student learning outcomes and that it is perceived as a valuable learning support tool [52,53]. A study among university students at the University of Jordan revealed a strong positive attitude toward using ChatGPT as a learning tool, with the majority agreeing on its potential to facilitate the learning process [9].

On the other hand, ChatGPT can provide personalized assistance and support to students, particularly those facing language barriers, and alleviate the workload of university staff [54]. A systematic review of 12 studies concluded that ChatGPT has a positive effect on the teaching–learning process but highlighted the importance of teacher training to use the tool appropriately [5].

However, students also express skepticism about the positive effects of ChatGPT on learning and are concerned with its potential negative effects, such as cheating and misinformation [11,55]. Students are skeptical about the positive impact of ChatGPT on learning and believe that universities should provide clearer guidelines and better education on how and where the tool can be used for learning activities [11].

Users are concerned about the potential negative effects on their cognitive ability when they are overly dependent on ChatGPT, although they also trust its accuracy and have moderate confidence in the information provided [2,56].

While students admire the capabilities of ChatGPT and consider it interesting, motivating, and useful for study and work, they also believe that its responses are not always accurate and that it requires good prior knowledge to work with it [53].

Consequently, ChatGPT is considered a tool that can be used to obtain educational benefits, but there are concerns about academic integrity and the decline in higher-order thinking skills among students who rely too heavily on it [7,10]. Therefore, the use of ChatGPT in education presents opportunities for students and instructors but also presents challenges such as issues of academic integrity, accuracy, and reliability. Precise recommendations are listed for students and instructors to address these challenges [7,57].

1.9. Unified Theory of Acceptance and Use of Technology (UTAUT2)

The application of UTAUT2 in educational AI contexts, particularly with ChatGPT, has revealed unique adoption patterns that extend beyond traditional technology acceptance models. Studies [23–25] have demonstrated that when applied to AI-powered educational tools, UTAUT2 constructs such as effort expectancy and performance expectancy take on new dimensions. For instance, effort expectancy in ChatGPT usage relates not only to technical operation but also to the ability to formulate effective prompts and critically evaluate AI-generated responses. The model's effectiveness in explaining ChatGPT adoption is particularly evident in research by [23,26,27], which shows how performance expectancy in educational contexts encompasses both immediate task completion benefits and longer-term learning outcomes. Furthermore, studies [5,7,11] have identified how social influence and facilitating conditions play crucial roles in educational settings, where institutional policies and peer attitudes significantly impact adoption decisions.

The unified theory of acceptance and use of technology (UTAUT2) has garnered significant attention in information systems research and other fields, with over 6000 citations and widespread use across various sectors [58,59]. UTAUT emphasizes the importance of technology going through phases such as design, planning, implementation, and utilization before it can change people's lives [60]. On the other hand, UTAUT2, an expanded version, has become popular for examining consumer-centric issues and has proven to be more explanatory in predicting behavioral intentions related to technology adoption [61,62].

Research on UTAUT2 has been increasing, and a structured analysis of the literature has been used to synthesize research patterns and growth trends from 2012 to 2019 [59]. UTAUT2 has been applied in various sectors, such as education, banking, healthcare, tourism, e-government services, and personality studies, demonstrating its versatility and relevance in different contexts [63]. Given its widespread use and growth in research, UTAUT2 appears to be a robust and versatile theory with practical implications for the acceptance, adoption, and use of technology in various contexts. However, it is important to note that the analysis is based on available abstracts, and a thorough review of the full articles is recommended for a deeper understanding.

The UTAUT2 model integrates several constructs that explain the adoption and use of ChatGPT by users. Along with expanded constructs such as perceived interactivity and privacy concerns, UTAUT2 can explain user interaction and engagement with ChatGPT [24,48,64]. On the other hand, performance expectancy, hedonic motivation, price value, and habits influence the behavioral intention to use ChatGPT [48]. Furthermore, habits, performance expectancy, and facilitating conditions influence behavioral intention and usage behavior [26,47].

1.10. Presentation of the Research Model

Figure 1 presents the research model, which contains 12 hypotheses grounded in the UTAUT2 model [63,65], used to investigate the acceptance and use of ChatGPT by university students. Instead of adopting the complete model, specific constructs deemed more relevant to the context of AI technologies in education were carefully selected, whereas others were excluded to maintain model parsimony and focus on key relationships.

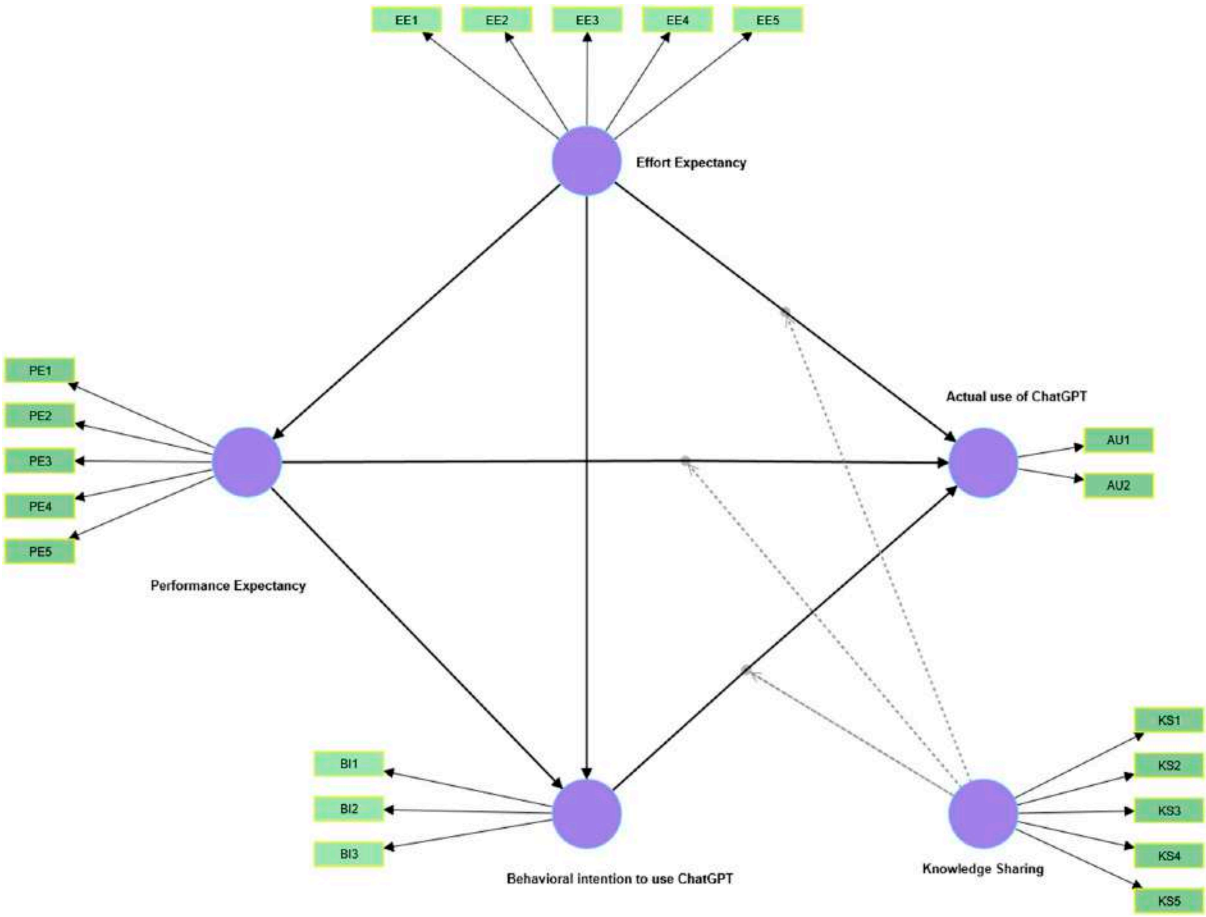


Figure 1. Proposed research model. Solid arrows represent direct relationships between variables, while dashed arrows indicate possible moderating effects.

The constructs included in the proposed model are EE, PE, BI, AU, and KS. EE and PE were selected because they represent two of the most influential predictors of technology use intention [63]. In the context of ChatGPT, EE captures the perceived ease of interacting with an AI tool, whereas PE reflects students' perceptions of how ChatGPT can enhance their academic performance [23,25]. These constructs are especially relevant since the adoption of ChatGPT by students is likely driven by pragmatic considerations of usability and utility.

Additionally, BI was included as a key mediator between EE, PE, and AU, aligning with the theory of planned behavior [60] and the original UTAUT2 model. The inclusion of KS as a new construct in the model is justified by the crucial role that peer knowledge sharing plays in learning and the adoption of new technologies in educational settings [51]. Given the novel nature of ChatGPT, students are likely to rely heavily on knowledge sharing to learn about its functionalities and applications, which in turn can influence their intention to use the tool and its actual use [23].

The decision to exclude certain UTAUT2 constructs was based on careful theoretical and contextual considerations:

Facilitating Conditions: While this construct is valuable in general technology adoption contexts, it was excluded because ChatGPT is freely accessible through web browsers, requiring minimal technical infrastructure beyond basic internet access. Additionally, the construct's core elements are partially captured within our effort expectancy measurements.

Hedonic Motivation: This construct was omitted because the study focuses primarily on the academic and learning-oriented use of ChatGPT rather than entertainment or pleasure-derived motivations. In educational settings, performance-related factors are more relevant for understanding adoption patterns than hedonic aspects.

Price Value: Given that ChatGPT is currently available at no direct cost to students, the price-value construct would not provide meaningful variation in our context. While there may be indirect costs (internet access, device usage), these are not specific to ChatGPT usage and would not significantly influence adoption decisions.

Habits: The habit construct was excluded due to ChatGPT's relatively recent introduction in educational settings. At this early stage of adoption, habitual use patterns have not yet been fully established, making this construct less relevant for current analysis. Future studies may benefit from including this construct as usage patterns become more established over time.

These exclusions allowed us to maintain model parsimony while focusing on the most relevant factors for understanding ChatGPT adoption in the specific context of Peruvian higher education. This focused approach aligns with previous studies [23,26,27] that have successfully adapted the UTAUT2 model by selecting the most contextually relevant constructs.

Similarly, the following is a conceptual definition of the constructs used in the study. EE refers to the perceived ease of use and cognitive effort necessary to use ChatGPT for learning. It directly impacts students' intentions to use ChatGPT and subsequently influences their actual use of the tool for learning purposes [23,25]. PE is a relevant construct in technology adoption models, representing the degree to which an individual believes that using a particular system will help them achieve performance gains at work [66]. In the context of higher education, considering the diverse applications of ChatGPT, the components of PE could include expectations related to efficiency in information acquisition, creativity, writing competence, linguistic competence, academic performance, and satisfaction [66,67]. BI is defined as an individual's readiness and motivation to use and adopt ChatGPT technology in their activities [68,69]. The BI of ChatGPT is grounded in the UTAUT2 model and is influenced by various factors, including facilitating conditions, social influence, trust, novelty of design, and institutional policy [47,70]. On the other hand, the AU construct, which is based on the study of [23], refers to the application and exploitation of this technology in the field of higher education. In this context, AU implies the integration of ChatGPT into teaching–learning processes, where university students evaluate its utility and limitations in enhancing their educational experience [5,71]. This usage encompasses students' interaction with the tool to generate detailed responses to their questions and requests, as well as to obtain assistance in specific academic tasks [10,72]. Finally, the KS construct, which is based on the study of [51], refers to the process by which students exchange, transfer, and disseminate knowledge, experience, skills, and relevant information related to the use and application of ChatGPT in their academic environment. This exchange can occur formally or informally through various channels and media, such as online forums, social networks, study groups, or face-to-face interactions.

1.11. Quantitative Support of the Research Hypotheses

Multiple studies have examined the determinants of students' intentions to use ChatGPT and their actual usage behavior [24,26,27,68]. Performance expectancy, effort expectancy, hedonic motivation, and habits significantly influence the intention to use ChatGPT [24,26,27,68]. Behavioral intention has been identified as a significant positive predictor of students' ChatGPT usage behavior [24,26,68]. Additionally, personal innovativeness, information accuracy, and institutional policies moderate the relationship between ChatGPT usage and its determinants [27,68]. Therefore, the following hypothesis is proposed:

Hypothesis 1. *Behavioral intention (BI) influences the actual use of ChatGPT (AU).*

Multiple studies using the unified theory of acceptance and use of technology (UTAUT) framework have shown that effort expectancy has a direct positive effect on students' intentions to use ChatGPT, which in turn promotes their actual use of the tool for learning purposes [23–26]. Furthermore, a previous study indicated that effort expectancy not only directly affects students' actual use of ChatGPT but also significantly increases their actual use indirectly through performance expectations and intentions to use ChatGPT [23]. A significant mismatch between EE and PE could diminish the level of intention and actual use of ChatGPT for learning [25].

These studies shed light on the educational environment by testing how higher-education students' intentions to use ChatGPT and subsequent use of ChatGPT are synthesized from the balance between high effort expectancy and performance expectancy [23–26].

Therefore, effort expectancy (EE) may influence users' actual use of ChatGPT (AU). Consequently, the following hypothesis is proposed:

Hypothesis 2. *Effort expectancy (EE) influences the actual use of ChatGPT (AU).*

The unified theory of acceptance and use of technology (UTAUT) model was used to explore the impact of EE on BI among higher-education students [25,66]. The findings suggest that EE has a direct positive effect on the likelihood of students adopting ChatGPT for learning purposes [23,24].

Additionally, a study in Indonesia reported that EE did not significantly influence BI, indicating inconclusive results [66]. However, the general consensus from available abstracts suggests that EE plays a significant role in influencing students' intentions to use ChatGPT [23–25].

Therefore, the findings of these studies provide mixed evidence on the influence of EE on the use of ChatGPT by university students for BI. While some studies support a direct positive impact, others present inconclusive results. Therefore, the influence of EE on BI may vary on the basis of different contexts and populations. Consequently, the following is established:

Hypothesis 3. *Effort expectancy (EE) influences the behavioral intention to use ChatGPT (BI).*

Various studies utilizing the UTAUT model have demonstrated the impact of EE and PE on students' intentions and actual use of ChatGPT. For example, Strzelecki [26] found that performance expectancy significantly influences students' behavioral intentions to use ChatGPT. Similarly, Foroughi et al. [27] demonstrated that both effort expectancy and performance expectancy are key determinants in ChatGPT adoption among university students. This is further supported by Duong et al. [23], who found that effort expectancy directly affects students' actual use of ChatGPT and indirectly increases its usage through performance expectations. The relationship between these constructs has been consistently validated in educational settings. Studies by Montenegro-Rueda et al. [5] and Valova et al. [6] confirmed that when students perceive ChatGPT as easy to use (high EE) and beneficial for their academic performance (high PE), they are more likely to adopt and continue using the technology. Additionally, research by Singh et al. [11] revealed that these relationships are particularly strong in higher-education contexts where students actively seek tools to enhance their learning experience.

Importantly, however, one study revealed the nonsignificant role of effort expectancy (EE) in the behavioral intention (BI) to use ChatGPT in learning [66]. Given this, the following is formulated:

Hypothesis 4. *Effort expectancy (EE) influences performance expectancy (PE) in the use of ChatGPT.*

Studies have shown that performance expectancy significantly influences the intention to use ChatGPT [25,27]. In addition to effort expectancy, performance expectancy directly affects the likelihood of students adopting ChatGPT for learning purposes [25]. Moreover, performance expectancy was found to have a direct positive effect on the likelihood of higher-education students intending to use ChatGPT, which in turn promoted its actual use for learning [23].

The use of ChatGPT was found to promote procrastination and memory loss and attenuate the academic performance of students [73]. Additionally, the perceived utility of ChatGPT positively influences its use and student satisfaction, leading to greater individual impacts [74].

Nevertheless, findings suggest that students are familiar with ChatGPT but do not regularly use it for academic purposes and are skeptical of its positive effects on learning [23]. Students believe that universities should provide clearer guidelines and better education on how and where the tool can be used for learning activities [11]. On the basis of the above, the following is formulated:

Hypothesis 5. *Performance expectancy (PE) influences the actual use of ChatGPT (AU).*

Multiple studies using the UTAUT model have consistently demonstrated that performance expectations significantly influence the intention to use ChatGPT for educational purposes [24–27]. Additionally, individual effort and performance expectations have a direct positive effect on the likelihood that higher-education students intend to use ChatGPT [25].

Performance expectations significantly influence behavioral intention, which in turn influences the actual usage behavior of ChatGPT by students [24,26]. On the other hand, performance expectancy has been identified as one of the significant predictors of the behavioral intention to use ChatGPT in learning among students [26]. Hence, the following is formulated:

Hypothesis 6. *Performance expectancy (PE) influences the behavioral intention to use ChatGPT (BI).*

1.12. The Moderating Role of Sharing Knowledge in the Use of ChatGPT

Knowledge sharing positively moderates the relationship between behavioral intention (BI) and the actual use of ChatGPT by university students [23,27,37,51]. The modified Technology Acceptance Model (TAM) indicates that knowledge sharing significantly increases the transformation of higher-education students from intending to use ChatGPT to actual users of ChatGPT [23]. The integrated chatbot acceptance–avoidance model reveals the positive role of knowledge sharing in influencing the use of chatbots for knowledge sharing [51]. Moreover, the UTAUT2 model also supports the impact of knowledge sharing on the acceptance and usage of ChatGPT by students in higher education [26]. Therefore, the following is formulated:

Hypothesis 7. *KS positively moderates the relationship between BI and the actual use of ChatGPT (AU).*

Ref. [23] demonstrated that effort expectancy directly impacts students' actual use of ChatGPT and indirectly increases its usage through performance expectations and intentions to use ChatGPT. Performance expectations significantly influence the intention to use ChatGPT [27]. The use of ChatGPT was more significantly predicted by behavioral intention (BI), which is associated with performance expectancy [66].

It was found that knowledge sharing significantly enhanced the transformation of higher-education students from intending to use ChatGPT to becoming actual users of this language system [23]. Thus, the following hypothesis is formulated:

Hypothesis 8. *KS positively moderates the relationship between PE and the actual use of ChatGPT (AU).*

Effort expectancy directly affects students' actual use of ChatGPT and indirectly increases its use through performance expectancy and intentions to use ChatGPT [23]. Effort expectancy, together with performance expectancy, has a direct positive effect on the likelihood that higher-education students will attempt to use ChatGPT, which in turn promotes its actual use for learning purposes [25]. Knowledge sharing significantly increases the transformation of higher-education students from intending to use ChatGPT to becoming actual users of the tool [23]. Given these insights, it can be inferred that knowledge sharing positively moderates the relationship between effort expectancy and the actual use of ChatGPT by university students [23,25]. Therefore, the following hypothesis is proposed:

Hypothesis 9. *KS positively moderates the relationship between EE and the actual use of ChatGPT (AU).*

1.13. The Mediating Role of Performance Expectancy (PE) on Effort Expectancy (EE) in the Use of ChatGPT

Various studies have demonstrated that age and experience can moderate the impact of several factors on the use of ChatGPT [26,47,64]. Moreover, the relationships among EE, PE, and actual usage behavior are also moderated by gender and education level [64].

Previous studies that used the UTAUT model were employed to explore the impact of PE and EE on students' intentions and the actual use of ChatGPT [23–25,27,75]. The findings suggest that both PE and EE have a direct positive effect on students' intentions to use ChatGPT [23–25,27,75].

However, it has not been directly mentioned that PE acts as a mediating variable in the relationship between EE and BI in available abstracts. Therefore, while some studies provide insight into the impact of PE and EE on students' intentions and the actual use of ChatGPT, there is no direct evidence to support the specific mediating role of PE in the relationship between EE and BI. Hence, the following is formulated:

Hypothesis 10. *Performance expectancy (PE) is a mediating variable of the effect of effort expectancy (EE) on the behavioral intention to use ChatGPT (BI).*

The behavioral intention to use ChatGPT acts as a mediating variable in the relationship between performance expectancy and the actual use of ChatGPT by university students [23,25,27,66,76]. Additionally, factors such as performance expectancy, effort expectancy, hedonic motivation, and learning value significantly influence the intention to use ChatGPT [24,27,66]. Social influence, facilitating conditions, and habits do not directly affect the use of ChatGPT, but they can influence the intention to use ChatGPT [24,27,66].

The use of ChatGPT has been linked to tendencies toward procrastination, memory loss, and attenuated academic performance [73]. These findings could help policymakers understand the determinants and initiate effective and efficient policies to increase the use of artificial intelligence in education, specifically ChatGPT [66,68]. The following is formulated:

Hypothesis 11. *The behavioral intention to use ChatGPT (BI) is a mediating variable in the effect of performance expectancy (PE) on the actual use of ChatGPT (AU).*

Previous studies have suggested that PE and BI play a role in sequential mediation in the actual use of ChatGPT by university students [23–26,51,66,68,75]. The impact of effort expectancy (EE) and performance expectancy (PE) on students' intentions to use

ChatGPT, which subsequently influences their actual use, has been highlighted in previous studies [23,25,51,66,68,75]. Therefore, based on the evidence from these previous studies, it can be inferred that performance expectancy (PE) and behavioral intention (BI) act as sequential mediating variables in the effect of effort expectancy (EE) on the actual use of ChatGPT by university students. Hence, the following is formulated:

Hypothesis 12. *Performance expectancy and behavioral intention to use ChatGPT act as sequential mediating variables in the effect of effort expectancy on the actual use of ChatGPT.*

2. Materials and Methods

The present study is based on an exploratory and explanatory quantitative approach because the purpose was to analyze the determinant constructs of the intention of behavioral use and current use of ChatGPT. On the other hand, the study has a nonexperimental design and is cross-sectional because it does not aim to manipulate the variables under study, and the measurements were performed over a single period.

2.1. Participants

A total of 772 university students from seven universities in the Lambayeque and La Libertad departments participated in the study. No probabilistic accidental sampling was used, i.e., the participation of the participants was voluntary. This type of sampling was used because it sought to facilitate the collection of data in an efficient and rapid manner, taking advantage of the availability and immediate access to the population of interest. This methodology made it possible to collect relevant information from a broad sample of university students, although it is important to recognize that since it is not probability-based, the results obtained are not necessarily generalizable to the entire student population of the Lambayeque and La Libertad regions. Additionally, the use of non-probabilistic accidental sampling is justified because it allows for the efficient and rapid collection of data by leveraging immediate availability and access to the target population. This approach facilitated the inclusion of a diverse group of participants willing to contribute to the study, providing valuable information on the variables of interest. Although the results should be interpreted with caution due to generalization limitations, this sampling method is particularly useful in exploratory studies of an explanatory nature, where the primary objective is to develop an initial understanding of a specific phenomenon.

The characteristics and sociodemographic details of the study sample are shown in Table 1. With respect to gender, the student population is almost balanced, with a slight predominance of female students (51.5%) over male students (48.5%). This ratio suggests the equitable inclusion and participation of both genders in the university environment in Lambayeque, which could reflect an increasing trend toward gender equality in higher education in the region. Most of the students (77.6%) were aged 18–22 years. This concentration indicates that most students enter university shortly after completing secondary education. The remaining 22.4%, corresponding to students aged 23 years or older, could include those who have taken nontraditional educational paths, such as breaks in their studies or late entry into university. The proportions of business science facilities and engineering facilities are practically equal, at 49.9% and 50.1%, respectively. This disparity reflects a balanced diversification of academic interests between these two areas. However, it could also indicate a regional trend toward focusing on fields considered critical for economic and technological development. Finally, regarding years of study, there was a significant concentration of students in the first two years (59.8%). This may imply a high rate of new enrollments or perhaps a high dropout rate in later years. The 30.5% in the third and fourth years and only 9.7% in the fifth year or beyond suggest that as the years progress, the number of students decreases, which could be related to various factors, such as academic difficulty, the need to work, or personal responsibilities that interfere with the continuity of studies.

Table 1. Sociodemographic summary.

Sociodemographic Characteristics	fi	%
Gender		
Male	350	48.5
Female	372	51.5
Age		
18–20	290	40.2
21–22	270	37.4
23 and over	162	22.4
Faculty		
Business Science	360	49.9
Engineering	362	50.1
Year of study		
1st and 2nd year	432	59.8
3rd and 4th year	220	30.5
5th year or more	70	9.7

Note: n = 722.

2.2. Instruments and Data Collection

To develop the data collection instruments, an exhaustive review of the literature was conducted. Therefore, to collect the data, an online questionnaire consisting of two sections was developed. The first section included sociodemographic questions about gender, age, faculty, and year of study, as well as a filter question to determine whether participants had prior knowledge and experience using ChatGPT. The second section contained 20 items measuring the constructs of EE, PE, BI, AU, and KS. These items were based on previously validated scales and adapted to the context of ChatGPT in higher education [23,25,51,65,68,69]. A 5-point Likert scale ranging from (1) strongly disagree to (5) strongly agree was used to measure participants' responses.

The data were collected through an online survey between December 2023 and March 2024. The average time to complete the questionnaire was 14 min. A total of 820 responses were collected, of which 719 were used in the final analysis. A total of 101 forms in which students either did not consent to participate by selecting the "I do not consent" option in a mandatory branching question or indicated having no knowledge or experience with ChatGPT were excluded. This exclusion process ensured that only the responses of participants who met the inclusion criteria and provided informed consent were included in the analysis.

To analyze the data, structural equation modeling (SEM) with the statistical software JASP-free version (version: 0.19.1) was used, which employs the partial least squares (PLS) technique to test the theoretical model. Reliability was assessed via Cronbach's alpha coefficient and composite reliability (CR), whose values were above 0.7 (Table 2). With the estimation of the average variance extracted (AVE), convergent validity was evaluated, whose values were above 0.5 (Table 2), except for the KS construct, which presented a value below this threshold (0.475). Similarly, to evaluate discriminant validity, the criterion of Fornell and Larcker (1981) [77] was followed, where the square root of the AVE of each construct was used to determine whether its values were greater than the correlations of all other constructs and the specific construct.

Table 2. Reliability and validity tests.

	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)	R^2	AU	BI	EE	KS	PE	HTMT
AU	0.759	0.709	0.563	0.354	0.751					0.456
BI	0.753	0.790	0.432	0.467	0.546	0.658				0.672
EE	0.816	0.874	0.585	-	0.399	0.470	0.765			0.561
KS	0.726	0.818	0.475	-	0.430	0.429	0.376	0.689		0.692
PE	0.758	0.838	0.510	0.343	0.438	0.579	0.586	0.442	0.714	0.762

The survey instrument was developed through a rigorous three-phase process:
Phase 1: Item Development and Content Validity

- The initial questionnaire items were adapted from previously validated UTAUT2 scales [23,25,51,65,68,69];
- Items were modified to specifically address ChatGPT usage in educational contexts;
- A panel of five experts in educational technology and research methodology reviewed the items;
- The content validity was assessed using Aiken's V coefficient, achieving a value of 0.86.

Phase 2: Pilot Testing and Refinement

- A pilot study was conducted with 50 university students;
- Preliminary reliability analysis yielded Cronbach's alpha values ranging from 0.726 to 0.816;
- Items with low item-total correlations (<0.4) were revised or eliminated;
- Factor loadings ranged from 0.562 to 0.835, exceeding the minimum threshold of 0.5.

Phase 3: Final Instrument Validation

- The final questionnaire consisted of 20 items measuring five constructs:
  - Effort Expectancy (5 items);
  - Performance Expectancy (5 items);
  - Behavioral Intention (3 items);
  - Actual Use (2 items);
  - Knowledge Sharing (5 items).
- All items were measured using a 5-point Likert scale;
- The instrument was administered in Spanish, with translations validated by language experts.

3. Results

3.1. Results of the Measurement Model

Table 3 shows a comprehensive view of how various items perform within a research study. The item means indicate, in general, favorable reception by respondents, and the low standard deviations suggest that responses among items do not vary drastically, indicating consistency in the opinions or perceptions captured by the instrument. When examining the factor loadings, most of the items are adequately aligned with the theoretical constructs they are intended to measure, reflected in high values. However, some items show lower loadings, which could imply a weaker connection with the underlying construct and therefore may require closer scrutiny to confirm their validity. For the variance inflation factor (VIF), the results are mostly satisfactory, with values below 3 indicating an absence of serious multicollinearity problems. However, several items approach a VIF of 2.5, a point at which researchers might begin to take precautions to ensure that multicollinearity does not distort future results. The set of items analyzed demonstrates good potential for the reliable measurement of constructs in a research context, complementing the content validity that the instrument has passed with an Aiken v index of 0.86. Careful attention to items with borderline values for both factor loadings and VIFs will help maintain the quality and accuracy of the study's findings.

Table 3. Descriptive statistics, factor loadings, and variance inflation factor.

Item	Article	Mean	Standard Deviation (STDEV)	Factorial Loading	VIF
AU1	I use ChatGPT on a daily basis.	4.8	0.049	0.677	1.023
AU2	I use ChatGPT frequently.	5.3	0.032	0.826	1.023
BI1	I intend to increase my use of ChatGPT.	5.5	0.042	0.703	1.033
BI2	It is worth recommending ChatGPT to other students.	5.6	0.040	0.697	1.066
BI3	I'm interested in using ChatGPT more frequently in the future.	5.4	0.058	0.562	1.045
EE1	Learning how to use ChatGPT is easy for me.	4.9	0.028	0.778	1.880
EE2	My interaction with ChatGPT is clear and easy to understand.	4.7	0.024	0.821	2.110
EE3	I find ChatGPT easy to use to manage knowledge.	4.8	0.020	0.835	2.311
EE4	ChatGPT is convenient and user-friendly.	5.1	0.031	0.735	1.596
EE5	ChatGPT is easy to access.	4.9	0.032	0.613	1.146
KS1	ChatGPT allows me to share knowledge with my instructor and classmates.	6.2	0.032	0.722	1.414
KS2	ChatGPT supports discussions with my instructor and classmates.	6.4	0.050	0.580	1.068
KS3	ChatGPT facilitates the process of knowledge sharing anytime anywhere.	6.5	0.028	0.762	1.860
KS4	ChatGPT enables me to share different types of resources with my class instructor and classmates.	6.7	0.034	0.713	1.698
KS5	ChatGPT through M-learning application strengthens the relationships with my instructor and classmates.	6.1	0.035	0.643	1.437
PE1	I find ChatGPT useful in my daily study.	5.7	0.028	0.720	1.679
PE2	ChatGPT increases my chances of achieving tasks that are important to me in my study.	5.8	0.034	0.736	2.071
PE3	Using ChatGPT helps me to accomplish tasks more quickly.	5.9	0.031	0.710	1.938
PE4	Using ChatGPT increases my productivity in my study.	5.6	0.030	0.722	2.257
PE5	Using ChatGPT can save my time.	5.5	0.034	0.675	2.137

In Table 2, the results of the reliability and validity tests for the constructs used in ChatGPT study are presented. The researchers provided a detailed analysis that revealed significant aspects of internal consistency and measurement adequacy. The Cronbach's alpha coefficients, which range from 0.726 to 0.816, exceed the commonly accepted threshold of 0.7, demonstrating satisfactory reliability in the constructs and corroborating the internal cohesion of the items. Similarly, the composite reliability, with values ranging from 0.709 to 0.874, reinforces the internal reliability of the constructs, suggesting that the associated items are consistent in assessing the corresponding latent variables. On the other hand, the average variance extracted (AVE) provides a more nuanced perspective, with values that, although exceeding the minimum threshold of 0.4, in some cases do not reach the preferred standard of 0.5. This indicates an area of potential improvement in capturing the variance of the items by their constructs.

Regarding the explanatory power of the models, reflected in the R^2 values, it was found that constructs such as AU explained a significant proportion of the variance in the data, with values reaching 0.354. This finding implies that one-third of the variance in the actual use of ChatGPT can be attributed to the variables included in the study model. Convergent and discriminant validity, assessed through the cross-correlation between constructs, is appropriately manifested in the research. Correlations between different constructs demonstrate adequate discrimination, suggesting that each construct maintains its uniqueness within the conceptual framework. The findings from the assessment provide compelling evidence of the psychometric robustness of the instruments used to measure perceptions and behaviors related to the use of ChatGPT. Despite the need for ongoing scrutiny in certain areas, particularly those associated with AVEs, the study establishes a solid foundation for data interpretation and supports the implementation of evidence-based intervention strategies within the higher-education domain.

These reliability and validity indicators demonstrate more than just statistical adequacy; they reveal important patterns in how Peruvian students interact with ChatGPT. The high composite reliability values (0.709–0.874) indicate that students' responses are highly consistent across different aspects of ChatGPT use, suggesting well-formed opinions about this technology despite its relative novelty. The AVE values, particularly strong for effort expectancy (0.585), indicate that students have clear and distinct perceptions about how much effort it takes to use ChatGPT effectively in their academic work, a crucial finding for universities planning implementation strategies.

Table 4 displays the results of the effect size analysis (F^2), where it can be observed that the intention to use ChatGPT, with an effect size of 0.250, exerts a moderate effect on its actual use, suggesting a significant but not overwhelming correlation between the willingness to use and the effective use of the technology. This discovery highlights the importance of users' predisposition to the effective adoption of ChatGPT. On the other hand, EE has a notable effect, both on AU (F^2 = 0.290) and on BI (F^2 = 0.320), indicating the relevance of perceived ease of use. Additionally, this factor had a considerable influence on performance expectancy (F^2 = 0.523), emphasizing that perceptions of comfort and simplicity in use are crucial determinants of the evaluation and planning of ChatGPT use by students.

Table 4. Effect size (F^2).

	AU	BI	EE	KS	PE
AU					
BI	0.250				
EE	0.290	0.320			0.523
KS	0.310				
PE	0.428	0.465			

The role of knowledge sharing is also highlighted, with an F^2 of 0.310 for the actual use of ChatGPT, indicating that collaboration and information sharing among peers are key elements in the adoption of new technologies. Moreover, PE was identified as an influential factor, with a significant impact both on the AU (F^2 = 0.428) and on the BI (F^2 = 0.465) of ChatGPT. This demonstrates that perceptions of how the tool can enhance academic performance are fundamental both for its immediate adoption and for its willingness to use it in the future. This analysis reflects the complexity of the factors influencing the adoption of emerging technologies in education. This study provides a deep understanding of how these elements interact, offering solid foundations for the development of educational strategies that effectively integrate artificial intelligence tools such as ChatGPT into educational processes.

The effect size analysis reveals particularly important insights for Peruvian higher education. The strong effect of effort expectancy on performance expectancy (F^2 = 0.523) suggests that universities should prioritize making ChatGPT easily accessible and user-friendly, as this significantly influences students' perceptions of its usefulness. The moderate effect of behavioral intention on actual use (F^2 = 0.250) indicates that while student intentions are important, other factors like institutional support and infrastructure may play crucial roles in actual adoption within the Peruvian context.

Table 5 presents the findings of the correlations between the constructs. The correlation between AU and BI was significant (0.546), suggesting a positive and moderate relationship. This finding indicates that users' intentions to utilize ChatGPT align with its effective use, reinforcing the idea that attitudes and prior intentions can be good predictors of AU. EE shows a positive correlation with both AU (0.399) and BI (0.470), reflecting that the perceived ease of use of ChatGPT is an important factor in both effective adoption and the willingness to adopt the technology.

Furthermore, KS is moderately correlated with AU (0.430) and BI (0.429), indicating that a culture of knowledge sharing among users can influence both actual use and attitudes toward future use of the tool. PE, on the other hand, shows the strongest correlation with BI (0.679), suggesting that perceptions of how ChatGPT can improve academic or professional performance are key determinants in the decision to use the tool. Additionally, PE is significantly correlated with AU (0.438), EE (0.586), and KS (0.442), implying an interdependence between performance perception and other key factors in the adoption of ChatGPT. These findings reflect the complexity of the relationships between various constructs and underline the importance of a holistic approach to understanding and facilitating the adoption of emerging technologies such as ChatGPT in educational settings.

Table 5. Correlations between constructs.

	AU	BI	EE	KS	PE
AU	1.000				
BI	0.546	1.000			
EE	0.399	0.470	1.000		
KS	0.430	0.429	0.376	1.000	0.442
PE	0.438	0.679	0.586	0.442	1.000

Table 6 details the evaluated indices, including SRMR, d_ULS, d_G, chi-square, and NFI, which are presented for both the saturated model and the estimated model. The standardized root means square residual (SRMR) is an absolute fit indicator, with values of 0.065 for the saturated model and 0.062 for the estimated model. Both values are below the general acceptance threshold of 0.08, suggesting that the estimated model fits adequately to the correlations observed in the data. In terms of d_ULS (discrepancy function for unweighted least squares) and d_G (discrepancy function for geomin), which assess the discrepancy between the observed and estimated covariance matrices, the values are lower in the estimated model (15.040 in d_ULS and 0.893 in d_G) than in the saturated model. This improvement indicates a more precise fit of the estimated model to the data.

Table 6. A summary of the goodness-of-fit indices of the study model.

	Saturated Model	Estimated Model
SRMR	0.065	0.062
d_ULS	16.948	15.040
d_G	0.965	0.893
Chi-square	640.518	490.797
NFI	0.972	0.979

The chi-square index, which measures the discrepancy between observed covariances and those expected under the model, also shows a reduction in the estimated model (490.797) compared with the saturated model (640.518). Although this index is sensitive to sample size, the decrease suggests a better fit of the estimated model. The NFI (normed fit index), a relative fit index, presents high values for both the saturated model (0.972) and the estimated model (0.979), exceeding the threshold of 0.90 generally considered indicative of a good fit. This finding implies that the estimated model fits the data significantly better than the null model does. Together, these fit indices indicate that the theoretical model proposed in the study fits well with the observed data. The consistency of the fit indices, especially the high value of the NFI, reinforces the validity of the model in research on the incorporation and use of ChatGPT in educational environments. These results are crucial for confirming the suitability of the study's theoretical framework and for ensuring that the interpretations and conclusions derived are robust and reliable.

3.2. Contrasting the Research Hypotheses

In the study exploring the adoption of ChatGPT in educational settings, the analysis of causal pathways and their statistical significance provides detailed insight into the relationships among various key factors (as shown in Table 7 and Figure 2). Through the examination of specific hypotheses (H1 to H12), the influence of variables such as BI, EE, PE, and KS on the use of ChatGPT is assessed. Hypothesis H1, which relates BI and AU, shows a significant pathway (0.443); thus, it is accepted. Hypotheses H2 and H3 are also accepted, indicating that EE has a positive effect both on AU (0.148) and on BI (0.103). H4, which relates EE to PE, shows the strongest pathway (0.593) and is accepted, indicating that EE significantly influences how users perceive that ChatGPT can improve their performance. However, H5, which explores the relationship between PE and AU, is rejected, suggesting that the perception of performance enhancement does not necessarily translate into the actual use of ChatGPT.

Table 7. Path coefficients and *p* values of the research hypotheses.

Hypothesis		Path	*p* Value	2.5%	97.5%	DE	Interpretation
H1	BI → AU	0.443	0.000	0.300	0.527	0.054	Accepted
H2	EE → AU	0.148	0.003	0.067	0.319	0.052	Accepted
H3	EE → BI	0.103	0.010	0.041	0.217	0.040	Accepted
H4	EE → PE	0.593	0.000	0.613	0.763	0.029	Accepted
H5	PE → AU	−0.029	0.567	0.151	0.326	0.053	Rejected
H6	PE → BI	0.626	0.000	−0.122	0.097	0.037	Accepted
H7	KS × BI → AU	0.015	0.615	0.542	0.707	0.044	Rejected
H8	KS × PE → AU	−0.020	0.625	−0.119	0.087	0.052	Rejected
H9	KS × EE → AU	0.043	0.267	−0.140	0.113	0.040	Rejected
H10	EE → PE → AU	−0.017	0.568	−0.048	0.180	0.031	Rejected
H11	EE → BI → AU	0.046	0.018	0.016	0.097	0.019	Accepted
H12	EE → PE → BI → AU	0.164	0.000	0.126	0.235	0.023	Accepted

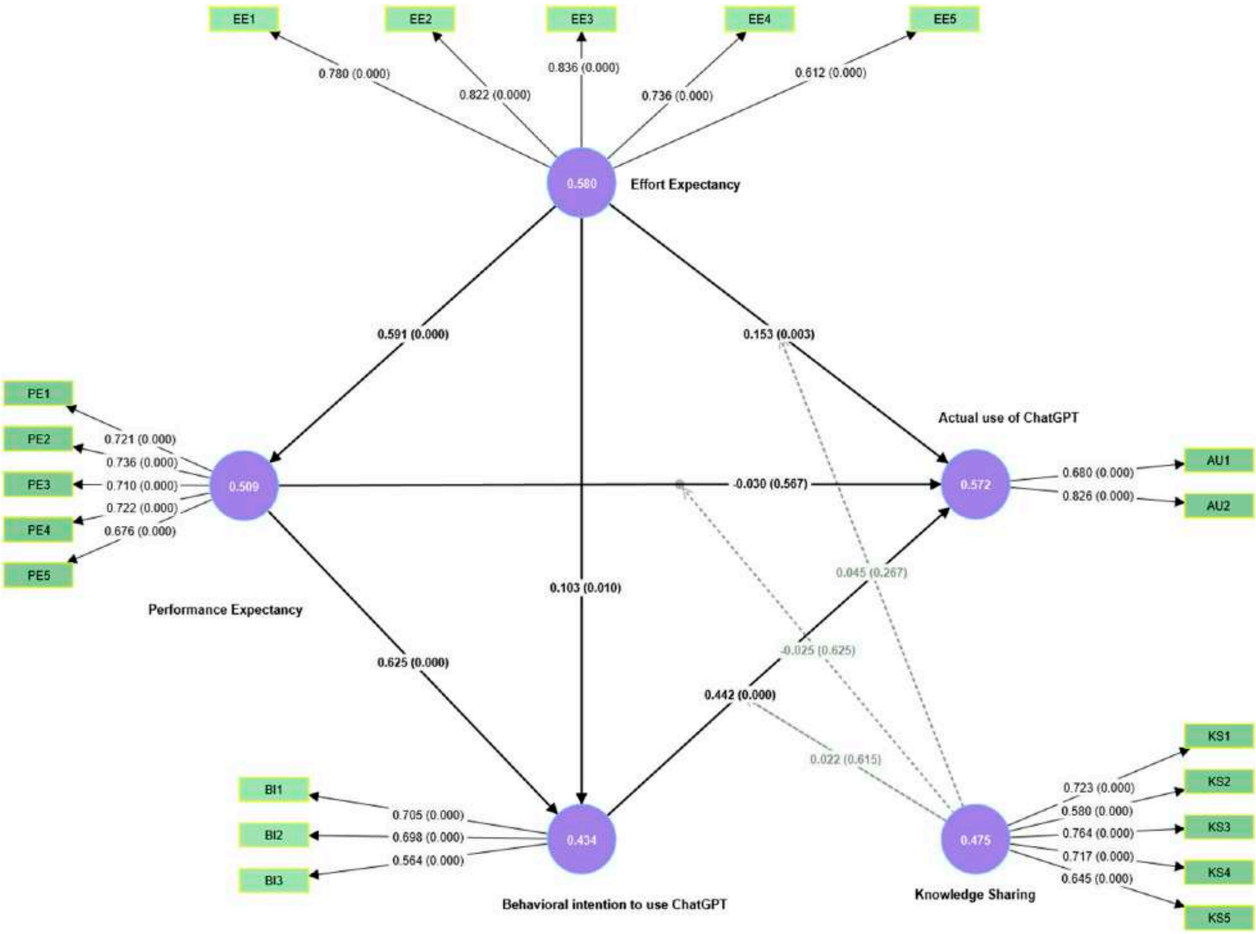


Figure 2. Research model solved.

Hypothesis H6, which relates PE to BI, is supported by a significant pathway (0.626), reaffirming the importance of performance perceptions in the intention to use technology. H7, H8, H9, and H10, which explore the interactions between KS and EE with the actual use of ChatGPT, are rejected, indicating that these interactions do not have a significant effect on the actual use of this language model. Finally, H11 and H12, which evaluate the mediating and indirect effects of EE through BI and PE on AU, are supported, indicating that there are significant pathways through these mediating variables.

4. Discussion

This study analyzed technology acceptance to explain the use of ChatGPT by higher-education students. The SEM showed goodness of fit indices of χ^2 = 490.797, SRMR = 0.062, d_ULS = 15.040, d_G = 0.893, and NFI = 0.979, which are considered acceptable. Additionally, the determination coefficients indicate that EE can explain 35% of the variation in performance expectancy. Moreover, PE explained 46% of the variation in the behavioral intention to use ChatGPT. EE and BI can explain 35% of the AU construct.

The study results demonstrate that BI positively and significantly influences AU (B = 0.443), suggesting that as BI increases, AU increases among university students. This finding indicates that as students perceive ChatGPT as easy to use and requiring little effort, they are more likely to form intentions to use it, which in turn increases the likelihood of actual use of this technology. Reference [27] used the UTAUT2 model to investigate the determinants of the intention to use ChatGPT for educational purposes, indicating a link between BI and AU. Additionally, the results of a study on the acceptance of ChatGPT by higher-education students revealed that BI has the most significant effect on usage behavior, suggesting a strong influence of intention on actual use [26]. Another study revealed that personal innovation and information accuracy negatively moderate the associations between the use of ChatGPT and its determinants, indicating the importance of individual intention in the use of ChatGPT [27].

On the other hand, the study proves that EE has a positive influence on AU (B = 0.148). Thus, the greater the effort expected by students to interact with this technology is, the greater the likelihood of its actual use. The literature has shown that EE has a direct positive effect on the likelihood that higher-education students will attempt to use ChatGPT, which in turn promotes its actual use for learning purposes [23–25]. A study involving Malaysian students revealed that effort expectancy significantly influences the intention to use ChatGPT for educational purposes [27]. Therefore, this study revealed that EE influences AU. However, a study did not find a significant role for EE in the use of ChatGPT in learning among students from higher-education institutions in Indonesia [66].

With respect to the influence of EE and its influence on BI, the study results demonstrate a positive influence (B = 0.103). This finding indicates that the greater the effort students expect to dedicate to using ChatGPT, the greater their intention to employ this artificial intelligence tool in their academic activities. In this context, other studies have shown that EE has a direct positive effect on the likelihood that higher-education students intend to use ChatGPT [23,25,66]. A significant discrepancy between EE and PE decreases the level of intentions and AU for learning [25]. Therefore, EE plays an insignificant role in BI [24,25,66].

Additionally, the study results support the hypothesis that EE influences students' PE when ChatGPT is used, demonstrating a positive and significant relationship (B = 0.593). This finding indicates that the greater the effort students dedicate to becoming familiar with and using ChatGPT, the greater their expectations that this AI tool will improve their academic performance. Similarly, previous studies have shown that EE and PE have a direct positive effect on the likelihood that higher-education students intend to use ChatGPT, which in turn promotes its actual use for learning purposes [23–25,27,66]. A significant discrepancy between EE and PE decreases the level of intention and actual use of ChatGPT for learning [25]. When there is an increasing discrepancy between EE and PE, whether positive or negative, the likelihood of students adopting ChatGPT for learning decreases [25]. EE not only directly affects students' AU but also indirectly increases their actual use of ChatGPT through PE and BI [25].

On the other hand, the study also demonstrated that PE positively and significantly influences BI (B = 0.626). This finding indicates that the greater the degree to which students' expect that the use of ChatGPT will increase their academic performance, the greater their intention to employ this artificial intelligence tool in their university activities. Similarly, various studies have shown that PE significantly influences the intention to use ChatGPT for educational purposes [23–25,27,66]. Furthermore, it has been found to have a direct positive effect on the likelihood that higher-education students intend to use ChatGPT [25]. Another study revealed that PE not only directly affects students' actual use of ChatGPT but also indirectly increases their AU through the use of BI in ChatGPT [25]. The BI to which ChatGPT was used was significantly predicted by PE [66]. BI has the most significant effect on AU, followed by habits and facilitating conditions [24]. These results have implications for ChatGPT developers, instructors, and universities, providing insights to accelerate the adoption of ChatGPT [27]. Consequently, policymakers could use these findings to increase the use of artificial intelligence in education, specifically ChatGPT [66].

The study results also demonstrated that the BI variable plays a mediating role in the effects of EE and AU (B = 0.046). Therefore, BI partially mediates the influence exerted by PE on the current usage behavior of this emerging technology. According to the literature, BI is a better predictor of learning efficacy in ChatGPT-assisted language learning than perceived satisfaction and PE [76]. Additionally, the BI is the most significant predictor of ChatGPT use [66]. On the other hand, ref. [23] demonstrated that EE directly affects AU for students and indirectly increases AU use through PE and the intention to use ChatGPT. Both EE and PE have a direct positive effect on the likelihood that higher-education students intend to use ChatGPT, which in turn promotes its actual use for learning purposes [25]. The quality of the information system and hedonic motivation are important for contributing to PE and perceived satisfaction in ChatGPT-assisted language learning [76].

Additionally, another significant contribution of the study is that PE and BI are sequential mediating variables in the effect of EE on AU (B = 0.164). This finding indicates that these two variables mediate in series the impact that the students' expected effort has on their actual adoption of this AI technology. The literature has shown that EE and PE have a direct positive effect on the likelihood that higher-education students intend to use ChatGPT, which in turn promotes its actual use for learning purposes [25,66]. Moreover, EE not only directly affects AU but also indirectly increases AU through PE and BI [23]. Furthermore, the use of the BI ChatGPT was the strongest determinant of AU [66]. PE and BI were found to be sequentially mediating variables among other influential factors and AU [76]. Additionally, it was found that behavioral intention was the strongest determinant of actual use [66].

However, hypotheses H7, H8, H9, and H10, which were not verified in the study, suggest the existence of complex variables and dynamics that have not been fully explored in the context of the acceptance and use of ChatGPT by higher-education students. The non-verification of these hypotheses opens new lines of research that could focus on identifying and understanding limiting factors, perceived barriers, or even cultural and contextual differences that could influence the adoption of this technology.

Importantly, user behavior toward new technologies, such as ChatGPT, is multifaceted and can be influenced by a wide range of personal, technological, and environmental factors. For example, variables such as trust in technology, privacy concerns, compatibility with students' needs and learning styles, and social influence may play critical roles in how and why students decide to adopt (or not adopt) ChatGPT for their educational purposes.

4.1. Long-Term Impact and Sustainability of ChatGPT Use

With respect to higher education, the innovative use of tools such as ChatGPT presents an unprecedented opportunity to enrich teaching and learning processes. However, to ensure the effective and sustainable integration of these technologies, it is crucial to consider not only their initial adoption but also their long-term impact and feasibility. This long-term approach involves a continuous evaluation of how ChatGPT and similar technologies adapt and evolve in response to changing educational needs and challenges. Moreover, considering the technological infrastructure necessary to support their ongoing use, including the ability of educational institutions to keep these tools up to date and the training required for students and faculty, is fundamental. The implications of an increasing reliance on AI in education, such as the risk of diminishing critical and creative skills among students, must also be addressed, ensuring that the use of ChatGPT complements and does not replace traditional teaching methods. Equally important is the development of strategies to measure the impact of ChatGPT on performance and student satisfaction, allowing for evidence-based adjustments to maximize its educational value. By addressing these aspects, the integration of ChatGPT into higher education can be not only innovative and effective but also sustainable and aligned with the long-term goals of education.

4.2. Theoretical and Practical Implications

This study has both theoretical and practical implications for the adoption of ChatGPT in higher-education contexts. Theoretically, the findings offer additional evidence supporting the usefulness of established models such as the UTAUT for examining and predicting the acceptance of novel technologies such as ChatGPT among university students. Furthermore, they clarify and reinforce previously hypothesized causal relationships regarding the mediating role of behavioral intention between beliefs such as effort expectancy or performance and the effective use of this artificial intelligence tool. Researchers emphasize that further inquiry is required regarding the potential moderating effects of individual and situational variables that could alter the associations found. Nevertheless, the study provides a solid theoretical model that will lay the groundwork for future research related to the acceptance of emerging AI technologies in higher learning environments.

Practically, the results highlight the importance for educational authorities and academics to manage students' effort expectations properly when incorporating ChatGPT into educational programs and to emphasize and communicate the potential benefits that this innovative tool can bring to their learning and performance. Strategies such as training students on the functionalities and advantages of using ChatGPT can foster positive perceptions and beliefs that later translate into higher intentions and effective adoption rates among university students. Ultimately, this study provides valuable guidance for institutional initiatives to implement this technology by identifying key barriers and facilitators linked to its acceptance by students.

4.3. Ethical and Academic Integrity Considerations

Exploring the integration of ChatGPT in higher education urgently requires addressing the ethical considerations and academic integrity issues that emerge with the adoption of artificial intelligence technologies. The ease with which students can generate content through these tools raises significant questions about the originality and authenticity of academic work. To ensure that the incorporation of ChatGPT in the educational realm is conducted ethically and responsibly, it is crucial to develop and implement clear and specific policies. These policies should focus on educating both students and faculty on the appropriate uses of ChatGPT, emphasizing the importance of maintaining academic integrity and the originality of critical thinking. Additionally, the creation of detection and verification systems that allow educators to identify AI-generated work is suggested, thus ensuring that academic standards are upheld without compromise. By fostering a culture of transparency and respect for academic norms, the educational community can leverage the potential of ChatGPT to enrich the learning process while preserving the fundamental values of higher education.

4.4. Long-Term Sustainability Implications and Recommendations

The findings of this study have significant implications for the sustainable integration of ChatGPT in higher education. Based on our empirical evidence, we propose the following framework for long-term sustainable implementation:

Infrastructure Sustainability:

- Universities should invest in reliable technological infrastructure that can support AI tools long-term;
- The regular assessment of digital resources and bandwidth requirements;
- The development of contingency plans for system updates and maintenance.

Academic Sustainability:

- The integration of ChatGPT into curriculum design while maintaining academic integrity;
- The development of guidelines for ethical AI use that can evolve with technological advances;
- Regular faculty training programs to ensure consistent and effective implementation.

Social Sustainability:

- The promotion of equitable access to ChatGPT across different student populations;
- The development of support systems for students with varying levels of digital literacy;
- The creation of knowledge-sharing communities to sustain long-term adoption.

Economic Sustainability:

- Cost–benefit analysis for long-term AI tool implementation;
- Resource allocation strategies for continuous system updates;
- Investment in local technical expertise for sustained support.

Policy Recommendations:

1. Universities should establish clear, adaptable policies for AI tool usage.
2. The regular assessment of implementation effectiveness through defined metrics.
3. The development of feedback mechanisms for continuous improvement.
4. The creation of institutional frameworks for sustainable AI integration.

These recommendations aim to ensure that ChatGPT integration moves beyond initial adoption to become a sustainable part of the educational ecosystem, supporting both current and future generations of students.

5. Conclusions

This study provides robust empirical evidence supporting the positive and highly significant influence of students' BI on their subsequent adoption of ChatGPT in academic activities. This finding reinforces the tenets of models such as UTAUT2 regarding the relevance of intentions in predicting the effective uses of new technologies. This research highlights the importance of designing strategies that foster positive perceptions and beliefs among students about the ease of use and benefits of ChatGPT, thereby promoting greater intentions and effective adoption rates of this innovative AI tool in university contexts.

Furthermore, the study's results clarify and support sequential causal relationships between different technological beliefs, highlighting the mediating roles of performance expectancy (PE) and behavioral intention (BI) in the influence of effort expectancy (EE) on the final adoption behavior of ChatGPT. These findings contribute a solid theoretical model that lays the groundwork for future research related to the acceptance of emerging AI technologies in higher-learning environments. However, further inquiry is needed regarding the potential moderating effects of individual and situational variables that could alter the associations found.

Research has shown that high effort expectancy (EE) of interaction with ChatGPT can promote, rather than discourage, its subsequent adoption among students, given the motivation to obtain the perceived benefits of its academic application. This novel result challenges previous assumptions and opens new lines of research that could focus on identifying and understanding limiting factors, perceived barriers, or even cultural and contextual differences that could influence the adoption of this technology. Nevertheless, more studies are needed to confirm the persistence of this effect.

Practically, the results underline the relevance for educational authorities and academics to properly manage students' effort expectations when incorporating ChatGPT into educational programs and to emphasize and communicate the potential benefits that this innovative tool can bring to their learning and performance. This study provides valuable guidance for guiding institutional initiatives to implement this technology by identifying key barriers and facilitators linked to its acceptance by students, such as training on the functionalities and advantages of using ChatGPT to foster positive perceptions and beliefs.

Although this study represents a significant advancement in understanding the acceptance of ChatGPT in higher education, it is crucial to recognize that user behavior toward new technologies is multifaceted and can be influenced by a wide range of personal, technological, and environmental factors not fully explored in this research. Variables such as trust in technology, privacy concerns, compatibility with students' needs and learning styles, and social influence may play critical roles in how and why students decide to adopt (or not adopt) ChatGPT for their educational purposes. Future research should address these limitations and examine the interaction of these factors across various cultural and disciplinary contexts.

Limitations and Implications for Future Research

The present study has several limitations that must be considered when the results are interpreted. First, the non-probabilistic accidental sampling limits the generalization of the findings to the student population of the Lambayeque and La Libertad regions in Peru. Additionally, the study focused on business and engineering students, which restricts the understanding of the acceptance and use of ChatGPT in other disciplines. Another limitation is the use of cross-sectional data collected at a single point in time, which prevents the capture of potential changes in students' perceptions and behaviors over time. Furthermore, the study relied on self-reported measures, which may be subject to biases. Finally, although the extended UTAUT2 model explained a significant proportion of the variance, other relevant factors not included may influence the adoption of ChatGPT.

These limitations create opportunities for future research. The use of probabilistic sampling techniques is recommended to ensure greater representativeness and allow for more robust generalizations. Additionally, expanding the scope of the study to include students from a wider range of academic fields would provide a more comprehensive perspective. Conducting longitudinal studies would allow for the identification of changes in the relationships between model constructs and the role of moderating variables over time. The use of additional methods, such as usage log analysis or direct observation, would help obtain more objective measures of actual usage behavior. Finally, exploring the role of additional variables, such as trust in technology, privacy concerns, compatibility with needs and learning styles, and social influence, would provide a more thorough understanding of the drivers of ChatGPT acceptance and use in higher education.

Additionally, while this study explores the adoption of ChatGPT in higher education, it is important to acknowledge that the implementation of AI tools in academic settings remains controversial. Several prestigious universities have implemented restrictions on ChatGPT use due to concerns about academic integrity, critical thinking development, and over-reliance on AI assistance [10,11]. Our study, while focusing on adoption factors, does not fully address these fundamental concerns about AI's role in education. Future research should investigate how universities can balance the potential benefits of ChatGPT with maintaining academic rigor and developing students' independent thinking skills. Additionally, comparative studies between institutions that restrict versus encourage ChatGPT use could provide valuable insights into the long-term educational impacts of these different approaches. This limitation also suggests the need for future research to examine not just how ChatGPT can be adopted, but whether and under what specific circumstances its adoption truly enhances educational outcomes.

Author Contributions: Conceptualization, G.C.F.C. and E.V.R.F.; methodology, G.C.F.C. and E.V.R.F.; software, M.A.A.B. and B.G.A.E.; validation, B.G.A.E. and M.A.A.B.; formal analysis, G.C.F.C. and J.C.A.C.; investigation, M.A.A.B. and B.G.A.E.; resources, E.V.R.F. and J.C.A.C.; data curation, H.D.G.J., J.E.B.S. and G.S.L.-R.; writing—original draft preparation, J.C.A.C. and H.D.G.J.; writing—review and editing, H.D.G.J. and J.E.B.S.; visualization, J.E.B.S. and L.E.C.S.; supervision, L.E.C.S. and G.S.L.-R.; project administration, L.E.C.S. and G.S.L.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Yordanova, K. Mobile Learning and Integration of Advanced Technologies in Education. In Proceedings of the 2007 International Conference on Computer Systems and Technologies, Amman, Jordan, 13–16 May 2007; Association for Computing Machinery: New York, NY, USA, 2007; pp. 1–6.
2. Bodani, N.; Lal, A.; Maqsood, A.; Altamash, S.; Ahmed, N.; Heboyan, A. Knowledge, Attitude, and Practices of General Population Toward Utilizing ChatGPT: A Cross-Sectional Study. *Sage Open* **2023**, *13*, 21582440231211079. [CrossRef]
3. Kim, M.; Adlof, L. Adapting to the Future: ChatGPT as a Means for Supporting Constructivist Learning Environments. *TechTrends* **2024**, *68*, 37–46. [CrossRef]
4. Shishakly, R.; Almaiah, M.A.; Lutfi, A.; Alrawad, M. The Influence of Using Smart Technologies for Sustainable Development in Higher Education Institutions. *Int. J. Data Netw. Sci.* **2024**, *8*, 77–90. [CrossRef]
5. Montenegro-Rueda, M.; Fernández-Cerero, J.; Fernández-Batanero, J.; López-Meneses, E. Impact of the Implementation of ChatGPT in Education: A Systematic Review. *Computers* **2023**, *12*, 153. [CrossRef]
6. Valova, I.; Mladenova, T.; Kanev, G. Students' Perception of ChatGPT Usage in Education. *Int. J. Adv. Comput. Sci. Appl. (IJACSA)* **2024**, *15*, 466–473. [CrossRef]
7. Arista, A.; Shuib, L.; Ismail, M.A. A Glimpse of ChatGPT: An Introduction of Features, Challenges, and Threads in Higher Education. In Proceedings of the 2023 International Conference on Informatics, Multimedia, Cyber and Informations System (ICIMCIS), Jakarta Selatan, Indonesia, 7–8 November 2023; pp. 694–698.
8. Dai, Y.; Liu, A.; Lim, C.P. Reconceptualizing ChatGPT and Generative AI as a Student-Driven Innovation in Higher Education. *Procedia CIRP* **2023**, *119*, 84–90. [CrossRef]
9. Ajlouni, A.; Wahba, F.; Almahaireh, A. Students' Attitudes Towards Using ChatGPT as a Learning Tool: The Case of the University of Jordan. *Int. J. Interact. Mob. Technol.* **2023**, *17*, 99–117. [CrossRef]
10. Putra, F.; Rangka, I.; Aminah, S.; Aditama, M. ChatGPT in the Higher Education Environment: Perspectives from the Theory of High Order Thinking Skills. *J. Public Health* **2023**, *45*, e840–e841. [CrossRef]
11. Singh, H.; Tayarani-Najaran, M.-H.; Yaqoob, M. Exploring Computer Science Students' Perception of ChatGPT in Higher Education: A Descriptive and Correlation Study. *Educ. Sci.* **2023**, *13*, 924. [CrossRef]
12. İpek, Z.; Gözüm, A.; Papadakis, S.; Kallogiannakis, M. Educational Applications of ChatGPT AI System: A Systematic Review Research. *Educ. Process Int. J.* **2023**, *12*, 26–55. [CrossRef]
13. Jain, K.; Raghuram, J. Unlocking Potential: The Impact of AI on Education Technology. *Multidiscip. Rev.* **2024**, *7*, 2024049. [CrossRef]
14. Murgia, E.; Pera, M.S.; Landoni, M.; Huibers, T. Children on ChatGPT Readability in an Educational Context: Myth or Opportunity? In Proceedings of the Adjunct Proceedings of the 31st ACM Conference on User Modeling, Adaptation and Personalization, Limassol, Cyprus, 26–29 June 2023; Association for Computing Machinery: New York, NY, USA, 2023; pp. 311–316.
15. Gupta, M.; Akiri, C.; Aryal, K.; Parker, E.; Praharaj, L. From ChatGPT to ThreatGPT: Impact of Generative AI in Cybersecurity and Privacy. *IEEE Access* **2023**, *11*, 80218–80245. [CrossRef]
16. Vassilakopoulou, P.; Hustad, E. Bridging Digital Divides: A Literature Review and Research Agenda for Information Systems Research. *Inf. Syst. Front.* **2023**, *25*, 955–969. [CrossRef] [PubMed]
17. Jo, H. Decoding ChatGPT Mystery: A Comprehensive Exploration of Factors Driving AI Language Model Adoption. *Inf. Dev.* **2023**, 02666669231202764. [CrossRef]
18. Simhadri, N.; Swamy, T.N.V.R. Awareness among Teaching on AI and ML Applications Based on Fuzzy in Education Sector at USA. *Soft Comput.* **2023**, 1–9. [CrossRef] [PubMed]
19. Toyokawa, Y.; Horikoshi, I.; Majumdar, R.; Ogata, H. Challenges and Opportunities of AI in Inclusive Education: A Case Study of Data-Enhanced Active Reading in Japan. *Smart Learn. Environ.* **2023**, *10*, 67. [CrossRef]

20. von Garrel, J.; Mayer, J. Artificial Intelligence in Studies—Use of ChatGPT and AI-Based Tools among Students in Germany. *Humanit. Soc. Sci. Commun.* **2023**, *10*, 799. [CrossRef]
21. Jafar, K.; Ananthpur, K.; Venkatachalam, L. Digital Divide and Access to Online Education: New Evidence from Tamil Nadu, India. *J. Soc. Econ. Dev.* **2023**, *25*, 313–333. [CrossRef]
22. Bhalla, N.; Brooks, L.; Leach, T. Ensuring a 'Responsible' AI Future in India: RRI as an Approach for Identifying the Ethical Challenges from an Indian Perspective. *AI Ethics* **2023**, *4*, 1409–1422. [CrossRef]
23. Duong, C.; Vu, T.; Ngo, T. Applying a Modified Technology Acceptance Model to Explain Higher Education Students' Usage of ChatGPT: A Serial Multiple Mediation Model with Knowledge Sharing as a Moderator. *Int. J. Manag. Educ.* **2023**, *21*, 100883. [CrossRef]
24. Strzelecki, A.; ElArabawy, S. Investigation of the Moderation Effect of Gender and Study Level on the Acceptance and Use of Generative AI by Higher Education Students: Comparative Evidence from Poland and Egypt. *Br. J. Educ. Technol.* **2024**, *55*, 1209–1230. [CrossRef]
25. Duong, C.; Bui, D.; Pham, H.; Vu, A.T.; Nguyen, V. How Effort Expectancy and Performance Expectancy Interact to Trigger Higher Education Students' Uses of ChatGPT for Learning. *Interact. Technol. Smart Educ.* **2023**, *21*, 356–380. [CrossRef]
26. Strzelecki, A. Students' Acceptance of ChatGPT in Higher Education: An Extended Unified Theory of Acceptance and Use of Technology. *Innov. High Educ.* **2024**, *49*, 223–245. [CrossRef]
27. Foroughi, B.; Senali, M.; Iranmanesh, M.; Khanfar, A.; Ghobakhloo, M.; Annamalai, N.; Naghmeh-Abbaspour, B. Determinants of Intention to Use ChatGPT for Educational Purposes: Findings from PLS-SEM and fsQCA. *Int. J. Hum. Comput. Interact.* **2024**, *40*, 4501–4520. [CrossRef]
28. Sánchez, X.; Ascencio, A. *Realización del Documental: "Y de Repente. . . Inteligencia Artificial"*; Trabajo de Suficiencia Profesional; Universidad de Lima: Santiago de Surco, Peru, 2023.
29. Peña, A. Brecha Digital en la Institución Educativa 7087 El Nazareno 2019. Ph.D. Thesis, Universidad César Vallejo, Trujillo, Peru, 2020.
30. Pari-Bedoya, I.N.M.; Ypanaque, I.; Callacondo, V. Brecha digital y la problemática del derecho a la educación en zonas rurales durante el estado de emergencia. *Derecho* **2022**, *10*, 44–56.
31. Sotelo, K. Uso de la Inteligencia Artificial en la Educación Superior Entre el 2018 y el 2023. Una Revisión Sistemática. Master's Thesis, Universidad César Vallejo, Trujillo, Peru, 2023.
32. Luna, M. El Estado Peruano en la Implementación de la Inteligencia Artificial en la Modernización del Estado, 2023. Master's Thesis, Universidad César Vallejo, Trujillo, Peru, 2023.
33. Berrones, L.; Buenaño, P. ChatGPT en el ámbito educativo. *Esprint Investig.* **2023**, *2*, 45–54. [CrossRef]
34. Aguilar, I. Relación Entre Inteligencia Artificial y Retención de Estudiantes de Cursos Virtuales del Instituto San Ignacio de Loyola, Año 2021. Ph.D. Thesis, Universidad de San Martín de Porres, Lima, Peru, 2022.
35. Pacsi, L.; Torres, K. Integración de las Tecnologías en la Educación Peruana: Políticas Públicas y Percepciones de los Actores Educativos. Bachelor's Thesis, Universidad Peruana de Ciencias Aplicadas, Lima, Peru, 2022.
36. Luna, D. Hacia Una Educación Digital: Factores Que Influyen en el Proceso de Implementación de la Competencia TIC en la Educación Básica Regular. El Caso del Proyecto Aula Digital en Ica en el 2017–2019. Bachelor's Thesis, Pontificia Universidad Católica del Perú, San Miguel de Allende, Peru, 2019.
37. Niloy, A.C.; Bari, M.A.; Sultana, J.; Chowdhury, R.; Raisa, F.M.; Islam, A.; Mahmud, S.; Jahan, I.; Sarkar, M.; Akter, S.; et al. Why Do Students Use ChatGPT? Answering through a Triangulation Approach. *Comput. Educ. Artif. Intell.* **2024**, *6*, 100208. [CrossRef]
38. Polyportis, A. A Longitudinal Study on Artificial Intelligence Adoption: Understanding the Drivers of ChatGPT Usage Behavior Change in Higher Education. *Front. Artif. Intell.* **2024**, *6*, 1324398. [CrossRef] [PubMed]
39. Dale, R. A Year's a Long Time in Generative AI. *Nat. Lang. Eng.* **2024**, *30*, 201–213. [CrossRef]
40. Guo, Y. AI-Fused Automation [From the Editor's Desk]. *IEEE Robot. Autom. Mag.* **2023**, *30*, 4. [CrossRef]
41. Miao, H.; Ahn, H. Impact of ChatGPT on Interdisciplinary Nursing Education and Research. *Asian/Pac. Isl. Nurs. J.* **2023**, *7*, e48136. [CrossRef] [PubMed]
42. Mich, L.; Garigliano, R. ChatGPT for E-Tourism: A Technological Perspective. *Inf. Technol. Tour.* **2023**, *25*, 1–12. [CrossRef]
43. Kshetri, N. ChatGPT in Developing Economies. *IT Prof.* **2023**, *25*, 16–19. [CrossRef]
44. Yan, Y.; Li, B.; Feng, J.; Du, Y.; Lu, Z.; Huang, M.; Li, Y. Research on the Impact of Trends Related to ChatGPT. *Procedia Comput. Sci.* **2023**, *221*, 1284–1291. [CrossRef]
45. Keshamoni, K. ChatGPT: An Advanced Natural Language Processing System for Conversational AI Applications—A Comprehensive Review and Comparative Analysis with Other Chatbots and NLP Models. In Proceedings of the ICT Systems and Sustainability, Goa, India, 3–4 August 2023; Tuba, M., Akashe, S., Joshi, A., Eds.; Springer Nature: Singapore, 2023; pp. 447–455.
46. Albayati, H. Investigating Undergraduate Students' Perceptions and Awareness of Using ChatGPT as a Regular Assistance Tool: A User Acceptance Perspective Study. *Comput. Educ. Artif. Intell.* **2024**, *6*, 100203. [CrossRef]
47. Hernandez, A.; Abisado, M.; Rodriguez, R.; Imperial, J.M. Predicting the Use Behavior of Higher Education Students on ChatGPT: Evidence from the Philippines. In Proceedings of the 2023 IEEE International Conference on Teaching, Assessment and Learning for Engineering (TALE), Auckland, New Zealand, 28 November–1 December 2023; pp. 1–7.
48. Romero-Rodríguez, J.; Ramírez-Montoya, M.; Buenestado-Fernández, M.; Lara-Lara, F. Use of ChatGPT at University as a Tool for Complex Thinking: Students' Perceived Usefulness. *J. New Approaches Educ. Res.* **2023**, *12*, 323–339. [CrossRef]

49. Zeb, A.; Ullah, R.; Karim, R. Exploring the Role of ChatGPT in Higher Education: Opportunities, Challenges and Ethical Considerations. *Int. J. Inf. Learn. Technol.* **2024**, *41*, 99–111. [CrossRef]
50. Gödde, D.; Nöhl, S.; Wolf, C.; Rupert, Y.; Rimkus, L.; Ehlers, J.; Breuckmann, F.; Sellmann, T. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) Analysis of ChatGPT in the Medical Literature: Concise Review. *J. Med. Internet Res.* **2023**, *25*, e49368. [CrossRef]
51. Al-Emran, M.; AlQudah, A.; Abbasi, G.; Al-Sharafi, M.; Iranmanesh, M. Determinants of Using AI-Based Chatbots for Knowledge Sharing: Evidence From PLS-SEM and Fuzzy Sets (fsQCA). *IEEE Trans. Eng. Manag.* **2024**, *71*, 4985–4999. [CrossRef]
52. Sane, A.; Albuquerque, M.; Gupta, M.; Valadi, J. ChatGPT Didn't Take Me Very Far, Did It? In Proceedings of the ACM Conference on Global Computing Education Vol 2, Hyderabad, India, 7–9 December 2023; Association for Computing Machinery: New York, NY, USA, 2023; p. 204.
53. Shoufan, A. Exploring Students' Perceptions of ChatGPT: Thematic Analysis and Follow-Up Survey. *IEEE Access* **2023**, *11*, 38805–38818. [CrossRef]
54. Hassan, A. The Usage of Artificial Intelligence in Education in Light of the Spread of ChatGPT. In *Emerging Trends and Innovation in Business and Finance*; El Khoury, R., Nasrallah, N., Eds.; Springer Nature: Singapore, 2023; pp. 687–702, ISBN 978-981-9961-01-6.
55. Famaye, T.; Adisa, I.O.; Irgens, G.A. To Ban or Embrace: Students' Perceptions Towards Adopting Advanced AI Chatbots in Schools. In Proceedings of the Advances in Quantitative Ethnography, Melbourne, Australia, 8–12 October 2023; Arastoopour Irgens, G., Knight, S., Eds.; Springer Nature: Cham, Switzerland, 2023; pp. 140–154.
56. Ali, O.; Murray, P.; Momin, M.; Al-Anzi, F. The Knowledge and Innovation Challenges of ChatGPT: A Scoping Review. *Technol. Soc.* **2023**, *75*, 102402. [CrossRef]
57. Gundu, T.; Chibaya, C. Demystifying the Impact of ChatGPT on Teaching and Learning. In Proceedings of the ICT Education, Melbourne, Australia, 13–15 August 2024; Van Rensburg, H.E., Snyman, D.P., Drevin, L., Drevin, G.R., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 93–104.
58. Tamilmani, K.; Rana, N.P.; Wamba, S.F.; Dwivedi, R. The Extended Unified Theory of Acceptance and Use of Technology (UTAUT2): A Systematic Literature Review and Theory Evaluation. *Int. J. Inf. Manag.* **2021**, *57*, 102269. [CrossRef]
59. Taneja, B.; Bharti, K. Mapping Unified Theory of Acceptance and Use of Technology (UTAUT) 2: A Taxonomical Study Using Bibliometric Visualisation. *Foresight* **2021**, *24*, 210–247. [CrossRef]
60. Al Maskari, A. *Theory of Planned Behavior (TPB) Ajzen (1988)*; Al-Suqri, M.N., Al-Aufi, A.S., Eds.; IGI Global: Hershey, PA, USA, 2015; ISBN 978-1-4666-8156-9.
61. Alghatrifi, I.; Khalid, H. A Systematic Review of UTAUT and UTAUT2 as a Baseline Framework of Information System Research in Adopting New Technology: A Case Study of IPV6 Adoption. In Proceedings of the 2019 6th International Conference on Research and Innovation in Information Systems (ICRIIS), Johor Bahru, Malaysia, 2–3 December 2019; pp. 1–6.
62. Tamilmani, K.; Rana, N.P.; Dwivedi, Y.K. A Systematic Review of Citations of UTAUT2 Article and Its Usage Trends. In Proceedings of the Digital Nations—Smart Cities, Innovation, and Sustainability, Delhi, India, 21–23 November 2017; Kar, A.K., Ilavarasan, P.V., Gupta, M.P., Dwivedi, Y.K., Mäntymäki, M., Janssen, M., Simintiras, A., Al-Sharhan, S., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 38–49.
63. Venkatesh, V.; Thong, J.; Xu, X. Unified Theory of Acceptance and Use of Technology: A Synthesis and the Road Ahead. *J. Assoc. Inf. Syst.* **2016**, *17*, 328–376. [CrossRef]
64. Menon, D.; Shilpa, K. "Chatting with ChatGPT": Analyzing the Factors Influencing Users' Intention to Use the Open AI's ChatGPT Using the UTAUT Model. *Heliyon* **2023**, *9*, e20962. [CrossRef]
65. Camilleri, M. Factors Affecting Performance Expectancy and Intentions to Use ChatGPT: Using SmartPLS to Advance an Information Technology Acceptance Framework. *Technol. Forecast. Soc. Chang.* **2024**, *201*, 123247. [CrossRef]
66. Habibi, A.; Muhaimin, M.; Danibao, B.; Wibowo, Y.; Wahyuni, S.; Octavia, A. ChatGPT in Higher Education Learning: Acceptance and Use. *Comput. Educ. Artif. Intell.* **2023**, *5*, 100190. [CrossRef]
67. Gutiérrez, O.; Delgado-Delgado, F.; Meza-Málaga, J.; Turpo-Gebera, O.; Ticona, F. Predictores del desempeño académico mediante el uso del chatgpt en estudiantes universitarios. *Hum. Rev. Int. Humanit. Rev./Rev. Int. Humanid.* **2023**, *21*, 411–421. [CrossRef]
68. Polyportis, A.; Pahos, N. Understanding Students' Adoption of ChatGPT Chatbot in Higher Education: The Role of Anthropomorphism, Trust, Design Novelty and Institutional Policy. *Behav. Inf. Technol.* **2024**, *6*, 1–22. [CrossRef]
69. Rahman, M.S.; Sabbir, M.M.; Zhang, D.J.; Moral, I.H.; Hossain, G.M.S. Examining Students' Intention to Use ChatGPT: Does Trust Matter? *Australas. J. Educ. Technol.* **2023**, *39*, 51–71. [CrossRef]
70. Emon, M.M.H.; Hassan, F.; Nahid, M.H.; Rattanawiboonsom, V. Predicting Adoption Intention of Artificial Intelligence. *AIUB J. Sci. Eng. (AJSE)* **2023**, *22*, 189–199. [CrossRef]
71. Halaweh, M. ChatGPT in Education: Strategies for Responsible Implementation. *Contemp. Educ. Technol.* **2023**, *15*, ep421. [CrossRef] [PubMed]
72. Qian, L.; Liu, Y.; Zhang, Z.; Li, X.; Xie, J.; Xu, Q.; Li, Y.; Guan, Z.; Li, X.; Wen, S. An Analysis on the Basic Technologies of ChatGPT. *Data Anal. Knowl. Discov.* **2023**, *7*, 6–15. [CrossRef]
73. Abbas, M.; Jam, F.A.; Khan, T.I. Is It Harmful or Helpful? Examining the Causes and Consequences of Generative AI Usage among University Students. *Int. J. Educ. Technol. High. Educ.* **2024**, *21*, 10. [CrossRef]
74. Boubker, O. From Chatting to Self-Educating: Can AI Tools Boost Student Learning Outcomes? *Expert Syst. Appl.* **2024**, *238*, 121820. [CrossRef]

75. Lai, C.Y.; Cheung, K.Y.; Chan, C.S. Exploring the Role of Intrinsic Motivation in ChatGPT Adoption to Support Active Learning: An Extension of the Technology Acceptance Model. *Comput. Educ. Artif. Intell.* **2023**, *5*, 100178. [CrossRef]
76. Cai, Q.; Lin, Y.; Yu, Z. Factors Influencing Learner Attitudes Towards ChatGPT-Assisted Language Learning in Higher Education. *Int. J. Hum. Comput. Interact.* **2023**, *40*, 7112–7126. [CrossRef]
77. Fornell, C.; Larcker, D.F. Structural Equation Models with Unobservable Variables and Measurement Error: Algebra and Statistics. *J. Mark. Res.* **1981**, *18*, 382–388. [CrossRef]

More info

UTM UNIVERSITI TEKNOLOGI MALAYSIA | UTM Library

SDi@JPUTM

SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

"Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions"

TITLE	SOURCE
9) The influence of using smart technologies for sustainable development in higher education institutions (2024)	INTERNATIONAL JOURNAL OF DATA & NETWORK SCIENCE (Article From : GROWING SCIENCE)

27th FEBRUARY 2025
SOURCE: PERPUSTAKAAN UTM

International Journal of Data and Network Science 8 (2024) 77–90

Contents lists available at GrowingScience

International Journal of Data and Network Science

homepage: www.GrowingScience.com/ijds

The influence of using smart technologies for sustainable development in higher education institutions

Rima Shishakly[a], Mohammed Amin Almaiah[b,c*], Abdalwali Lutfi[d,f*] and Mahmaod Alrawad[g,h]

[a]*Management Department, College of Business Administration, Ajman University, Ajman 346, United Arab Emirates*
[b]*Department of Computer Science, Aqaba University of Technology, Aqaba 11947, Jordan*
[c]*Applied Science Research Center, Applied Science Private University, Amman 11931, Jordan*
[d]*Department of Accountig, College of Business, King Faisal University, Al-Ahsa 31982, Saudi Arabia*
[f]*MEU Research Unit, Middle East University, Amman 541350, Jordan*
[g]*Quantitative Method, College of Business Administration, King Faisal University, Al-Ahsa 31982, Saudi Arabia*
[h]*College of Business Administration and Economics, Al-Hussein Bin Talal University, Ma'an 71111, Jordan*

C H R O N I C L E

Article history:
Received: July 18, 2023
Received in revised format: September 3, 2023
Accepted: October 16, 2023
Available online: October 16, 2023

Keywords:
Smart Technologies Integration
Sustainability
Higher Education
Awareness

A B S T R A C T

Promoting sustainability development in education is a global endeavor, aiming to foster the sharing of experiences and knowledge on sustainability development. To achieve that, educational institutions worldwide have increasingly embraced educational technology and integrated online learning components into their instructional methods. This research focuses on the pivotal role of students as influential catalysts for advancing sustainable development within higher education. Specifically, it investigates the extent of students' familiarity with sustainable development initiatives within higher education institutions in the UAE. To achieve this objective, the study introduces the Technology-Integration Framework for Education Sustainable Development (TIFESD), which serves as an evaluative tool for appraising students' awareness of technology-driven elements woven into the broader context of Education for Sustainable Development (ESD) within their respective universities. The research employs a quantitative methodology, encompassing the collection of 513 survey responses from students across nine universities in the UAE. This data analysis explores the potential relationship between the integration of technology and students' cognizance of factors that bolster sustainable development. The study's outcomes underscore students' profound awareness of a spectrum of technology-driven elements, including Green Campus initiatives, Smart Education strategies, Smart Campus facilities, and the influence of curriculum and course offerings—all of which collectively contribute to the advancement of sustainable development practices within higher education institutions.

1. Introduction

Higher education institutions have increasingly acknowledged the significance of (ESD) in recent years while also recognizing the essential role of technology in advancing sustainable development (SD) (UNESCO, 2017; Tarrant et al., 2021) state that to achieve sustainable education, it is necessary to implement a sustainable development strategy that aims to foster policies and practices that are sustainable both on an individual and societal level. Sustainability is a vital strategic view for businesses; universities are no exemption (Zhao, et al., 2021). Wals (2014) mentions that some universities find sustainability as an additional way of profiling and organizing themselves. However, the sustainability of universities can be promoted by skilled persons such as researchers, students, and academics, who have been viewed as the key component of sustainable development strategies by institutions and nations (Wang & Hu, 2017; Hodges et al., 2020). ESD is an approach that promotes interdisciplinary learning, problem-solving, critical thinking, and active learning to address sustainability challenges at various levels

* Corresponding author.
E-mail address: mohammad7ups@yahoo.com (M. A. Alamiah) aalkhassawneh@kfu.edu.sa (A. Lutfi)

ISSN 2561-8156 (Online) - ISSN 2561-8148 (Print)

doi: 10.5267/j.ijdns.2023.10.015

(UNESCO, 2021). Additionally, the report emphasizes the role of ESD in contributing to the achievement of the United Nations' Sustainable Development Goals (SDGs) and fostering a more equitable and sustainable future for all (UNESCO, 2017; UNESCO, 2021). However, students are powerful agents of change for sustainable development in higher education. UNESCO (2019); UNESCO (2021, 2023). The UNESCO reports admit that students play a vital role as change agents in promoting (ESD) and empowering them with the knowledge, skills, values, and attitudes needed to act as agents of change. According to João Marcelo Pereira Ribeiro et al., (2021), students are future leaders who will be expected to make decisions to achieve sustainability as they take up key roles in education in sustainable development. Furthermore, Heiskanen et al. (2016) argue that students should acquire the necessary skills and qualities to become agents of sustainability. Sterling (2010) agrees that students become catalysts for positive change by empowering students with knowledge, critical thinking skills, and a sense of responsibility towards the environment and society. Furthermore, students' engagement in sustainability-focused courses and research projects, recycling programs, energy conservation campaigns, and sustainable transportation efforts, develop a sense of responsibility, social and economic issues, and a deeper understanding of the environment (Leal Filho et al., 2019a). However, Leal Filho et al. (2019b) declare that one of the Barriers is the low levels of awareness among the stakeholders about sustainability development in higher educational institutions. Accordingly, González-Zamar, et al., (2020) state that the educational field seeks to increase knowledge about the link between information technologies and education for sustainable development, as suggested by UNESCO and the SDGs of the 2030 Agenda. However, limited studies have been conducted on the initiative to promote Education for Sustainable Development (ESD) in the Gulf Cooperation Council (GCC) countries, including the UAE, Saudi Arabia, Bahrain, Oman, Qatar, and Kuwait (Alotaibi, 2022; Alkhayyal, 2019; Mojilis, 2019; Alsaati et al., 2020; Heiskanen et al., 2016). However, MCKeown and Hopkins (2007) stress the need for significant efforts across all education system levels to ensure ESD's success. Consequently, researchers in the GCC countries highlight the importance of fostering sustainability awareness among students in higher education institutions, as they are powerful agents of change and play an essential role in achieving effective, sustainable development and building a sustainable future (Stephens et al., 2008).

To illustrate the limited studies in this area, Heiskanen et al. (2016) conducted a study in Bahrain, which revealed that students exhibited a lack of awareness regarding the sustainability initiatives implemented on their campus. Jiwane, (2013) states that education is essential to disseminating information about all dimensions of sustainability in Bahrain. In Saudi Arabia, Alotaibi (2022) emphasizes highlighting the role of higher educational institutions in sustainable development. However, Alsaati et al. (2020) noted a lack of sustainability awareness among students in Saudi universities. In Oman, Ambusaidi and Al Rabbani (2009) found that female university students developed a positive attitude toward reducing environmental issues and embracing ESD. Qatar has made significant progress in integrating ESD into its education system through national strategies and collaborations, benefiting from experiences in curriculum integration and fostering bilateral partnerships. In line with global trends, Higher Education Institutions in the UAE are gradually transitioning towards sustainability, although more research is needed in this context. The (UAE) began to invest in a smart learning program named Mohammed Bin Rashid Smart Learning Program (MBRSLP) in 2012, which aims to shape a new learning environment and culture in their national schools by launching smart classes. However, the UAE has recognized the importance of sustainability by designating 2023 as the "year of sustainability" and has implemented strategies to actively promote Education for Sustainable Development (ESD) and Sustainable Development (SD). Few Previous studies in the UAE have shown a positive attitude toward ESD among students, with the progress made in integrating sustainability into university curricula and research activities (Baroudi, 2023; Al-Naqbi & Alshannag, 2017). However, the literature review highlights a research gap in exploring students' awareness of sustainable development in higher education, particularly in the United Arab Emirates (UAE).

Despite some efforts, further work is required to promote sustainable practices within higher education institutions in the UAE. To address this research gap, the primary focus of this study will be to examine the level of students' awareness regarding technology-related factors that contribute to sustainable development in universities and colleges in the UAE. A practical framework will also be developed to assess students' awareness of technology integration factors associated with sustainable development in universities. Additionally, the study aims to answer the question: Are students aware of technology-integrated sustainability practices, initiatives, and efforts within their university toward sustainable development (SD)? The study will consider various technology-integrated factors such as Green Campus, Smart Education, Smart Campus, and Curriculum and Courses to assess students' awareness of sustainable development practices. The paper will be structured into sections that provide an overview of technology-integrated Education for Sustainable Development (ESD), present the proposed framework for exploring the students' awareness, outline the research methodology encompassing data collection and analysis, present the study's findings, offer conclusions, discuss implications, highlight limitations, and propose areas for future research.

2. A Technology-Integrated (ESD)

Technology has experienced rapid development and extraordinary growth (Almaiah et al., 2022a; Marei, 2022). According to Sadh (2019), Technology can help to spread awareness about Green and make it more feasible and accessible for everyone. Segalàs et al. (2010) state that students perceived sustainability as mainly related to technology. However, scholars have acknowledged the importance of technology in enhancing e-learning, supporting student engagement, collaboration among students and emerging technologies such as the IoT (Internet of Things) and AI (Artificial Intelligence) across various levels and directions (Alrfai et al., 2023), and presents numerous applications that can be joined for success in education which leads to more effective and sustainable management of natural resources (Almaiah et al., 2022b; Leal Filho et al., 2023). As technological advancements unfold, the importance of strategically utilizing technology to promote sustainable development becomes increasingly evident (UNDP, 2020). Similarly, Silva-da-Nóbregaet al. (2022) state that higher education institutions create an ecosystem by ICTs to reach sustainability using a collaborative, governance-based, and adaptive learning-model to endorse better stakeholder liability Based on the goal of sustainability, Previous studies have identified factors contributing to technology-integrated Education for Sustainable Development (ESD), Silva-da-Nóbrega et al., 2022; Liao et al. (2022) propose various essential factors, namely smart campus infrastructure, smart education, IT green, and social engagement, which collectively address different aspects of sustainability. These components emphasize the role of technology in establishing eco-friendly campuses, implementing sustainable practices in educational processes, and encouraging active community participation.

3. Developing the Proposed Framework

Previous studies have significant practical growth in the field of Education for Sustainable Development (ESD) practice, making it a prominent topic in the agenda of numerous higher education institutions globally (Machado & Davim, 2023). Scholars such as Silva-da-Nóbrega et al. (2022) have proposed comprehensive frameworks that align dimensions with the Sustainable Development Goals (SDGs) and advocate for the integration of technology-driven initiatives, such as the Smart Campus Framework (SCF). This framework encompasses various components, including smart economy, smart education, smart environment, smart living, smart management, smart mobility, smart technology, and smart security. Dawodu et al. (2022) highlight the importance of contextual factors in implementing Campus Sustainability Assessment Tools (CSATs) and shaping sustainable campuses, emphasizing environmental, educational, and governance dimensions. Lim et al. (2022) classify ESD factors as commitment and awareness, assessment and critique, course coordination, structural transformation, and universities management, recognizing the active engagement of communities in advocating for sustainable development. Moreover, Zeeshan et al. (2022) proposed a Smart and Sustainable School framework comprising five key characteristics: Reliable and ICT infrastructure, emphasizing the need for secure, readily available, cost-effective, and environmentally friendly applications to achieve sustainability. Technology-driven smart classrooms to enhance learning experiences. Technology-enabled sustainable resource management for efficient utilization of resources. Smart school transport and in-campus security systems to ensure safety and convenience. Advanced pedagogies curriculum and interactive Learning Management Technologies to support innovative teaching methods. Moreover, the UN Environment Program (2021) introduced a framework that outlines a four-step process for universities to become sustainable. The framework provides valuable tips on quick wins and how to initiate this transformative journey.

This model aims to establish the essence of a sustainable university and charts a course towards achieving it. It also depicts the ways in which sustainability can progress in the four fundamental areas of a university: teaching & research, environment & climate, people & society, and governance & Administration. However, despite these progressions, there is a shortage of studies employing a conceptual framework that explores the technology integration factors contributing to sustainable development practice in the educational field (significant). The framework will answer the question What technology factors emphasize sustainability development in higher education? This study introduces the Technology-integrated Education for Sustainable Development (TIFESD) framework, encompassing technology-related factors like smart campus, smart education, green campus, and curriculum/course design as pillars of sustainable development in the context of technology. TIFESD offers a comprehensive approach to sustainable development, integrating technology factors that promote sustainability specifically within higher education institutions. These variables are Green Campus (Silva-da-Nóbrega et al., 2022; Sertyeşilışık, et al., 2018). Smart Campus (Polin et al., 2023; Liao et al. 2,022; Silva-da-Nóbrega et al., 2022) Curriculum and courses design (UNESCO. (2013, 2020), Smart Education (Silva-da-Nóbrega et al. 2022) and dependent variable Student awareness of ESD (Mojilis, 2019; Alsaati et al. 2020; Al-Naqbi, & Alshannag, 2017).

3.1 Green Campus

Previous research acknowledges the concept of a Green Campus as an innovative strategy that utilizes green technology and a green economy to address societal sustainability challenges (Sadh, 2019). This approach, called green ICT or green computing, involves applying environmental criteria and sustainability principles (Radu, 2016). Zeng et al. (2022) argue that the emergence of green technology innovation (GTI) offers a novel and impactful approach that prioritizes green environmental protection. Furthermore, Ulucak (2020) agrees that Green Technology has become one of the best alternative strategies for sustainable development. However, Green Technology is a term that encompasses various environmentally friendly practices such as energy efficiency, health and safety considerations, recycling, and the use of renewable resources. Organizations must adopt optimal resource utilization strategies in today's challenging and competitive business environment to ensure sustainable growth (Almaiah et al., 2022a). Higher education institutions can potentially foster connections between science, sustainability, and technology within their campuses (González-Zamar et al., 2020). Nada and Elgelany (2014) highlight that educational interventions play a crucial role in fostering attitudes and raising environmental awareness among students. However, it is crucial to implement a comprehensive green campus strategy that encompasses e-waste management, sustainable procurement, paperless strategies, and recycling. The presence of e-waste and its associated health risks pose a potential hindrance to achieving sustainable development goals. The Green Campus movement has gained significant momentum and is deemed crucial for higher education institutions in delivering an optimal learning experience for college students. Recognizing the Green Campus as an integrated approach, Gandasari et al. (2020) emphasize its role within educational research and community service systems, with a strong focus on environmental management. Similarly, Leal Filho et al. (2019b) suggest that establishing green offices and similar governance structures support sustainable development efforts within higher education institutions. Therefore, it can be hypothesized that:

H$_1$: *The adoption of Green Campuses positively influences students' awareness of Education for Sustainable Development (ESD) in their universities.*

3.2 Smart Campus

Universities can enhance their services, streamline processes, and effectively work towards achieving sustainability goals. The concept of a smart campus is an emerging trend that holds the potential to revolutionize the education system. Smart campus initiatives, enabled by digital transformation in higher education, aim to create technologically advanced and sustainable educational environments to meet the evolving needs of students, faculty, and staff (Polin et al., 2023). A Smart Campuses initiates with pervasive, trusted wired, wireless connectivity outdoors and indoors (Valks, et al., 2021; Caţă, 2015; Adomßent et al., 2019). Alwaer et al. (2010) define Smart buildings as technologically aware, sustainable, healthy buildings that meet the needs of occupants and businesses, flexible and adaptable to deal with change. Furthermore, Martins et al., (2021) indicate that a Smart Campus fits into three conceptual categories: Smart Living, Smart Learning, and Smart Security and Safety. Liao et al. (2022) highlight the importance of sustainable design in campus buildings to reduce resource depletion and lower carbon to create a healthy environment for occupants. These initiatives involve implementing smart campus infrastructure, which includes technologies such as smart buildings, Internet of Things (IoT) devices, and sensors, to enhance energy efficiency, reduce carbon emissions, optimize resource utilization, and improve sustainability performance in higher education institutions (Martins et al., 2021; Abuarqoub et al., 2017). Moreover, integrating smart technology with the physical infrastructure on a smart campus can significantly enhance campus sustainability and improve decision-making outcomes. Automated systems in smart buildings can regulate temperature and lighting based on occupancy levels, leading to significant energy savings. Recognizing the role of universities in societal transformation, sustainability, and digital revolutions, universities are increasingly acknowledged as vital stakeholders in driving positive change (Silva-Da-Nóbrega et al., 2022). Based on the aforementioned context, the following hypothesis is developed

H$_2$: *Implementing Smart Campus positively students' awareness of ESD in their universities.*

3.3 Smart Education

While there is no consensus on the exact definition of smart learning, scholars unanimously recognize the positive influence of technology in facilitating smart learning and education. Integrating e-learning, IoT, virtual reality, gamification, augmented reality, and interactive multimedia has proven to enhance students' comprehension, engagement, critical thinking, and problem-solving abilities. Zeeshan et al. (2022) emphasize the transformative potential of the Internet of Things (IoT) in delivering sustainable, high-quality education and promoting equal learning opportunities. They highlight how IoT can address the challenges encountered by education providers and managers, ultimately fostering sustainability in education. Kim et al. (2011) mention the significance of cloud computing in creating smart learning environments. Additionally, Sood and Singh (2018) note the rising gamification trend in e-learning. Furthermore, Lampropoulos et al. (2023), and Terras et al. (2019) confirm the effectiveness of combining augmented reality with gamification elements and serious games, leading to appropriate challenge levels, increased engagement, and improved learning experiences for students. However, integrating smart education and modern information and communication technologies to enhance education quality aligns with sustainable development goals outlined by UNESCO (2015) and the United Nations (2005). Zhang et al. (2004) further support using multimedia-based e-learning systems, incorporating diverse media like text, images, sound, and video to present learning materials. The integration of technology in e-learning not only provides convenient access to educational resources and reduces travel requirements and carbon emissions while enhancing teaching and learning experiences. Colás-Bravo and Quintero-Rodríguez (2023) recognize YouTube's role in promoting sustainable education by overcoming barriers and catering to individual learner needs. Smart education contributes to Education for Sustainable Development (ESD) by fostering inclusive and equitable learning environments, personalized and flexible learning approaches, and the acquisition of 21st-century skills. Educational institutions can further enhance the effectiveness of ESD and support students' sustainable development knowledge and skills. Given these considerations, students need to recognize that their educational institutions integrate technologies into learning activities to achieve sustainable development goals. Hence, the following hypothesis is proposed.

H$_3$: *Integrating Smart Education effect positively affects students' awareness of ESD in their universities.*

3.4 Curriculum and courses Design

Incorporating technology into higher education curriculum and course design is crucial for advancing Education for Sustainable Development (ESD) goals and preparing students for a sustainable future (UNESCO, 2019). According to Osman et al. (2017), a sustainability-focused curriculum should offer students opportunities to holistically explore, analyze, and engage with the world, developing competencies necessary to tackle its complexity and achieve the agenda of vision 2030. However, higher education institutions should not only concentrate on campus greening but also implement pedagogic reforms within the context of ESD. Biancardi et al. (2023) highlighted the significance of introducing relevant tools in the course curriculum to address economic opportunities, social inequalities, and environmental challenges in a sustainable energy system. Similarly, Msengi et al. (2019) stress the need for a curriculum that equips pupils to address and recognize sustainability challenges. Aligning assessment strategies with sustainability principles further enhances the integration of sustainability in syllabi. Furthermore, Hammer & Lewis (2023) propose that comprehensive empowerment should be included to address sustainable development challenges effectively. This empowerment can be achieved by emphasizing competency development throughout the program of study and enhancing educational elements, including learning outcomes, learning/teaching arrangement, and evaluations. However, Zeeger and Clark (2014) argue that a sustained impact on students' perceptions of sustainability is better achieved through its integration across the curriculum, rather than focusing on individual courses. Educators play a vital role in activating critical competencies within sustainability programs and course development, as Alkhayyal et al. (2019) emphasized. UNESCO (2017, 2013) recommends integrating sustainability principles and practices throughout all curricula, emphasizing critical thinking, problem-solving, and decision-making skills. To effectively integrate sustainability into educational programs, Tasdemir and Gazo (2020) highlight the importance of practical application within the curriculum. Universities should design their curriculum, practice, and courses to promote sustainability by incorporating interdisciplinary learning, experiential approaches, and specific tools and concepts (Barth et al., 2007; Franco et al., 2019). Various teaching approaches, such as social learning, gaming, case studies, problem-based learning, and project-based approaches, have proven successful in promoting ESD (Wals & Blewitt, 2010). Moreover, Kioupi and Voulvoulis (2022) stress the importance of aligning learning outcomes with sustainability and generating evidence of developing translated competencies in learners. Additionally, according to Ali et al., (2013), integrating environmental education into the curriculum heightens students' awareness of environmental issues and sustainability (Ali et al., 2013). This evidence will aid curriculum planners in creating appropriate programs. Lotz-Sisitka and Lupele (2015) affirm that incorporating sustainable practices into the curriculum enhances students' knowledge, skillfulness's, and attitudes. However, According to Winter and Cotton (2012), engaging in extracurricular projects and activities not explicitly integrated into the sustainable curriculum, like participating in faculties research, can enhance sustainable literacy and promote a culture change by fostering self-reflective abilities. In summary, integrating technology, interdisciplinary learning, experiential approaches, and sustainability-aligned assessment strategies into higher education curricula is essential for promoting ESD and empowering students to address sustainability challenges effectively. Therefore, the following hypothesis is proposed.

H4: Curriculum and courses Design impact positively students' awareness of ESD.

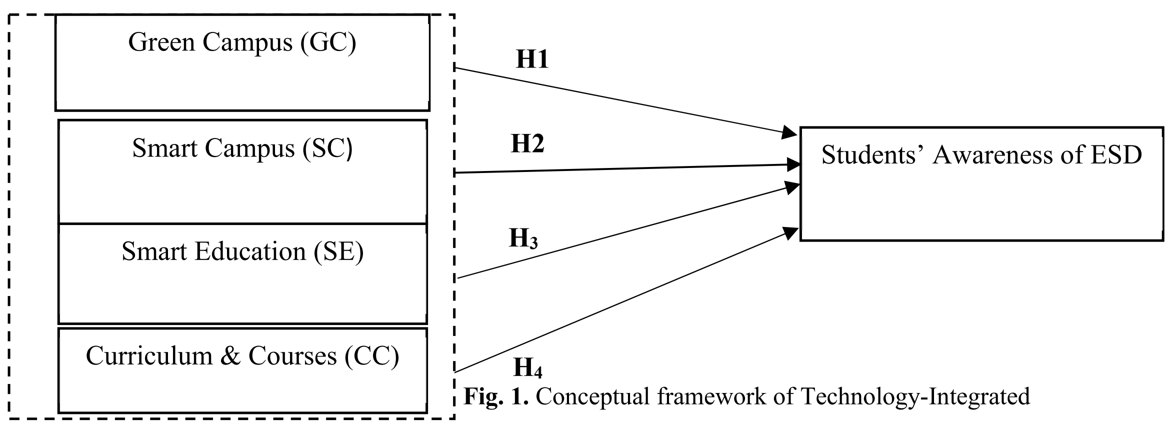


Fig. 1. Conceptual framework of Technology-Integrated

3.5 Students' Awareness and Knowledge

Empowering students and increasing their awareness and knowledge of sustainability are pivotal in fostering Education for Sustainable Development (ESD) and building a sustainable future (Wals & Blewitt, 2010; UNESCO, 2021; Tsaprouni & Papatheodorou, 2021). Higher education institutions are critical in empowering students as change agents for sustainable development and establishing a pervasive culture of sustainability on campus (Tsaprouni & Papatheodorou, 2021). To secure a more sustainable future, universities and policymakers should prioritize investments in sustainable education and awareness-raising initiatives (Tsaprouni & Papatheodorou, 2021). Integrating sustainability education into higher education enhances students' awareness, knowledge, and personal and professional development and equips them to become more actively engaged in sustainability (Mojilis, 2019). Furthermore, Alsaati et al. (2020) mention that sustainability awareness must be offered to learners through numerous channels, including university initiatives, governmental programs, and media. Moreover, as Barth et al. (2007) emphasized, educational institutions must foster interdisciplinarity and assist learners to take responsibility for their actions. However, Lozano (2006) acknowledges that the process of sustainability development within institutions is likely to encounter resistance from internal and external stakeholders. Corcoran & Wals (2004) ensure that introducing education for sustainability within the academy is not without its dilemmas. Sustainable universities ought to empower the younger generation by fostering student involvement in real-world projects and nurturing lasting, structured teachers-students' relations (Biancardi, et al., 2023). Higher education institutions must proactively foster students' awareness of sustainability practices and understanding related issues through diverse avenues, including curricula, co-curricular activities, and programs.

4. Methodology

This study proposes the factors related to technology-integrated education for sustainable development (ESD). It explores students' awareness of these factors in higher education institutions in the UAE, considering factors from previous studies such as Green Campus, Smart Campus, Smart Education, curriculum, and courses. The study employed a previously validated framework to conduct a quantitative descriptive-exploratory study using purposive sampling. Purposive sampling is a non-probability sampling method that involves selecting participants based on their relevance to the research objective. The study selects students from various nine universities located in Ajman, Sharjah, Dubai, and Abu Dhabi appropriate for the study. The survey included demographic questions and five sections. The questions were designed utilizing items from prior research to measure the constructs of the smart campus infrastructure (Silva-da-Nóbrega et al., 2022), Green Campus (Silva-da-Nóbrega et al., 2022; Sertyeşilışık, et al. 2018; Zeegers & Francis Clark, 2014) Smart Education (Silva-da-Nóbrega, et al. 2022; Junco, 2012) Curriculum and Courses and Students Awareness (Mahmud, 2017; AlNaqbi, & Alshannag, 2017; Zeeger & Clark, 2014).

4.1 Data Collection

The research was conducted across nine universities in the UAE, specifically in Abu-Dhabi, Dubai, Ajman, and Sharjah Emirates. A total of 513 surveys were collected from more than nine universities ln the UAE. These universities include Ajman University (AU), American University of Sharjah (AUS), United Arab Emirates University (UAEU), the University of Sharjah, Gulf Medical University, New York University Abu Dhabi, and Middlesex University Dubai, Arab Academy for Maritime Transport and Science Technology, and Heriot-Watt University. The participants were undergraduate and postgraduate students. Government and private universities are accredited by Ministry of Education (MoE) and align with the UAE's sustainability development (SD) strategy, which includes adopting Environmental, Social, and Economic Sustainability (ESD) principles. The universities should have national and international recognition and meet the standards set by MoE. Data collection took place in April 2023 using a hybrid method collect the data that involved an online survey administered through Google Forms and face-to-face interactions and social media (SM) platforms such as Instagram, Facebook, and WhatsApp’s. The survey utilized a 5-point Likert scale, with respondents rating items on importance and performance. Demographic information, such as gender, majors, university campus, and academic year, was also collected.

5. Analysis of the data

5.1 Demographical Analysis

Table 1 presents the demographic analysis of this study participants and reveals key characteristics of the sample, including gender distribution, nationalities, academic year, universities attended, and colleges represented. Most respondents were female students, comprising 73.9% of the sample, while males represented 26.1%. Nationality: Most respondents had UAE nationality, accounting for 10.9% of the sample. Arab nationality was the most prevalent, with 52.6% of respondents. Asian nationality represented 17.0%, followed by European nationality (5.3%), African nationality (12.7%), and other nationalities (1.6%). Academic Year: Respondents were distributed across various academic years as follows: First Year (16.4%), Second Year (13.6%), Third Year (21.8%), Fourth Year (24.2%), Fifth Year (7.2%), Last Year (8.2%), and Postgraduate (8.6%). University: Most respondents were from Ajman University (70.0%). Other universities represented in the sample included the University of Sharjah (6.8%), Gulf Medical University (2.1%), American University of Sharjah (4.7%), New York University Abu Dhabi (2.9%), Middlesex University (3.1%), the Arab Academy for Science, Maritime Transport, and Technology (0.6%), Heriot-Watt University (2.3%), United Arab Emirates University (2.1%), and other universities (5.3%). The respondents’ students were enrolled in various colleges: Business (32.0%), Engineering (11.7%), IT (6.6%), Medicine (9.6%), Law (4.5%), Dentistry (15.4%), Mass Communication (3.1%), Pharmacy (6.2%), Humanities and Sciences (4.7%), and Art & Design (6.2%).

Table 1
Demographic Characteristics Analysis

Attributes	Category	Frequency	Percentage
Gender	Male	134	26.1
	Female	379	73.9
Nationality	UAE Nationality	56	10.9
	Arab Nationality	270	52.6
	Asian Nationality	87	17.0
	European Nationality	27	5.3
	African Nationality	65	12.7
	American Nationality	8	1.6
University	Ajman University	359	70.0
	University of Sharjah (US)	35	6.8
	Gulf Medical University	11	2.1
	American University of Sharjah	24	4.7
	New York University Abu Dhabi	15	2.9
	Middlesex University	16	3.1
	Arab Academy for Science, Technology, and Maritime Transport	3	0.6
	Heriot-Watt University	12	2.3
	United Arab Emirates University	11	2.1
	Other universities	27	5.3

Table 1
Demographic Characteristics Analysis (Continued)

Attributes	Category	Frequency	Percentage
Colleges	Business	164	32.0
	Engineering	60	11.7
	IT	34	6.6
	Medicine	49	9.6
	Law	23	4.5
	Dentistry	79	15.4
	Mass Communication	16	3.1
	Pharmacy	32	6.2
	Humanities and Sciences	24	4.7
	Art & Design	32	6.2
Academic Year	First Year	84	16.4
	Second Year	70	13.6
	Third Year	112	21.8
	Fourth Year	124	24.2
	Fifth Year	37	7.2
	Last Year	42	8.2
	Postgraduate	44	8.6

5.2 Construct Validity

Table 2 presents the results of the construct validity analysis for five constructs: Green Campus (GC), Smart Campus (SC), Smart Education (SE), Curriculum and Courses (CC), and Student ESD Awareness (SEA). The table includes information such as outer loadings (λ), composite reliability (CR), average variance extracted (AVE), Cronbach's alpha α, and rho_A values for each construct. Specific values are provided for some items, while others are not specified. AVE values above 0.5 indicate acceptable variance captured by the construct. CR values above 0.7 indicate satisfactory internal consistency reliability. Similarly, Cronbach's α values above 0.7 suggest reliable internal consistency. Rho_A values serve as an alternative reliability measure comparable to Cronbach's α. The results demonstrate good construct validity for all constructs, with significant AVE, CR, Cronbach's α, and rho_A values at the p<.001 level, indicating the reliable measurement of each construct.

Table 2
Constructs Validity

Constructs	Items	λ	AVE	CR	Cronbach's α	rho_A
Green Campus (GC)	GC1	0.905	0.797	0.922	0.873	0.874
	GC2	0.88				
	GC3	0.844				
	GC1	0.706				
Smart Campus (SC)	SC1	0.813	0.558	0.863	0.801	0.802
	SC2	0.798				
	SC3	0.751				
	SC4	0.738				
Smart Education (SE)	SE1	0.887	0.722	0.912	0.872	0.875
	SE2	0.882				
	SE3	0.85				
	SE4	0.834				
Curriculum and Courses (CC)	CC1	0.89	0.764	0.907	0.846	0.847
	CC2	0.858				
	CC3	0.85				
	CC4	0.833				
Student ESD Awareness (SEA)	SEA1	0.871	0.796	0.921	0.872	0.873
	SEA2	0.826				
	SEA3	0.812				
	SEA4	0.732				

5.3 Discrimination Validity

To assess the discriminant validity. Hence, the study proposed using the Heterotrait–Monotriait ratio (HTMT) and Fornill–Larcker criterion as the dominant approaches for evaluating discriminant validity. (Almaiah et al., 2022c; Alrawad et al., 2023; Hair et al. 2017; Henseler, et al. 2015). Therefore, Table 3 presents the findings of the discriminant validity analysis using the Fornell-Larcker Criterion (1981) and the HTMT Ratios. The Fornell-Larcker Criterion assesses the distinctiveness of different constructs in the study, while the Heterotrait-Monotrait Ratio measures the correlation between constructs relative to their average correlations with themselves. According to the Fornell-Larcker Criterion, the square correlations between constructs should be smaller than the average variance extracted (AVE) for each construct. The table shows the square correlations and AVEs for Green Campus (GC), Smart Campus (SC), Smart Education (SE), Curriculum and Courses (CC), and Student ESD Awareness (SEA). Not all AVE values are specified in the table. Additionally, the Heterotrait-Monotrait Ratio between pairs of constructs is provided. The Heterotrait-Monotrait Ratios for GC, SC, SE, CC, and SEA with other constructs are mentioned.

Table 3
Discriminant validity

Fornell-Larcker Criterion (1981)					
Green Campus (GC)	GC	SC	SE	CC	SEA
Smart Campus (SC)	**0.893**[a]				
Smart Education (SE)	0.611	**0.747**			
Curriculum and Courses (CC)	0.458	0.454	**0.85**		
Student ESD Awareness (SEA)	0.63	0.685	0.46	**0.874**	
Heterotrait-Monotrait Ratio					
Green Campus (GC)					
Smart Campus (SC)	0.728				
Smart Education (SE)	0.523	0.546			
Curriculum and Courses (CC)	0.731	0.833	0.534		
Student ESD Awareness (SEA)	0.549	0.592	0.435	0.494	

Note: The bold values in the above matrix are the square correlations between the latent constructs and diagonals are AVE's. HTMT<0.850 (Kline, 2011)

5.4 Assessment of Structural Model

Table 4 presents the structural model assessment, focusing on the direct effects of independent variables (GC, SC, SE, CC) on the dependent variable (SEA). It includes parameters (β), standard errors (SE), t-values, 95% BCa-CIs (bias-corrected and accelerated confidence intervals), and remarks indicating hypothesis support. H1: GC → SEA shows a strong positive relationship (β =.670, SE = 0.030, t = 22.206, $p < 0.001$, 95% BCa-CIs: 0.605 to 0.725). H2: SC → SEA demonstrates a positive relationship (β =.123, SE = 0.045, t = 2.741, $p < 0.01$, 95% BCa-CIs: 0.042 to 0.218), albeit smaller than GC. H3: SE → SEA exhibits a strong positive relationship (β =.516, SE = 0.052, t = 9.872, $p < 0.001$, 95% BCa-CIs: 0.408 to 0.614). H4: CC → SEA shows a positive relationship (β =.443, SE = 0.056, t = 7.915, $p < 0.001$, 95% BCa-CIs: 0.330 to 0.546). All the hypotheses are supported, indicating significant direct effects of GC, SC, SE, and CC on SEA. These findings highlight the influence of these constructs in enhancing student awareness of ESD within the study's context.

Table 4
Structural model Assessment

Direct effects

Relationships	**Beta**	**S.E**	**t-values**	**95% BCa-Cis**	**Results**
H1) GC → SEA	0.67	0.03	22.206**	[0.605; 0.725]	Accepted
H2) SC → SEA	0.123	0.045	2.741*	[0.042; 0.218]	Accepted
H3) SE → SEA	0.516	0.052	9.872**	[0.408; 0.614]	Accepted
H4) CC → SEA	0.443	0.056	7.915**	[0.330; 0.546]	Accepted

*Note; *$p < 0.01$, **$p < 0.001$*

6. Discussion

Students are the powerful agents of change, for higher education sustainable development. Their awareness is essential to promote sustainability. This study explores students' awareness of sustainable development practices in the higher education institutions in the UAE. The study findings align with Koskela and Kärkkäinen (2021), who state that student learners play a significant role as change agents in the education for sustainable development. Mohammadi et al. (2023) corroborate the study finding that students' commitment to sustainability was positively influenced by their sustainability knowledge and attitudes, as well as the leadership and culture within the university. According to the study findings, students demonstrate a high level of awareness regarding their university's commitment to sustainable practices, including using curriculum promoting sustainability, implementing green campus initiatives, utilizing smart campus technologies, and integrating smart education methodologies. According to Sertyeşilışık et al. (2018) results, there is a need to enhance awareness about sustainability through education. Universities have a crucial role to play in tackling climate changes, particularly by offering courses on sustainability, promoting sustainable practices, and creating green campuses. This aligns with Ali et al. (2014) on students' awareness of the connection between technology use for learning, sustainability, and employability. Accordingly, João Marcelo Pereira Ribeiro et al., (2021) in Brazil agree that implementing sustainable development (SD) dissemination strategies in universities enhances students' understanding and awareness of SD significance. However, Mahmud (2017) in Malaysia states that a lack of awareness among the important stakeholders in curriculum development is a barrier to implementing ESD. However, the study results indicate that students recognize that curricula and courses in their universities are designed to support and advance sustainable development practices. These findings are in align with prior research conducted by Islam et al. (2021), who also observed that students fully understand sustainable development principles when technology is integrated into their educational experiences. Additionally, the findings support Al-Naqbi and Alshannag (2017) previous study confirming significant student awareness of ESD. However, the finding is inconsistent with Alsaati et al. (2020) study, which found in Saudi Arabia that students lack awareness regarding sustainability, particularly when recognizing renewable materials or recycling materials that form a part of their daily routine. Unlike the findings of João Marcelo Pereira Ribeiro et al.'s (2021) study, which showed that students did not prominently perceive campus green infrastructure. Leal Filho et al. (2019a) also emphasized the significance of supporting campus sustainability initiatives and fostering awareness among learners and staff to promote SD.

Furthermore, the study's findings strengthen the understanding that students know the smart campuses' existence in their university to foster (ESD). This aligns with previous studies advocating adopting smart technologies and creating smart educational infrastructure, such as smart technologies in creating smarter educational environments, reducing energy, smart building management systems, creating smarter educational environments, and promoting sustainable campus practices. However, Silva-da-Nóbrega et al. (2022) point out, the importance of not relying solely on technology attributes in the smart campus process. Universities must align themselves with modern societies' present and future society needs and the social, and technological manner. However, the study indicates that students' awareness of the smart education method, such as e-learning, using IoT, virtual reality, gamification, and augmented reality adopted by their universities to promote sustainable educational practice, is consistent with Alotaibi, (2022), which emphasizes the potential of Saudi Arabia's higher education institutions in various aspects related to sustainable development, including their capacities for e-learning, improvisation, and organizations readiness. Furthermore, Cebrián et al. (2022) agree that Smart Classroom is well-suited for employing project-based and problem learning, cooperative inquiry and case study methods due to its technological advancements, environmental conditions, and processes. Zhang et al. (2004) emphasize that integrating digital technology into e-learning environments allows personalized learning experiences tailored to individual students' needs and preferences. Zeeshan et al. (2022) emphasize that IoT-based smart learning contributes to Customized learning environments, and online or distance learning can be improved effectively by IoT. Moreover, the study indicates that students are highly aware of promoting sustainable development within their curriculum this finding is consistent with previous studies emphasize that when students are made aware of sustainability issues through their curriculum, they become more conscious of their impact on the environment and are motivated to adopt sustainable practices. Furthermore, the work indicates that learners are highly aware of promoting sustainable development within their curriculum this finding is consistent with Yuan, et al. (2021) mentioned that to enhance the implementation of ESD, a comprehensive approach that includes both formal and non-formal education, along with curriculum integration, is essential. This approach raises competencies, knowledge, and students' awareness related to sustainability and promotes their active engagement in sustainable practices. The results further support the notion that students are actively engaged and informed about the importance of sustainability within their curriculum and coursework to enhance learners' overall commitment and academic accomplishment (Tarrant et al., 2021). Likewise, in Korea, Gress and Shin (2017) recognize the necessity of systemic transformations in current educational practices to effectively incorporate sustainable principles and methods into technical curricula when implementing green curricula. Nevertheless, the study is consistent with earlier works stating that incorporate sustainability into Business schools curricula, teaching, research, and operational practices, enhances students' understanding and motivation to address sustainability challenges (Painter-Morland et al., 2016).

7. Research Implications

Despite utilizing empirical findings from the UAE, the central issue addressed in this study possesses universal significance across diverse higher education systems in our interconnected world. Consequently, scholars from other countries, particularly those in developing nations, may find it valuable to investigate the applicability of the predictors identified in this work. This work contributes to the comprehension of the significance of technology in advancing Education for Sustainable Development (ESD) within a Gulf country. It provides valuable insights for further implementing technology-driven sustainability initiatives in higher education. A theoretical framework contains potential starting points for subsequent ESD research. the Technology-Integrated Framework of Education Sustainable Development (TIFESD), is introduced, underlining technology's role in enhancing ESD. The TIFESD framework incorporates four key factors: Green Campus, smart Education, and curriculum and Course Design, integrating technology into the sustainable practices of higher education institutions, recognizing its potential to revolutionize and amplify sustainability efforts. Applying TIFESD to educational settings, offer new avenues for transformative and impactful sustainability practices to emerge within higher education. The framework expands understanding of the association between technology and sustainability and provides practical guidelines to maximize the potential of technology in promoting sustainable development within educational environments. This study presents an extensive and inclusive framework that promotes technology's effective integration and utilization to advance sustainable development goals in higher education. Its implementation holds the potential to revolutionize sustainability practices, foster innovation, and contribute to the realization of a more sustainable future through education. The study practically validates the framework by examining how these factors influence the awareness levels of students from different cultures, genders, majors, and academic years.

8. Limitations and Future Research

The study acknowledges certain limitations. Firstly, the study model is restricted to factors that serve as tools for exploring technology-integrated educational sustainable development. Additional variables may be included in future studies to align with researchers' objectives in ESD. Moreover, as our research findings are derived from a single country, the UAE experiences, yet will still provide significant inputs and benefits to a global society and discussions about ESD's future worldwide.

Additionally, this study has shed light on the relevance of ESD practice in one of the Gulf countries. However, future studies can clarify further by examining a broader range of locations. Another limitation pertains to the nature of the data collected. The work relied on an online and face-to-face written voluntary orientation task, which may not ensure that all students were fully engaged and responded accurately to the questions.

9. Conclusion

Promoting sustainability development in education is a global endeavor, aiming to foster the sharing of experiences and knowledge on sustainability development from various regions and countries worldwide. This collective sharing of insights has the potential to expedite the advancement of sustainability initiatives and the achievement of Sustainable Development (SD) goals. The study focused on students' awareness of technology-integrated factors that support SD significance, and sustainable development practices in universities. The findings suggest that there are no barriers in universities regarding students' awareness of the effective integration of technology in sustainability development practices. Furthermore, the study results confirm the extent of students' awareness of sustainability development concerning technology. However, universities should also emphasize promoting sustainability through other factors in education. The study yielded two significant findings. Firstly, the study results provide empirical evidence for ESD practice and the students' awareness as they can actively contribute to creating sustainable communities and tackling change challenges. Secondly, the study presented the Technology-Integrated Framework of Educational Sustainable Development (TIFESD). This conceptual framework explores the influence of technology integration factors, such as green campus, smart campus, smart education, and curriculum and course design, on students' awareness of Education for Sustainable Development (ESD). This framework provides valuable insights into the role of technology in promoting ESD and establishes a solid foundation for integrating technology into sustainability practices within higher education institutions.

Acknowledgement

This research was funded through the annual funding track by the Deanship of Scientific Research, from the vice presidency for graduate studies and scientific research, King Faisal University, Saudi Arabia, Grant No. [GRANT4538].

References

Abuarqoub, A., Abusaimeh, H., Hammoudeh, M., Uliyan, D., Abu-Hashem, M. A., Murad, S., ... & Al-Fayez, F. (2017, July). A survey on internet of things enabled smart campus applications. In *Proceedings of the International Conference on Future Networks and Distributed Systems* (pp. 1-7).

Adomßent, M., Grahl, A., & Spira, F. (2019). Putting sustainable campuses into force: Empowering students, staff and academics by the self-efficacy Green Office Model. *International Journal of Sustainability in Higher Education*, *20*(3), 470-481.

Ali, A., Murphy, H. C., & Nadkarni, S. (2014). Hospitality students' perceptions of digital tools for learning and sustainable development. *Journal of Hospitality, Leisure, Sport & Tourism Education*, *15*, 1-10.

Ambusaidi, A., & Al-Rabaani, A. (2009). Environmental education in the Sultanate of Oman: Taking sustainable development into account. In *Environmental education in context* (pp. 37-50). Brill.

Alwaer, H., & Clements-Croome, D. J. (2010). Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Building and environment*, *45*(4), 799-807.

Alkhayyal, B., Labib, W., Alsulaiman, T., & Abdelhadi, A. (2019). Analyzing sustainability awareness among higher education faculty members: A case study in Saudi Arabia. *Sustainability*, *11*(23), 6837.

Alotaibi, N. S. (2022). The Significance of Digital Learning for Sustainable Development in the Post-COVID19 World in Saudi Arabia's Higher Education Institutions. *Sustainability*, *14*(23), 16219.

Almaiah, M. A., Alfaisal, R., Salloum, S. A., Al-Otaibi, S., Shishakly, R., Lutfi, A., ... & Al-Maroof, R. S. (2022a). Integrating teachers' TPACK levels and students' learning motivation, technology innovativeness, and optimism in an IoT acceptance model. *Electronics*, *11*(19), 3197.

Almaiah, M. A., Hajjej, F., Shishakly, R., Lutfi, A., Amin, A., & Awad, A. B. (2022b). The role of quality measurements in enhancing the usability of mobile learning applications during COVID-19. *Electronics*, *11*(13), 1951.

Almaiah, M. A., Alfaisal, R., Salloum, S. A., Hajjej, F., Shishakly, R., Lutfi, A., ... & Al-Maroof, R. S. (2022c). Measuring institutions' adoption of artificial intelligence applications in online learning environments: Integrating the innovation diffusion theory with technology adoption rate. *Electronics*, *11*(20), 3291.

Al-Naqbi, A. K., & Alshannag, Q. (2018). The status of education for sustainable development and sustainability knowledge, attitudes, and behaviors of UAE University students. *International Journal of Sustainability in Higher Education*, *19*(3), 566-588.

Alrawad, M., Lutfi, A., Alyatama, S., Al Khattab, A., Alsoboa, S. S., Almaiah, M. A., ... & Al-Khasawneh, A. L. (2023). Assessing customers' perception of online shopping risks: A structural equation modeling–based multigroup analysis. *Journal of Retailing and Consumer Services*, *71*, 103188.

Alrfai, M. M., Alqudah, H., Lutfi, A., Al-Kofahi, M., Alrawad, M., & Almaiah, M. A. (2023). The influence of artificial intelligence on the AISs efficiency: Moderating effect of the cyber security. *Cogent Social Sciences*, *9*(2), 2243719.

Alsaati, T., El-Nakla, S., & El-Nakla, D. (2020). Level of sustainability awareness among university students in the eastern province of Saudi Arabia. *Sustainability*, *12*(8), 3159.

Baroudi, S. (2023). Exploring Teacher Education for Sustainable Development in the UAE. *Sustainability*, *15*(3), 1981.

Barth, M., Godemann, J., Rieckmann, M., & Stoltenberg, U. (2007). Developing key competencies for sustainable development in higher education. *International Journal of sustainability in higher education*, *8*(4), 416-430.

Biancardi, A., Colasante, A., & D'Adamo, I. (2023). Sustainable education and youth confidence as pillars of future civil society. *Scientific Reports*, *13*(1), 955.

Caţă, M. (2015, September). Smart university, a new concept in the Internet of Things. In *2015 14th RoEduNet international conference-networking in education and research (RoEduNet NER)* (pp. 195-197). IEEE.

Cebrián, G., Palau, R., & Mogas, J. (2020). The smart classroom as a means to the development of ESD methodologies. *Sustainability*, *12*(7), 3010.

Corcoran, P. B., & Wals, A. E. (2004). Higher education and the challenge of sustainability. *Dordrecht: Kluwer Academic Publishers*, *10*, 0-306.

Colás-Bravo, P., & Quintero-Rodríguez, I. (2023). YouTube as a Digital Resource for Sustainable Education. *Sustainability, 15*(7), 5687.

Ulucak, R. (2020). How do environmental technologies affect green growth? Evidence from BRICS economies. *Science of the Total Environment*, *712*, 136504.

Dawodu, A., Dai, H., Zou, T., Zhou, H., Lian, W., Oladejo, J., & Osebor, F. (2022). Campus sustainability research: indicators and dimensions to consider for the design and assessment of a sustainable campus. *Heliyon*.

Franco, I., Saito, O., Vaughter, P., Whereat, J., Kanie, N., & Takemoto, K. (2019). Higher education for sustainable development: Actioning the global goals in policy, curriculum and practice. *Sustainability Science*, *14*, 1621-1642.

Leal Filho, W., Will, M., Salvia, A. L., Adomssent, M., Grahl, A., & Spira, F. (2019a). The role of green and Sustainability Offices in fostering sustainability efforts at higher education institutions. *Journal of Cleaner Production*, *232*, 1394-1401.

Leal Filho, W., Skouloudis, A., Brandli, L. L., Salvia, A. L., Avila, L. V., & Rayman-Bacchus, L. (2019b). Sustainability and procurement practices in higher education institutions: Barriers and drivers. *Journal of cleaner production*, *231*, 1267-1280.

Leal Filho, W., Yang, P., Eustachio, J. H. P. P., Azul, A. M., Gellers, J. C., Gielczyk, A., ... & Kozlova, V. (2023). Deploying digitalisation and artificial intelligence in sustainable development research. *Environment, development and sustainability*, *25*(6), 4957-4988.

Gandasari, I., Hotimah, O., & Miyarsah, M. (2020). Green Campus As a Concept in Creating Sustainable Campuses. *KnE Social Sciences*, 1-9.

González-Zamar, M. D., Abad-Segura, E., López-Meneses, E., & Gómez-Galán, J. (2020). Managing ICT for sustainable education: Research analysis in the context of higher education. *Sustainability*, *12*(19), 8254.

Gress, D. R., & Shin, J. (2017). Potential for knowledge in action? An analysis of Korean green energy related K3–12 curriculum and texts. *Environmental Education Research*, *23*(6), 874-885.

Hair, J., Hollingsworth, C. L., Randolph, A. B., & Chong, A. Y. L. (2017). An updated and expanded assessment of PLS-SEM in information systems research. *Industrial management & data systems*, *117*(3), 442-458.

Hammer, T., & Lewis, A. L. (2023). Which competencies should be fostered in education for sustainable development at higher education institutions? Findings from the evaluation of the study programs at the University of Bern, Switzerland. *Discover sustainability*, *4*(1), 19.

Heiskanen, E., Thidell, Å., & Rodhe, H. (2016). Educating sustainability change agents: The importance of practical skills and experience. *Journal of Cleaner Production, 123*, 218-226.

Henseler, J., Ringle, C. M., & Sarstedt, M. (2015). A new criterion for assessing discriminant validity in variance-based structural equation modeling. *Journal of the academy of marketing science*, *43*, 115-135.

Hodges, C. B., Moore, S., Lockee, B. B., Trust, T., & Bond, M. A. (2020). The difference between emergency remote teaching and online learning.

Islam, M. S., Siddique, A. B., Akter, R., Tasnim, R., Sujan, M. S. H., Ward, P. R., & Sikder, M. T. (2021). Knowledge, attitudes and perceptions towards COVID-19 vaccinations: a cross-sectional community survey in Bangladesh. *BMC public health*, *21*(1), 1-11.

Ali, M. I., Abduh, A., Mahmud, R., & Dunakhir, S. (2023). Raising Students' Awareness on Environmental Education Issues. *Indonesian Journal of Educational Research and Review*, *6*(1), 1-8.

Ribeiro, J. M. P., Hoeckesfeld, L., Dal Magro, C. B., Favretto, J., Barichello, R., Lenzi, F. C., ... & de Andrade, J. B. S. O. (2021). Green Campus Initiatives as sustainable development dissemination at higher education institutions: Students' perceptions. *Journal of Cleaner Production*, *312*, 127671.

Jiwane, A. (2013) Cultural Awareness: Facilitator for Sustainable Community Development- Case Study of Bahrain Anamika Jiwane. International Journal of Science and Research (IJSR) ISSN (Online): 2319-7064 Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438.

Kim, S., Song, S. M., & Yoon, Y. I. (2011). Smart learning services based on smart cloud computing. *Sensors*, *11*(8), 7835-7850.

Kioupi, V., & Voulvoulis, N. (2022). The Contribution of Higher Education to Sustainability: The Development and Assessment of Sustainability Competences in a University Case Study. *Education Sciences*, *12*(6), 406.

Koskela, T., & Kärkkäinen, S. (2021) Student Teachers' Change Agency in Education for Sustainable Development. *Journal of Teacher Education for Sustainability, 23*(1), 84-98. https://doi.org/10.2478/jtes-2021-0007.

Lampropoulos, G., Keramopoulos, E., Diamantaras, K., & Evangelidis, G. (2023). Integrating Augmented Reality, Gamification, and Serious Games in Computer Science Education. *Education Sciences*, *13*(6), 618.

Liao, C. W., Lin, J. H., & Chen, T. W. (2022). Research on a Framework for Sustainable Campus Eco-Architecture Selection: Taking a Taiwan High School as an Example. *Sustainability*, *14*(10), 6265.

Lotz-Sisitka, H., & Lupele, J. (2017). ESD, learning and quality education in Africa: Learning today for tomorrow. *Schooling for sustainable development in Africa*, 3-24.

Lozano, R. (2006). Incorporation and institutionalization of SD into universities: breaking through barriers to change. *Journal of cleaner production*, *14*(9-11), 787-796.

Lim, C. K., Haufiku, M. S., Tan, K. L., Farid Ahmed, M., & Ng, T. F. (2022). Systematic review of education sustainable development in higher education institutions. *Sustainability*, *14*(20), 13241.

Marei, A. (2022). The effect of e-procurement on financial performance: Moderating the role of competitive pressure. *Uncertain Supply Chain Management, 10*(3), 855-866.

Martins, P., Lopes, S. I., Rosado da Cruz, A. M., & Curado, A. (2021). Towards a smart & sustainable campus: An application-oriented architecture to streamline digitization and strengthen sustainability in academia. *Sustainability*, *13*(6), 3189.

Machado, C. F., & Davim, J. P. (2023). Sustainability in the Modernization of Higher Education: Curricular Transformation and Sustainable Campus—A Literature Review. *Sustainability*, *15*(11), 8615.

MCKeown, R., & Hopkins, C. (2007). Moving beyond the EE and ESD disciplinary debate in formal education. *Journal of education for sustainable development*, *1*(1), 17-26.

Mojilis, F. (2019). Sustainability awareness of students from a green university in Sabah, Malaysia. *Journal of Tourism, Hospitality and Environment Management*, *4*(13), 24-33.

Mohammadi, Y., Monavvarifard, F., Salehi, L., Movahedi, R., Karimi, S., & Liobikienė, G. (2023). Explaining the Sustainability of Universities through the Contribution of Students' Pro-Environmental Behavior and the Management System. *Sustainability*, *15*(2), 1562.

Msengi, I., Doe, R., Wilson, T., Fowler, D., Wigginton, C., Olorunyomi, S., ... & Morel, R. (2019). Assessment of knowledge and awareness of "sustainability" initiatives among college students. *Renewable Energy and Environmental Sustainability*, *4*, 6.

Mahmud, S. N. D. (2017). Systems structure of education for sustainable development in higher education institution. *Creative Education*, *8*(9), 1379-1400.

Nada, N., & Elgelany, A. (2014). Green technology, cloud computing and data centers: The need for integrated energy efficiency framework and effective metric. *International Journal of Advanced Computer Science and Applications*, *5*(5).

Osman, A., Ladhani, S., Findlater, E., & McKay, V. (2017). Curriculum Framework for the Sustainable Development Goals First Edition. Available online: https://www.thecommonwealth-educationhub.net/wp-content/uploads/2017/01/Curriculum_Framework_for_SDGs_July_2017.pdf (accessed on 7 july 2023).

Polin, K., Yigitcanlar, T., Limb, M., & Washington, T. (2023). The Making of Smart Campus: A Review and Conceptual Framework. *Buildings*, *13*(4), 891.

Radu, L. D. (2016). Determinants of green ICT adoption in organizations: a theoretical perspective. *Sustainability*, *8*(8), 731.

Sadh, VG. (2019). Green Technology in Education: Key to Sustainable Development. Proceedings of Recent Advances in Interdisciplinary Trends in Engineering & Applications (RAITEA) 2019, Available at SSRN: https://ssrn.com/abstract=3368186 or http://dx.doi.org/10.2139/ssrn.3368186.

Segalàs, J., Ferrer-Balas, D., & Mulder, K. F. (2010). What do engineering students learn in sustainability courses? The effect of the pedagogical approach. *Journal of Cleaner production*, *18*(3), 275-284.

Sertyeşilışık, B., Giritli, H., Tezel, E., & Sertyeşilışık, E. (2018). An Investigation into University Students' Perceptions of Sustainability. In *Proceedings of 3rd International Sustainable Buildings Symposium (ISBS 2017) Volume 2 3* (pp. 338-346). Springer International Publishing. DOI: 10.1007/978-3-319-64349-6_27.

Silva-da-Nóbrega, P. I., Chim-Miki, A. F., & Castillo-Palacio, M. (2022). A Smart Campus Framework: Challenges and Opportunities for Education Based on the Sustainable Development Goals. *Sustainability*, *14*(15), 9640. https://doi.org/10.3390/su14159640.
https://www.researchgate.net/publication/362508687_A_Smart_Campus_Framework_Challenges_and_Opportunities_for_Education_Based_on_the_Sustainable_Development_Goals [accessed Mar 17 2023].

Sterling, S. (2010). Learning for resilience, or the resilient learner? Towards a necessary reconciliation in a paradigm of sustainable education. *Environmental Education Research*, *16*(5-6), 511-528.

Sood, S. K., & Singh, K. D. (2018). An Optical-Fog assisted EEG-based virtual reality framework for enhancing E-learning through educational games. *Computer Applications in Engineering Education*, *26*(5), 1565-1576.

Tasdemir, C., & Gazo, R. (2020). Integrating sustainability into higher education curriculum through a transdisciplinary perspective. *Journal of Cleaner Production*, *265*, 121759. DOI: 10.1016/j.jclepro.2020.121759

Tarrant, M., Schweinsberg, S., Landon, A., Wearing, S. L., McDonald, M., & Rubin, D. (2021). Exploring student engagement in sustainability education and study abroad. *Sustainability*, *13*(22), 12658. https://doi.org/10.3390/su132212658.

United Nations. (2005). United Nations Decade of Education for Sustainable Development. Retrieved from.https://sustainabledevelopment.un.org/index.php?page=view&type=30022&menu=2993&nr=22UNESCO. (2017). Education for

Sustainable Development Goals: Learning Objectives. ISBN: 978-92-3-100209-0 Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000247444.
UNESCO (2017) A Decade of Progress on Education for Sustainable Development: A reflection from UNESCO Chair Programme. available on https://books.google.be/books?hl=en&lr=&id=ZjIuDwAAQBAJ&oi=fnd&pg=PA4&dq=UNESCO+Chairs+Programme.+UNESCO+Publishing.+&ots=hWor1DqcNi&sig=WnAIsAgLzTfSMg8eiNF5OdvLHdc#v=onepage&q=UNESCO%20Chairs%20Programme.%20UNESCO%20Publishing.&f=false
UNESCO. (2019). Education for Sustainable Development Goals: Learning Objectives. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000371451
UNESCO 2021 World Conference on Education for Sustainable Development. https://www.unesco.org/en/articles/unesco-2021-world-conference-education-sustainable-development
UNESCO (2023) What you need to know about education for sustainable development. https://www.unesco.org/en/education-sustainable-development/need-know
UNESCO. (2013). Shaping the Education of Tomorrow: 2012 Full-length Report. Retrieved from [link]
UN Environment Program (2021) UNEP's Sustainable University Framework. Available @https://www.unep.org/resources/toolkits-manuals-and-guides/uneps-sustainable-university-framework.Valks, B., Arkesteijn, M., Koutamanis, A., & Den Heijer, A. (2021). Towards smart campus management: Defining information requirements for decision making through dashboard design. *Buildings*, *11*(5), 201. https://doi.org/10.3390/buildings11050201.
Wals, A. E., & Blewitt, J. (2010). Third-wave sustainability in higher education: Some (inter) national trends and developments. In *Sustainability education* (pp. 55-74). Routledge.
Wals, A. E. (2014). Sustainability in higher education in the context of the UN DESD: a review of learning and institutionalization processes. *Journal of Cleaner Production*, *62*, 8-15. http://dx.doi.org/10.1016/j.jclepro.2013.06.007.
Wang, X., & Hu, H. (2017). Sustainability in Chinese higher educational institutions' social science research: A performance interface toward efficiency. *Sustainability*, *9*(11), 1952.
Winter, J., & Cotton, D. (2012). Making the hidden curriculum visible: sustainability literacy in higher education. *Environmental Education Research*, *18*(6), 783-796. doi: 10.1080/13504622.2012.670207.
Yuan, X., Yu, L., & Wu, H. (2021). Awareness of sustainable development goals among students from a Chinese senior high school. *Education Sciences*, *11*(9), 458. https:// doi.org/10.3390/educsci11090458.
Zeegers, Y., & Francis Clark, I. (2014). Students' perceptions of education for sustainable development. *International Journal of Sustainability in Higher Education*, *15*(2), 242-253.
Zeeshan, K., Hämäläinen, T., & Neittaanmäki, P. (2022). Internet of things for sustainable smart education: An overview. *Sustainability*, *14*(7), 4293.
Zeng, S., Li, G., Wu, S., & Dong, Z. (2022). The impact of green technology innovation on carbon emissions in the context of carbon neutrality in China: Evidence from spatial spillover and nonlinear effect analysis. *International Journal of Environmental Research and Public Health*, *19*(2), 730. https://doi.org/10.3390/su14074293Academic
Zhang, D., Zhao, J. L., Zhou, L., & Nunamaker Jr, J. F. (2004). Can e-learning replace classroom learning?. *Communications of the ACM*, *47*(5), 75-79. DOI:10.1145/986312.986216. doi.acm.org
Zhao, X., Yin, H., Fang, C., & Liu, X. (2021). For the sustainable development of universities: Exploring the external factors impacting returned early career academic's research performance in China. *Sustainability*, *13*(3), 1333. https://doi.org/10.3390/su13031333

More info

UTM Library
UTM
UNIVERSITI TEKNOLOGI MALAYSIA

SDi@JPUTM
SELECTIVE DISSEMINATION OF INFORMATION

library.utm.my

ARTICLES FOR UTM SENATE MEMBERS

“Advancing Sustainability in Higher Education : How Universities Are Contributing to Global Innovating Solutions”

TITLE	SOURCE
10) Transformative Approaches to Sustainable Education: Technology, Leadership and SDGs in Higher Education Institutions (2024)	INTERNATIONAL JOURNAL OF LEARNING, TEACHING & EDUCATIONAL RESEARCH (Article From : IJLTER)

27th FEBRUARY 2025

SOURCE: PERPUSTAKAAN UTM

International Journal of Learning, Teaching and Educational Research
Vol. 23, No. 5, pp. 41-67, May 2024
https://doi.org/10.26803/ijlter.23.5.3
Received Mar 25, 2024; Revised May 9, 2024; Accepted May 22, 2024

Transformative Approaches to Sustainable Education: Technology, Leadership and SDGs in Higher Education Institutions

Abdulrahman A. Alhazemi*
Associate Professor of Human Resource Management
College of Business, Jazan University, Saudi Arabia

Abstract. The present study examines the relationship between the adoption of technology, the implementation of sustainable leadership practices, guided by Transformational Leadership Theory, and the attainment and the attainment of Sustainable Development Goals (SDGs) at academic institutions in Saudi Arabia. The study used a questionnaire-based technique from students, alumni and professors. The population consists of students, alumni and professors from these institutions, with a sample size of 383 participants. The research approach employed in this study is Partial Least Squares Structural Equation Modeling (PLS-SEM), a robust statistical technique. PLS-SEM enables simultaneous analysis of multiple variables, making it ideal for exploring complex relationships in the data. The results highlight the favorable influence of incorporating technology and implementing sustainable leadership practices on achieving SDGs. The study emphasizes its significant contributions to objectives, including clean energy, responsible consumption and reduced inequalities. The research also highlights the importance of involving stakeholders and implementing strategies that promote environmental sustainability practices in higher academic institutions. The study indicates that educational institutions, policymakers and stakeholders should take note of the practical consequences. It emphasizes the significance of making strategic technological investments, fostering sustainable leadership and spreading awareness to advance sustainability activities. The findings enhance our comprehension of the intricate relationships associated with attaining SDGs, underscoring the necessity of adopting a comprehensive strategy that encompasses leadership, technology, culture and stakeholder involvement.

Keywords: Technology Adoption; Sustainable Leadership; Sustainable Development Goals; Sustainability Awareness; Academic Institutions

*Corresponding author: Abdulrahman A. Alhazemi; anselmus.sudirman@ustjogja.ac.id

1. Background of the study

In an era of rapid technological advancements and growing global awareness of sustainability concerns, integrating technology adoption (TA) and sustainable leadership practices (SLP) has become a critical priority (Najjar et al., 2023; Suhluli & Ali Khan, 2022). Academic institutions and communities throughout the globe are facing a growing need to effectively navigate this ever-changing environment, not only to maintain their competitiveness but also to make significant contributions toward achieving the SDGs (Chaiyasit et al., 2023; Hajikhani & Suominen, 2022) set forth by the United Nations (UN) (González-Campo et al., 2022; SDG-2, 2022). Saudi Arabia, under the influence of its transformative initiative known as "Saudi Vision 2030" (Alharthi et al., 2019; Islam & Faisal Ali Khan, 2023), serves as an intriguing subject for analysis within this particular framework. The nation strives to expand its intellectual horizons, promote sustainability and align its endeavors with global development goals. Notwithstanding the ambitious objectives outlined in Saudi Vision 2030, there is a notable deficiency in scholarly study about comprehending the complex interconnections among TA (Chumnumporn et al., 2022), SLPs and the advancement and consequences of SDGs within the academic institutions of Saudi Arabia.

The integration of TA and SLP into universities is anticipated to have a substantial influence on the progress and impact of SDG PI. TA, SLP, and SDGs in academic institutions are a multifaceted area of study with rich literature. Extensive research has been conducted to explore how the integration of technology and SLPs can contribute to the achievement of SDGs in educational settings (Islam & Ali Khan, 2024b). Regarding TA, scholars have examined the role of various technologies, including information and communication technology (ICT), renewable energy technologies and digital platforms, in promoting sustainability initiatives within academic institutions. Studies have highlighted the potential of technology to enhance energy efficiency, facilitate resource management, and foster collaboration among stakeholders in support of SDGs related to clean energy (SDG 7) and climate action (SDG 13) (Hakami et al., 2023; Islam & Faisal Ali Khan, 2023). Sustainable leadership theory, particularly Transformational Leadership Theory (Tang et al., 2022), has garnered attention for its emphasis on ethical, visionary and socially responsible leadership practices. Research in this area has explored how leaders within academic institutions can inspire and empower stakeholders to embrace sustainability principles, align organizational strategies with SDGs, and cultivate a culture of environmental stewardship. Sustainable leadership has been linked to advancements in responsible consumption (SDG 12) and partnerships for sustainable development (UN, 2015).

Furthermore, the literature underscores the interconnected nature of TA, SLP and SDGs, highlighting the need for a holistic approach to sustainability in higher education. Studies have emphasized the importance of stakeholder engagement, interdisciplinary collaboration and the integration of sustainability principles into academic curricula and institutional policies. By fostering awareness, innovation and collective action, educational institutions can contribute significantly to SDGs related to quality education (SDG 4), decent work and economic growth (SDG 8), reduced inequalities (SDG 10), and industry, innovation and infrastructure (SDG 9).

Environmental sustainability practices within institutions (SSP) are hypothesized to work as a mediating mechanism, enabling the conversion of technology uptake and leadership commitment into concrete sustainability results. Furthermore, stakeholder engagement (SE) for SLP is anticipated to provide a comparable intermediary function, hence establishing a more vital link between the implementation of sustainable technology and leadership practices and its influence on the SDGs. The moderating variable, AWS, is suggested to have an impact on and determine the connections among these variables, emphasizing the significance of an institutional culture that prioritizes sustainability in achieving SDGs. This conceptual framework serves as the foundation for investigating the intricate relationships among TA, SLP, SSP (Stakeholder Sustainability Practice within Academic Institutions), SE (Stakeholder Engagement for Sustainable Leadership Practice), AWS and SDG PI within the research landscape.

The primary objective of this study is to address the existing disparity by examining the diverse aspects of TA and SLPs among universities in Saudi Arabia. The study examines the incorporation of sustainable leadership concepts, the dedication of leaders to sustainability objectives, and the use of sustainability frameworks. Furthermore, the present study investigates the significance of mediating factors, such as implementing environmental sustainability measures and SE, in influencing sustainable results by examining sustainability awareness as a moderating factor. The analysis seeks to contribute to the ongoing discussion on global sustainability and fill the existing research void about Saudi Vision 2030.

The research aims to comprehensively understand the intricate dynamics among these crucial factors in Saudi Arabia. By doing so, it seeks to offer valuable insights that can be utilized by policymakers and stakeholders who are dedicated to promoting sustainable development in academia. Moreover, the results of this research can make a valuable contribution to the broader international comprehension of how technology, leadership and sustainability converge to influence the trajectory of societies.

The significance of our research lies in its potential to advance sustainability practices within academic institutions, thereby contributing to broader global sustainability objectives. By elucidating the positive impact of TA and SLPs on SDGs, our study underscores the pivotal role that universities can play in fostering environmental stewardship and social responsibility. This insight not only informs current practices but also serves as a blueprint for future initiatives aimed at promoting sustainability within academic settings.

There is little research on how universities actively contribute to the SDGs in terms of quality education. Several have focused on how organizations have achieved sustainability goals but less on how academic institutions connect their operations with the SDGs in the context of Saudi Arabian universities. Since academic institutions make up a significant part of the global landscape and contribute to sustainable development, understanding their context and dynamics in connection with sustainability and the SDGs is vital.

2. Literature Review

The SDGs signify a worldwide commitment to tackle urgent environmental, social, and economic issues (Bennich et al., 2020; Erin et al., 2022). The attainment of these objectives necessitates the utilization of inventive methodologies, and the convergence of technology and sustainable leadership has emerged as a propitious pathway (Gerard et al., 2017; Piwowar-Sulej & Iqbal, 2023; Shehawy & Ali Khan, 2024). The present literature analysis offers valuable insights into technology's significant role in promoting and enhancing SLPs to address the SDGs among academic institutions in Saudi Arabia effectively.

The study adopted the Transformational Leadership Theory (Siangchokyoo et al., 2020) for the current research of its exceptional relevance and efficacy in promoting sustainable practice and quality education. The theory proposed by Bass (1985) offers a comprehensive framework for comprehending leadership that surpasses conventional management methods. It highlights how leaders inspire, motivate and reshape their teams by presenting a compelling vision and fostering an innovative culture. Transformational leadership in sustainable institutions (Liu et al., 2020) directly focuses on the crucial connections between leadership and the adoption of technology (Purbiyantari et al., 2023; Shuib et al., 2019), the implementation of environmental sustainability practices within academic institutions (Muralidharan & Pathak, 2018), the engagement and support of stakeholders (Balwant et al., 2020) for SLPs, the awareness of sustainability and the SDG PI and quality education. The literature has widely recognized its effect on the adoption of technology, incorporation of sustainable practices, involvement of stakeholders in sustainability efforts, understanding of sustainability concerns and alignment with global sustainability objectives toward quality education. The study selects this extensive and proven theory to serve as a solid theoretical basis for examining sustainable leadership and its contribution to promoting environmental sustainability and achieving SDG effect in academic institutions emphasizing universities. Hence, based on the previous reviews, the following framework for the study has been developed, as illustrated in Figure 1.

SDG PI pertains to the quantification and assessment of the forward movement and consequences of endeavors undertaken to attain the SDGs (Erin et al., 2022). The SDGs encompass a comprehensive collection of 17 worldwide objectives formulated by the UN. These goals aim to tackle urgent global issues about poverty, inequality, climate change, environmental sustainability, peace and various other areas of concern. The process of monitoring the development of SDGs and evaluating their impact entails the systematic observation and measurement of designated indicators and outcomes linked to each target. This enables the assessment of the extent to which advancements have been achieved in attaining these goals, as well as the examination of the consequences of these endeavors on different dimensions of society, the economy and the environment. In essence, this entails assessing the efficacy of initiatives and policies targeted at achieving the SDGs and comprehending their impact on worldwide progress and welfare (UN, 2015).

2.1 Conceptual Framework of the Study

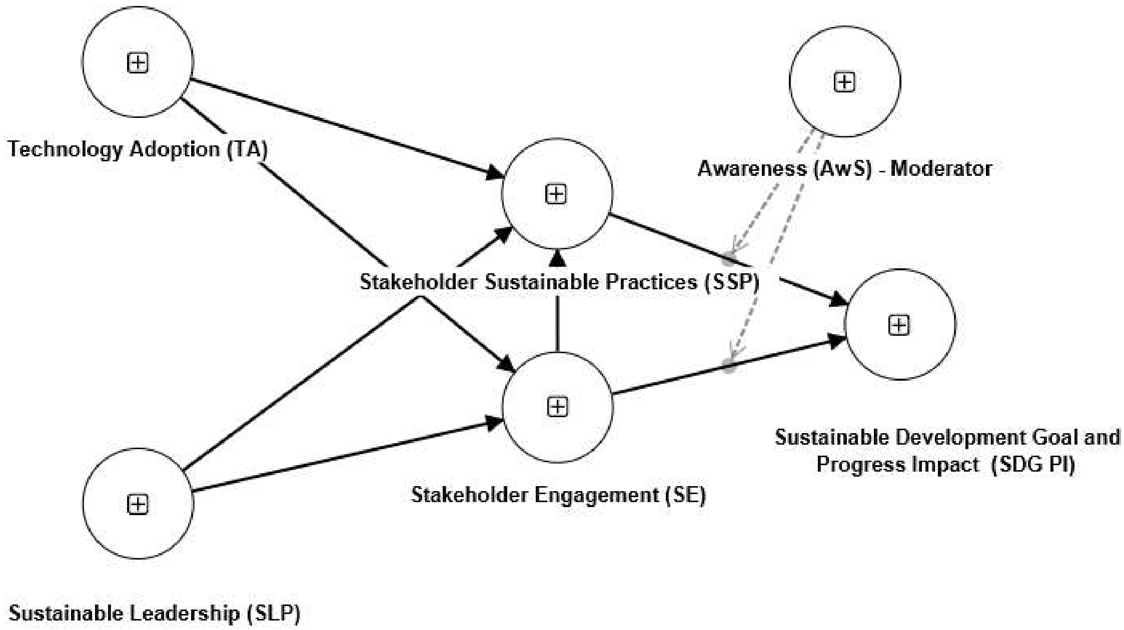


Figure 1: Framework of Study (Source: Author)

2.2 Technology Adoption and SDG Progress and Impact

Like other nations worldwide, Saudi universities are confronted with the significant task of attaining the SDGs established by the UN. The implementation of technology and the adoption of environmentally sustainable practices are essential to effectively tackle climate change by addressing SDG 13 (Department of Economic and Social Affairs, n.d.). Within this particular context, there is an increasing acknowledgment of the crucial significance that the adoption of technology, the specific sorts of technologies employed, and the extent of investment in technical infrastructure have in promoting the achievement of these SDGs (Alharthi et al., 2019; Ashraf Alwy Balabel & Hamad Raja Almujibah, 2022; Berawi, 2016). The purpose of this literature study is to examine the correlation between the level of TA, the types of technologies utilized, infrastructure investment and their collective influence on the advancement of SDGs in Saudi Arabian Universities. Studies have mentioned that the adoption of innovative technologies, such as big data analytics, is seen as a critical enabler for addressing societal challenges, including those targeting the SDGs. However, there needs to be more appreciation for the organizational issues associated with societal challenges, specifically those targeting the SDGs (El-Haddadeh et al., 2021). Challenges related to the SDG indicator framework include overburdening of national statistical systems, coordination failures and lack of funding for statistical modernization. Solutions proposed include aligning global requirements with national priorities and establishing a global financing facility for development data (Avendano et al., 2020). Barriers to TA in the public sector include a need for top management support, resources, user involvement, awareness, training, change resistance and cultural and structural changes. Proposed change management strategies include top management support, more resources, and user involvement in project development (Abdelhakim et al., 2022).

2.3 Digital Transformation Initiatives

Saudi Arabia has undertaken ambitious digital transformation programs, exemplified by Vision 2030, that prioritize the use of technology across multiple institutions (Alshuaibi, 2017). The significant incorporation of technology is positioned to have a crucial impact on expediting advancements toward the achievement of SDGs and quality education within the nation (Schwindenhammer & Gonglach, 2021).

2.4 E-University Services

E-University Services offer many services that improve education quality and accessibility (Zekaj, 2023). Virtual classrooms allow students to hear lectures and engage in discussions remotely. Interactive modules, e-books and multimedia tools enrich educational content. E-University Services also offer digital tests and comments to evaluate student achievement quickly (Quinonez-Beltran et al., 2023). Online enrollment systems, digital grading platforms, and communication technologies streamline student, instructor and administrative staff interactions. E-University Services use AI and data analytics to personalize learning and track student success. Collaborative technologies and platforms encourage student-faculty interaction, building community and improving learning (Bamaga et al., 2024). These services make education more flexible and accessible and advance SDG 4 by meeting the worldwide need for quality education.

2.5 Sustainable Leadership and SDG Progress and Impact

University leadership practices are crucial to achieving the SDGs. As educational and research institutions, universities need to promote sustainable development. Sustainable leadership includes environmental protection, social responsibility, and ethical decision-making (Sathorar et al., 2023). Sustainability in universities' core activities can boost SDG progress. This includes green campus activities, energy-efficient technologies and responsible consumption and production. Sustainable leadership goes beyond infrastructure and operations to include academic programs in sustainable development. SDG-related content in university courses promotes student knowledge and accountability (Islam & Ali Khan, 2024a; Shishakly et al., 2024). Sustainable leadership also encourages research that addresses SDG-related global issues. Innovative solutions to poverty, climate change and inequality may require interdisciplinary collaborations. Universities empower students and staff to improve their communities by promoting sustainability. Sustainable university leadership practices affect campus operations, academic courses and research, which impacts SDG progress. Universities contribute to the global SDGs effort through various projects, improving the world's sustainable development trajectory.

2.6 Stakeholder Engagement

In higher education, stakeholder participation is crucial for promoting sustainability practices and quality education. Students, instructors, staff, communities, industry partners and governments are stakeholders. Effective SE promotes teamwork, decision-making and sustainability activities, according to research. University stakeholders have varied interests and viewpoints, making engagement strategies essential for meaningful and inclusive sustainability outcomes (AlShamsi & Quirke, 2023; Ibrahim et al., 2024). Universities influence sustainable practices through teaching, research and operations. Higher education sustainability includes environmental, social and economic factors. University sustainability literature covers green campus efforts, curriculum integration and responsible resource management. Leadership commitment, institutional regulations and sustainability principles in institutional culture are crucial to sustainable practice implementation, according to research (Vargas-Merino et al., 2024). Research on the relationship between stakeholder participation and sustainability in universities is ongoing. Effective SE helps achieve sustainability goals. Studies emphasize open communication, collaboration and different voices in decision-making. Engagement of stakeholders can provide insights, resources and support for more comprehensive and practical university sustainability projects (Solano-Olivares et al., 2024). Literature acknowledges difficulties in balancing multiple stakeholder interests, ensuring meaningful engagement and overcoming change opposition. It also shows how universities may innovate and lead in sustainability by utilizing stakeholder expertise, developing collaborations and aligning sustainability goals with education and societal well-being. Hence, university SE and sustainability practices literature emphasize their interconnectedness and the need for collaborative, inclusive and strategic approaches to achieve the SDGs.

Research highlights challenges in SE, such as fragmented understanding of SDGs, lack of leadership from government, and overemphasis on goal-based focus (Banerjee et al., 2020). Additionally, constraints on projects to meet deadlines and concerns about overburdening stakeholders can reduce SE (O'Shea et al., 2021). Despite challenges, SE is crucial for SDG progress. It is emphasized that meaningful engagement of business, in partnership with a broader circle of stakeholders, is essential for positive transformation and SDG realization (Amato, 2021).

2.7 Stakeholder Sustainability Practice

University sustainability and stakeholder strategies are essential to ethical and impactful higher education. Effective SE is critical to university sustainability, according to the research. Students, instructors, staff, local communities, industry partners and policymakers are stakeholders. Research repeatedly shows that strong stakeholder practices identify key stakeholders, understand their perspectives, and incorporate their input into decision-making (Cayabas et al., 2023; Gonzalez-Torres et al., 2023). Building a university sustainability vision requires effective communication and engagement with these varied groups (Krishnamurthy & Sahay, 2023). University sustainability practices integrate environmental, social and economic factors. Campus operations, academic programmers and institutional policies should incorporate sustainability concepts, according to the literature. Discussions include green campus efforts, responsible resource management and curriculum design for sustainability. Leadership commitment and a sustainable institutional culture are typically cited as critical factors in these strategies' success (Akudugu & Ogwu, 2024). Stakeholder practices and sustainability at universities are crucial for lasting influence. Engaged stakeholders provide insights and resources and keep institutions accountable for sustainability. The literature regularly shows that stakeholder participation boosts sustainability programmers' legitimacy and credibility, resulting in better environmental and social success (Abidi & Faisal AU Khan, 2018; Mulyani, 2024). Stakeholder practices and university sustainability are also linked to the global sustainability agenda, particularly the UN SDGs. University practices must connect with SDGs, and literature typically examines how SE can affect SDGs. SDGs in university sustainability activities help address global issues and ensure that local efforts contribute to global goals. Finally, university stakeholder practices and sustainability programmers are interdependent, as shown by the literature. Effective SE enhances university sustainability practices and positions higher education institutions as critical contributors to the global sustainability agenda, notably through SDG alignment.

2.8 Sustainability Awareness

The influence of sustainability awareness (Medabesh & Khan, 2020) on academic institutions and individuals (Alsaati et al., 2020; M. Khan & Chawla, 2015) plays a crucial role in the impact of technological advancements on SDG PI (Zhou et al., 2022), as it affects the level of commitment toward sustainable practices. Previous studies have demonstrated that fostering AWS can significantly help the advancement of SDGs (Leiva-Brondo et al., 2022) in institutions.

Hence, from the above literature review following hypothesis could be postulated:

H1: Technology Adoption has a significant impact on SDG Progress and Impact.

H2: Sustainable Leadership has a significant impact on SDG Progress and Impact.

H3: Sustainability Awareness moderates the relationship between Technology Adoption and SDG Progress and Impact.

H4: Sustainability Awareness moderates the relationship between Sustainable Leadership and SDG Progress and Impact

3. Research Methodology

For this investigation, a cross-sectional survey design was chosen as the research methodology (Zangirolami-Raimundo et al., 2018). This design allows the researcher to collect data from a large number of participants efficiently. With this survey design, quantitative data collection is also possible (Allwood, 2012). Quantitative research uses positive (concrete) data as numbers to be measured and statistics to derive conclusions about the topic. The quantitative analysis validates theories by generating new hypotheses to address problems and by validating prior research. Explanatory research uses hypothesis testing to explain the correlations between variables.

3.1 Data Collection

The study's primary data collection instrument was a questionnaire devised with the investigation's objectives in mind and drawing on prior research. The questionnaire was meticulously crafted to elicit information pertinent to the study objectives, focusing on variables such as TA, SLPs and SDGs attainment. The design of the questionnaire encompassed a mix of closed-ended and Likert-scale questions, allowing for both quantitative analysis and qualitative insights. Questions were formulated to gauge participants' perceptions, attitudes and behaviors related to TA, SLP and SDG PI. The sample included students, alumni and faculty (teaching and non-teaching) from selected Saudi universities. The sampling process in this study comprised two technique. A purposive sampling method was used to choose five public and private universities located in various geographic locations of Saudi Arabia. In addition, snowball sampling was used to acquire information from the faculties of these institutions. Sampling encompassed both public and private institutions to ensure comprehensive representation. The deliberate inclusion of universities from diverse sectors aimed to capture a broad spectrum of perspectives and practices within the academic landscape. This strategic approach to sampling at the initial level facilitated a more nuanced understanding of the relationship between TA, SLP and SDG PI across different institutional settings and contexts. Sampling was conducted using a stratified random sampling approach to ensure representation across different academic departments and levels within the institutions. The population targeted comprised students, alumni and professors actively engaged in educational activities. Response rates were monitored throughout the data collection process to assess the level of participant engagement. Efforts were made to maximize response rates through personalized communication, reminders and incentives where appropriate.

The response rate was calculated as the percentage of completed questionnaires returned relative to the total number distributed. The research needed a suitably powered sample. Therefore, 500 questionnaires were distributed selected individuals. Of these, 384 valid responses were appropriate for data analysis. Data integrity and reliability were ensured by routinely removing biased and incomplete replies. Structural Equation Modeling (SEM) recommended a sample size of 20 times the number of elements in the research questionnaire. To ensure statistical power and reliability for our research analysis, we used the SEM guideline to get 340 responses to our 17-item questionnaire. This method was used to assure statistical validity and correct representation of the study's variables' linkages and dynamics while retaining statistical power. However, a larger sample is generally better for accurate results (Hair et al., 2019).

3.2 Sample Size Selection Criteria

For data collection, a self-administered survey questionnaire was used (Rada, 2019). The questionnaire's objective was to collect data on the variables identified by the study. The survey contains multiple-choice, free-text, and Likert 5-point scale questions (Douven, 2018). To increase efficiency and accessibility, the survey was administered online. The statistical program SEM-PLS was used to analyze the study's collected data (Lateef, 2023). (Mishra et al., 2019) used descriptive statistics such as means, frequencies, percentages and standard deviations to characterize the properties of the study variables. The study hypotheses were tested using inferential statistics, including regression, correlation and mediation/moderation analyses (Sand, 2022).

3.3 Criteria for Selecting Sample Size

According to Leguina (2015), it is recommended that the minimum sample size PLS-SEM should be equal to ten times the highest number of structural routes oriented toward a particular construct in the structural model. However, it has been suggested in previous studies (Barroso et al., 2010; Benzidia et al., 2021) that increasing the sample size can enhance the statistical power, precision, consistency, and reliability of estimations conducted using PLS-SEM (Hair et al., 2020). PLS-SEM has been found to exhibit excellent performance when used on datasets with substantial sample sizes, as demonstrated by Hair (2023).

3.4 Time Horizon

The researchers used a cross-sectional survey to acquire study-related data (Philips et al., 2008), and the results were positive. Data was collected from July 2023 to September 2023.

3.5 Statistical Approach

Smart PLS 4 is used for descriptive data analysis. It employs PLS-SEM due to its suitability in analyzing complex relationships in theoretical models with latent variables. PLS-SEM is particularly advantageous when dealing with smaller sample sizes and complex models, offering robustness and flexibility in estimating parameters. To test the proposed relationships, we used PLS-SEM to assess the direct and indirect effects of TA and SLPs on SDGs attainment. By specifying the structural model and assessing path coefficients, we examined how changes in TA and sustainable leadership influenced SDG outcomes. Additionally, we evaluated the significance of mediation effects, providing insights into the underlying mechanisms driving the relationships between variables.

Using the alpha test, the consistency and dependability of research tools were determined. Statistics included tests for multicollinearity, means, standard deviations, frequencies and percentages. By using software, the structural equation model was implemented. In this investigation, the bootstrapping functionality of SMART PLS4 was also used. Following the example set by Lateef (2023), the current study employed SMART PLS4 for statistical analysis. After the measurement model had been developed, the convergent and discriminant validity of the scales was assessed. The objective of convergent validity is to determine if items measure the same concept. The composite reliability and average variance were derived from this. According to Ermawati (2018), acceptable composite reliability (CR) levels exceed 0.70, and average variance extracted (AVE) values exceed 0.50. P-values, t-statistics, confidence intervals and coefficient values were computed to develop a structural model for testing the hypotheses.

3.6 The Justification for Employing PLS in Structural Equation Modeling

SEM uses two approaches to estimate associations: PLS-Measurement Model and PLS-Structural Model. The PLS-Measurement Model and the PLS Structural

Model are the two fundamental components of the PLS statistical method, which is extensively employed in SEM. Evaluating the associations between latent variables and their respective observable indicators is a critical task accomplished with the PLS-Measurement Model, as illustrated in Figure 2. Researchers use this element to assess the extent to which observed variables accurately represent the latent constructs they intend to measure indirectly. It provides a quantitative measure of information by evaluating the dependability and accuracy of latent constructs (Figure 2). As an alternative, the PLS Structural Model examines the causal connections and interrelationships among latent variables using the knowledge obtained from the measurement model. It facilitates hypothesis testing concerning the interrelationships among various latent constructs. This facet of PLS-SEM is indispensable for elucidating the intricate network of connections among latent constructs and ascertaining direct and indirect impacts, as illustrated in Figure 5.

Partial Least Squares (PLS) are an indispensable tool in our studies owing to their versatility and resilience in confronting contemporary research obstacles' intricate and ever-changing characteristics. PLS-SEM provides a practicable and adaptable solution in an era where small sample sizes, non-normal distributions and complex relationships between variables frequently characterize data. It empowers us to confidently analyze data, even in situations where conventional statistical methods are inadequate. Furthermore, its versatility extends to numerous disciplines, including social sciences and data science, promoting interdisciplinary cooperation and research. The flexibility afforded by PLS-SEM in modelling reflective and formative constructs facilitates the advancement and verification of theories, thereby enhancing our comprehension of intricate systems. PLS-SEM facilitates the extraction of significant insights from complex data, enabling us to address contemporary research investigations and practical challenges with inventive resolutions in both academic and applied domains.

4. Data Analysis Interpretation and Discussion

A measuring model in research and statistics shows how latent constructs affect observable indicators. It explains how variables are measured and underpins structural models in psychology, sociology and economics. The approach allows researchers to quantify abstract notions and assess measurement instrument reliability and validity, as illustrated in Figure 2.

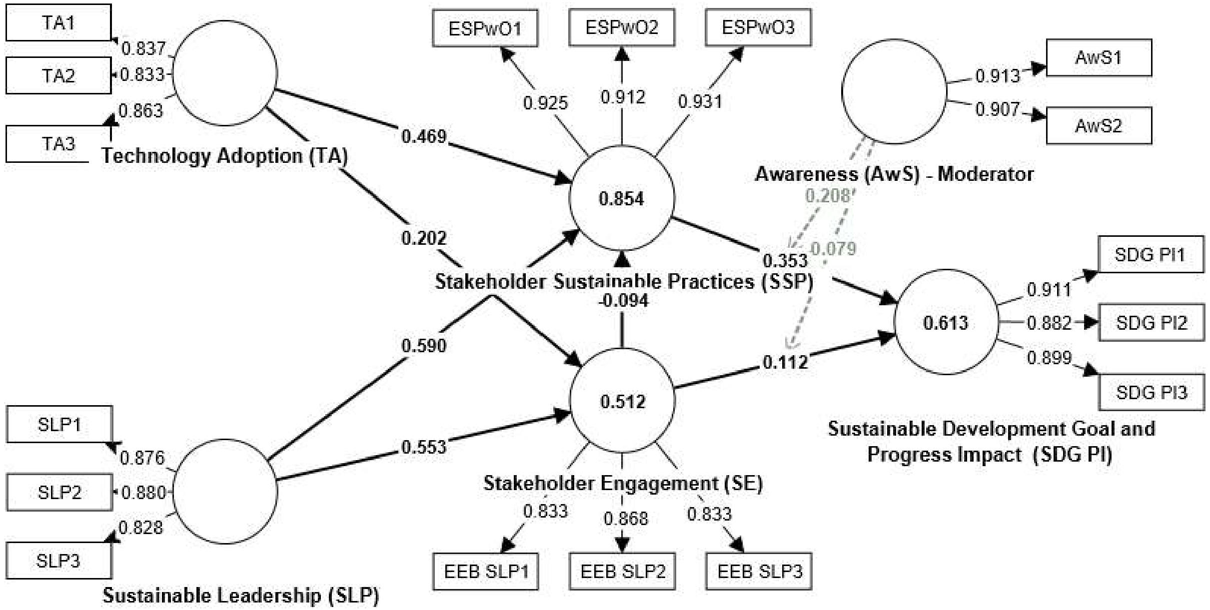


Figure 2: SEM – Measurement Model

Table1: Construct Reliability

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
AWS	0.792	0.793	0.906	0.828
SE	0.806	0.846	0.882	0.714
SSP	0.912	0.914	0.945	0.851
SDG PI	0.879	0.879	0.925	0.805
SLP	0.826	0.827	0.896	0.743
TA	0.799	0.804	0.882	0.713

Discriminant – Validity Fornell-Larcker criterion

AWS	SE	SSP	SDG PI	SLP	TA
0.910					
0.717	0.845				
0.735	0.607	0.922			
0.730	0.595	0.680	0.897		
0.758	0.702	0.871	0.689	0.862	
0.643	0.610	0.847	0.668	0.738	0.844

The following equation for Discriminant Validity: Fornell – Larcker $\mathrm{AVE}_i > \max\limits_{j \neq i} r_{ij}^2$

where:

- AVEi is the average variance extracted from the ith construct
- rij is the correlation between the ith and jth constructs
- i and j are indices of different constructs in the model

The results of construct reliability measures, namely Cronbach's alpha, rho_a, rho_c, and AVE for each of the essential constructs investigated in our study, are displayed in Table 1. The reliability measures offer valuable insights into the internal consistency and dependability of the constructs examined in our study. Cronbach's alpha, a commonly employed metric for assessing internal consistency, provides evidence of the reliability of our constructs, exhibiting values that span from 0.792 to 0.912. The numbers above demonstrate good coherence in the data obtained for each construct. Typically, a Cronbach's alpha value of 0.7 is deemed satisfactory, and our findings surpass this established criterion. In addition, the CR metrics, specifically rho_a and rho_c, enhance the strength and resilience of our constructions. The observed values in this study vary from 0.793 to 0.914, suggesting that the constructs under investigation demonstrate a notable level of internal consistency and reliability. The results align with our initial hypotheses, as our objective was to build measures that effectively represent the fundamental nature of the studied variables. The observed AVE values, which range from 0.714 to 0.851, indicate that the constructs under investigation have a significant amount of variance that can be accounted for by the indicators associated with each construct. The assessment of variance explained (AVE) is an essential indicator for validating our constructs' distinctiveness and ability to capture significant variability in the data. Within the given framework, the AVE values we obtained exceed the suggested threshold of 0.5, providing additional support for the convergent validity of our constructs. Hence, the construct reliability measures outlined in Table 1 highlight the strength and consistency of our research constructs. Utilizing these metrics instills assurance in the coherence and dependability of the data gathered for our study, hence validating the robustness of our research methodology and bolstering the legitimacy of our conclusions.

Table 2: F-square matrix & R- Square

	AWS	SE	SSP	SDG PI	SLP	TA	AWS x SSP	AWS x SE	R-square	R-square adjusted
AWS				0.122						
SE			0.029	0.015					0.512	0.510
SSP				0.137					0.854	0.853
SDG PI									0.613	0.608
SLP		0.286	0.849							
TA		0.038	0.663							
AWS x SSP				0.069						
AWS x SE				0.012						

The following equation was used to find the R-Square

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \grave{y})^2}$$

where n is the number of observations

- yi is the actual value of the response variable for the ith observation
- y^i is the predicted value of the response variable for the ith observation
- y¯ is the mean value of the response variable

In our study, the f-square values offer significant insights regarding the magnitudes of the effects of diverse relationships among key variables. The effect sizes provide insights into the practical implications of our findings that extend beyond mere statistical significance. Significantly, an f-square value of 0.849 indicates that SLP has a substantial effect on SSP, highlighting the critical role that leadership plays in influencing sustainable engagement and practices in academic institutions. On the contrary, the f-square value of 0.029 associated with SE and SDG PI on SDG and quality education suggests a comparatively diminished effect size. This implies that although SE does contribute to SDG PI, its immediate effects might be comparatively restricted. On the other hand, the f-square values of 0.069 and 0.012 for the combined effect of AWS, SSP, and SE as moderators of SDG PI on SDG PI indicate that awareness enhances the impact of stakeholder practices and engagement on SDG 4.

The R-square and adjusted R-square values provide additional evidence that our regression models are robust. The R-square value of 0.854 for SSP suggests that the model accounts for around 85.4% of the observed variability in sustainable practices. Likewise, with an R-square value of 0.613 for SDG PI, our model accounts for approximately 61.3% of the variability observed in the advancement toward achieving the SDGs. The significant R-square values indicate that the selected independent factors effectively explain the observed discrepancies in SSP and SDG PI. In summary, our research emphasizes the critical significance of SSP, TA, and stakeholder dynamics in influencing sustainability practices within academic institutions in Saudi Arabia and making contributions toward the advancement of the SDGs. The nuanced effect sizes and explanatory capacities enhance the comprehensive comprehension of the complex interconnections between these variables. This knowledge is of great value to policymakers, practitioners and scholars who are striving to promote sustainability initiatives in educational environments.

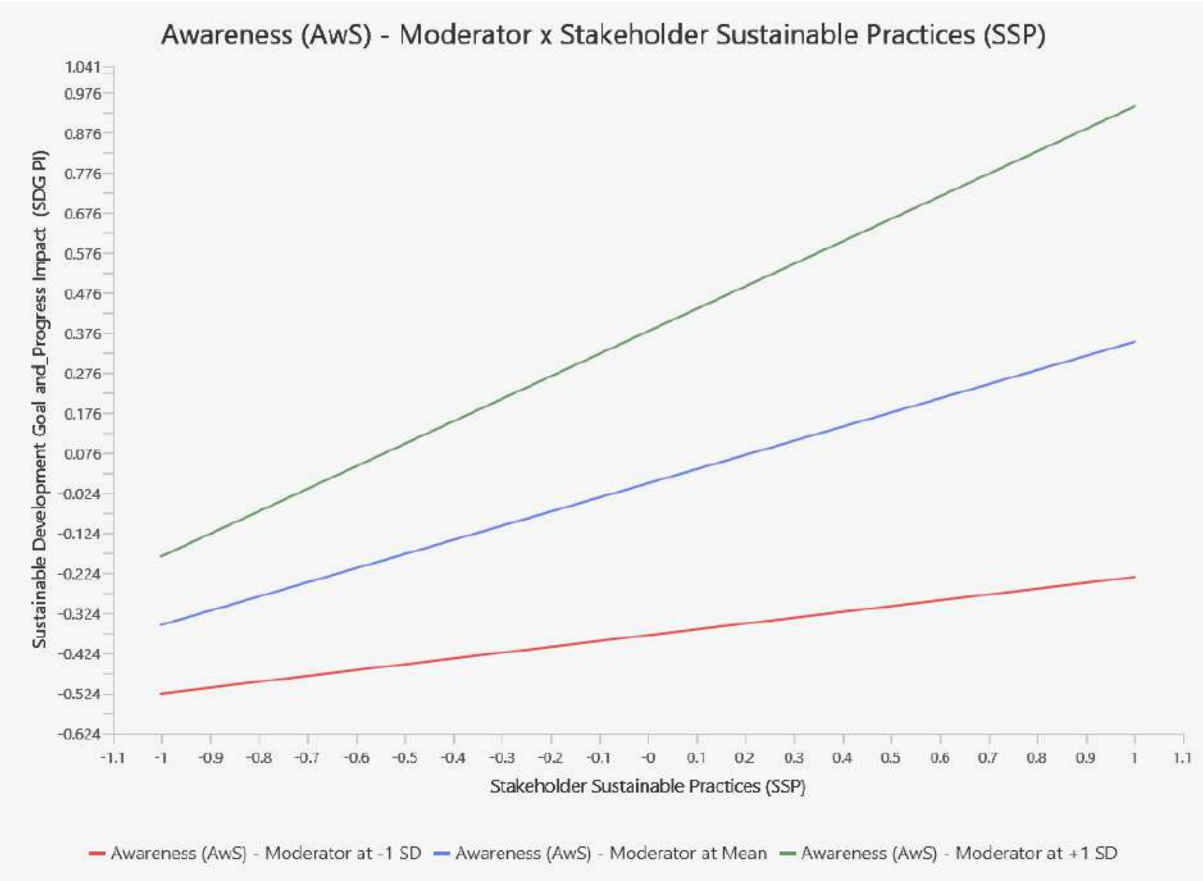


Figure 3: Slope Analysis – Moderation Effect 1

The equation for slope analysis is as follows:

$$\text{Slope} = b_1 + b_3 \times M$$

Where:

- b_1 is the main effect of the independent variable on the dependent variable
- b_3 is the interaction effect of the independent variable and the moderator variable on the dependent variable
- M is the value of the moderator variable

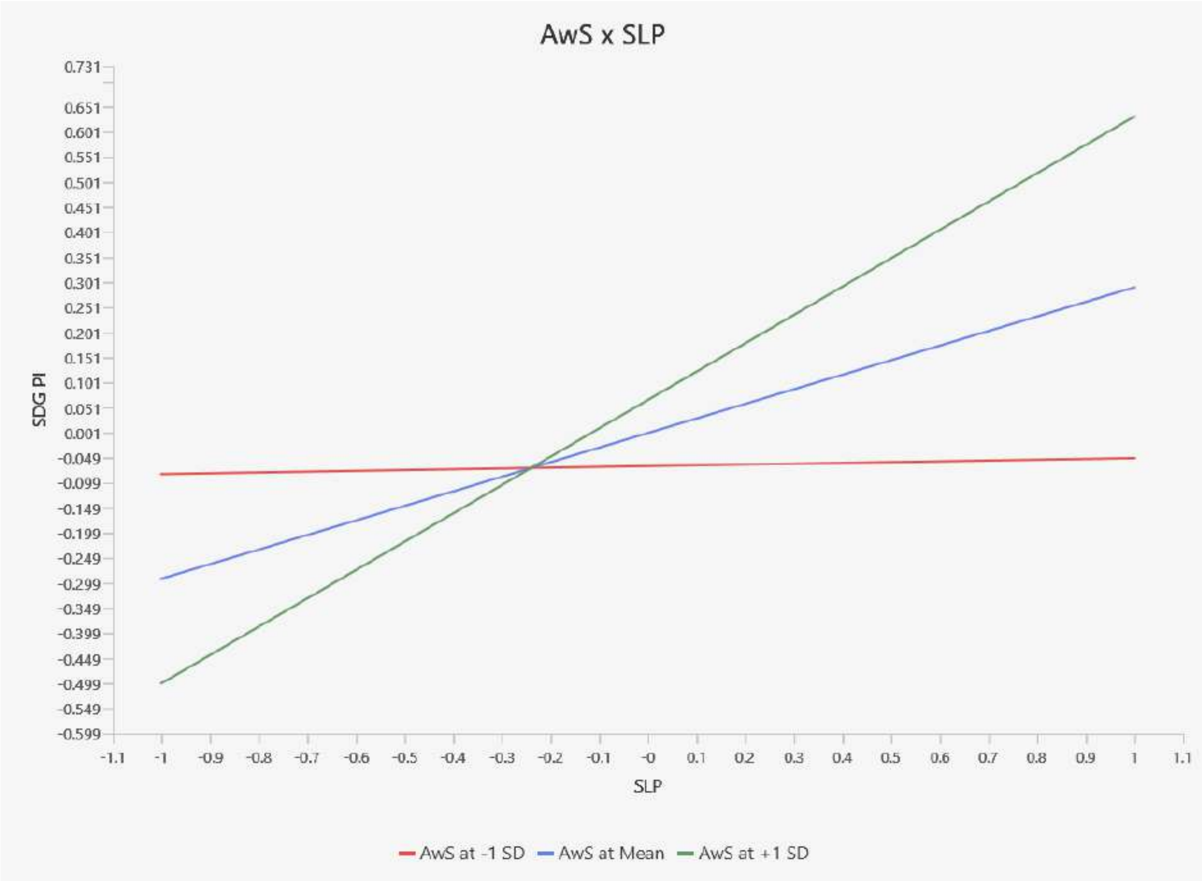


Figure 4: Slope Analysis – Moderation Effect 2

Researchers and statisticians use structural models to show latent construct linkages and interactions. Beyond the measurement model, structural models show causal or correlational paths between variables. By studying these structural links, scholars may grasp complicated dynamics and interdependencies within a conceptual framework and fully understand the events, as indicated in Figure 5.

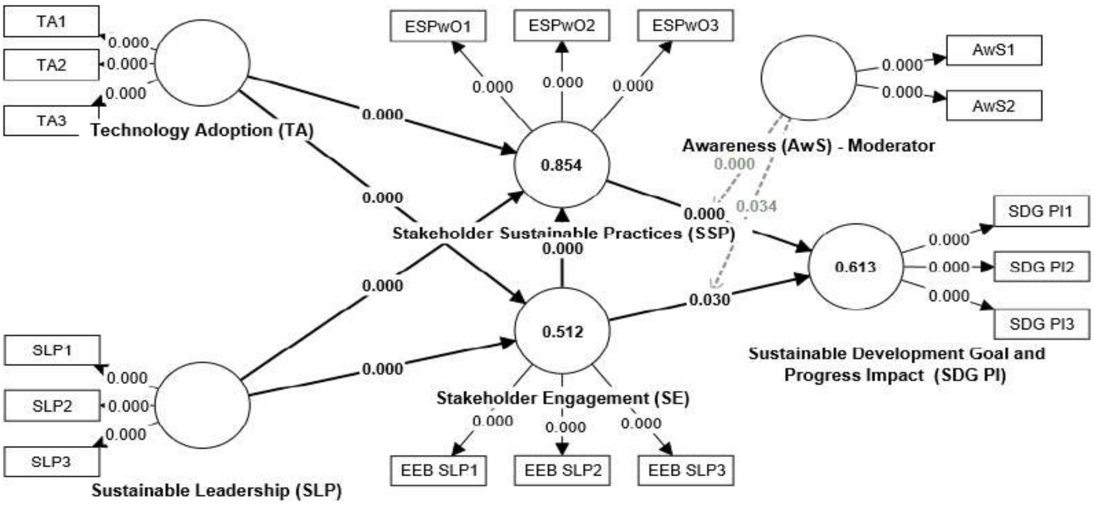


Figure 5: SEM- Structural Model

Table 3: Hypothesis Testing

Hypothesis	Path	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T-statistics (|O/STDEV|)	P-values	Remarks
H1	TA -> SDG PI	0.182	0.180	0.028	6.393	0.000	Supported
H2	SLP -> SDG PI	0.252	0.251	0.034	7.332	0.000	Supported
H3	AWS x TA -> SDG PI	0.208	0.204	0.05	4.181	0.000	Supported
H4	AWS x SLP -> SDG PI	0.275	0.291	0.137	2.000	0.046	Supported

The bootstrapping outcomes obtained with SMART PLS in Table 3 provide insights into the proposed relationships in the hypotheses. The data shows hypothesis testing on the effects of TA, SLP, AWS and their combined impact on SDG PI. All hypotheses were accepted due to their statistically significant t-statistics and low p-values, which support the hypothesized correlations. H1 shows a positive relationship between TA and SDG PI, with a t-statistic of 6.393 and a p-value of 0.000. As technology adoption rises, SDG PI improves; therefore, H1 is acceptable. H2 shows a similar positive correlation between SLP and SDG PI, with a t- statistic of 7.332 and a p-value of 0.000. Again, stronger university sustainable leadership favorably impacts SDG PI. Hence, H2 is acceptable. H3 includes an interaction term, showing that AWS and TA positively affect SDG PI (t-statistic: 4.181, p-value: 0.000). H3 is embraced because stakeholders who are aware of sustainability and employ technology advance sustainability goals. H4 uses a similar interaction term, AWS and SLP. The t-statistic is 2.0. However, the p-value is 0.046, suggesting a slightly significant result. This indicates that knowledge and sustainable leadership may moderately affect SDG PI; hence, H4 is provisionally accepted.

Hence, these findings can help Saudi universities achieve sustainable development. The positive relationships between TA, SLP, and AWS in influencing SDG PI emphasize the importance of strategic technology investments, sustainable leadership and awareness to boost sustainability initiatives. As Saudi universities expand, incorporating these aspects can help them achieve national and global sustainability goals and advance UN socioeconomic and environmental goals.

5. Discussion

Through an extensive examination of existing literature and meaningful interactions with university stakeholders, the study reveals a set of noteworthy findings specifically centered around the circumstances faced by faculty and students in academic institutions. The conclusions are derived from primary data obtained through surveys carried out in Saudi Arabian universities. The report clarifies the direct contribution of sustainable practices among Saudi universities to the achievement of important UN SDGs. More precisely, these findings are strongly related to SDG 4, 7, 8, 9, 10, 12, 13 and 17.

The research highlights a significant and essential correlation between the TA and the SDG PI, particularly about renewable energy and climate action. Saudi universities contribute to the achievement of SDG 7 (Affordable and Clean Energy) and Sustainable Development Goal 13 (Climate Action) by promoting the use of technology (Shobande & Ogbeifun, 2022). Moreover, the study highlights the crucial impact of SLP on improving SDG PI. Universities managed by stakeholders who prioritize sustainability have made significant advancements, especially in promoting responsible consumption. This aligns with the goals outlined in SDG 12 (Responsible Consumption and Production) and SDG 17 (Partnerships for the Goals) (Islam et al., 2017; Khan & Damanhouri, 2017). The complex network of connections within the study also emphasizes the crucial significance of SE and SSP. The study indicates that SE has a minor impact, whereas SSP had a notable effect. This emphasizes the importance of SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities) in Saudi academic institutions (Saratun, 2016). The research indicates that an enhanced understanding of sustainability among faculties and students influences favorable progress in SDG PI, underscoring the significance of alliances and cooperation (SDG 17) in attaining the SDGs. Ultimately, this study, which relies on firsthand data obtained through surveys from universities and higher academic institutions, plays a crucial role in advancing the UN SDG 4, 7, 8, 9, 10, 12, 13 and 17. These findings give excellent information for Saudi universities to promote sustainable practices and make a substantial contribution to the global sustainability debate.

In addition to the significant findings highlighted in the study, further insights have emerged from the comprehensive examination of existing literature and interactions with university stakeholders. These insights shed light on the multifaceted challenges and opportunities faced by faculties and students within academic institutions, particularly in the context of sustainability initiatives. One noteworthy aspect is the direct contribution of sustainable practices in Saudi universities toward the attainment of key the SDGs. Through the TA and SLPs, academic institutions in Saudi Arabia are actively contributing to SDGs 4, 7, 8, 9, 10, 12, 13 and 17. Precisely, the promotion of renewable energy and climate action, as facilitated by TA, aligns with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

Moreover, the study underscores the pivotal role of sustainable leadership in driving progress toward SDGs. Universities led by stakeholders who prioritize sustainability have demonstrated significant advancements, particularly in promoting responsible consumption (SDG 12) and fostering partnerships for sustainability (SDG 17). This emphasizes the interconnectedness between sustainable leadership and the achievement of various SDGs. Furthermore, the research highlights the importance of SE and sustainability practices in driving sustainable development within academic institutions. While SE alone may have a minor impact, SSPs significantly contribute to SDGs 8 (Decent Work and Economic Growth) and 10 (Reduced Inequalities). This underscores the importance of collaborative efforts and alliances in advancing sustainability agendas.

6. Conclusion

The objective of this study was to investigate the complex correlation between SLP, TA and the achievement of SDGs. By conducting an extensive analysis of existing literature, the research emphasized the increasing acknowledgment of technology's crucial contribution to the advancement of SDGs and the importance of SLP in this particular context. The results of the research confirm that the TA (Kearns, 2011), including programs for digital transformation and renewable energy technologies, has great potential to advance sustainability objectives. Similarly, SLP (Fazlagić & Skikiewicz, 2019), which is defined by its dedication to ethical, enduring and socially accountable strategies, has become a crucial facilitator in the quest for SDGs in academic institutions. The empirical evidence has not only confirmed but also enhanced these conclusions. The findings demonstrate that the deployment of technology has a substantial and positive impact on the SDG PI (Nathaniel et al., 2023). This emphasizes the same feelings expressed in the literature, highlighting the crucial importance of technology in tackling global sustainability concerns. Moreover, our research underscores the pivotal significance of sustainable leadership in facilitating the progress of SDGs. Academic institutions managed by top management level who prioritize sustainability demonstrate outstanding skill in aligning their plans and operations with the SDGs, resulting in beneficial outcomes.

The study explores the complex dynamics within these interactions. Technology adoption continues to influence the advancement of SDGs strongly. However, the impact of stakeholder participation in SLPs is also apparent, although it may vary depending on the individual environment. Moreover, whereas SE and environmental sustainability policies have a statistically significant impact, their combined contribution enhances the understanding of the SDG landscape by introducing additional considerations. The research emphasizes that integrating sustainability awareness into academic operations is a clear catalyst for SDG advancement. This finding aligns with the literature's demand for more understanding and concern for sustainability.

Nevertheless, it also emphasizes the intricate correlation between awareness of sustainability and participation of students and faculties, emphasizing the necessity for a more profound comprehension of these interconnected processes. The study highlights the importance of adopting a comprehensive approach to achieve the SDGs. TA and SLP are essential foundations, while SE and the integration of environmental sustainability strategies enhance the whole experience. Moreover, the awareness of sustainability becomes a powerful driver, promoting a culture of accountability and creativity.

The current study emphasizes that the attainment of SDGs goes beyond technical or management efforts. It involves a thorough and all-encompassing change that includes elements like leadership, technology, culture and involvement. The present study highlights the crucial significance of aligning university practices with the broader sustainability agenda while recognizing the inherent complications that academic institutions may face in doing so. Hence, it is evident that the present study is in line with the fundamental objectives of the SDGs, thereby highlighting the crucial role of leadership, technology, culture, and engagement in promoting sustainable development, in line with the objectives of SDGs 4, 7, 8, 9, 10, 12, 13 and 17 . By cultivating a more profound comprehension of these interconnections, Saudi universities' engagement and their intricate contextual subtleties, actively contribute to the worldwide endeavor of achieving a sustainable future. This study serves as a connection between the knowledge gained from existing literature and the practical facts, facilitating progress toward a future that is both environmentally sustainable and economically profitable in academia.

Future research in this field could investigate cross-cultural differences in the relationships between SLP, TA and SDG PI, shedding light on how various cultural contexts impact sustainability efforts. In sector-specific studies, the unique challenges and opportunities encountered by industries such as healthcare, finance and manufacturing may be examined in greater depth. Longitudinal analyses monitoring the sustainability journeys of academic institutions over extended periods may reveal evolving patterns and lasting effects. Additionally, it may be of interest to investigate the perspectives of faculties on SLP and TA, as well as the role of government policies in promoting sustainability within academic institutions. Future research must quantify the environmental impact of TA, investigate multi-stakeholder collaborations and focus on strategies for sustainable leadership development. In addition, emerging technologies, sustainable supply chains and cross-regional comparative studies could cast light on innovative routes to achieving the SDGs. This research can ultimately enlighten policy recommendations and best practices for fostering sustainable leadership and TA to advance global sustainability objectives.

Furthermore, the present research highlights several areas for future inquiry. Cross-cultural studies could explore how different cultural contexts influence the relationship between sustainable leadership, TA and SDG progress. Sector-specific analyses might delve into the unique challenges and opportunities faced by industries such as healthcare, finance and manufacturing in implementing sustainability practices. Longitudinal studies could track the evolution of sustainability efforts within academic institutions over time, providing insights into sustainable development trajectories. Additionally, investigations into the environmental impact of TA, strategies for sustainable leadership development, and the effectiveness of multi-stakeholder collaborations offer valuable guidance for policymakers and practitioners alike.

The study has numerous implications for academic institutions and policymakers. In the first place, it emphasizes the importance of TA and sustainable leadership in advancing SDGs in academic institutions. To contribute meaningfully to these global objectives, academic institutions should consider investing in sustainable technologies, nurturing a culture of sustainability, and equipping leaders with sustainable leadership skills. The study also emphasizes the significance of faculty participation in sustainable initiatives. Initiatives that encourage university employees to buy in and participate in sustainability practices can be prioritized by academic institutions. Finally, policymakers can leverage these findings to develop supportive regulatory frameworks that encourage TA and sustainable leadership within academic institutions, thereby facilitating progress toward SDGs.

The research presented here suggests several critical takeaways for faculties, teachers, students and university leaders within academic institutions. It begins by emphasizing the significance of incorporating sustainability principles into leadership practices. University leaders should align their leadership strategies with sustainability objectives to cultivate a culture of accountability and environmental stewardship. Second, the study encourages stakeholders to consider the strategic incorporation of technology, particularly in areas such as renewable energy and information communication technology, to improve environmental sustainability. Lastly, sustainable leaders can improve stakeholders' engagement toward sustainable practices by fostering an inclusive and supportive workplace that encourages participation in sustainability initiatives.

From a social perspective, the research highlights the potential of TA and SSP to resolve the SDGs' most pressing societal challenges, such as poverty, inequality and environmental degradation. Sustainable practices and technologies can improve living conditions, decrease inequalities, enhance living conditions, decrease inequalities, and increase community access to clean energy and resources. In addition, the study emphasizes the role of stakeholder awareness in promoting sustainable practices and the need for educational and awareness programs to engage society in sustainable development initiatives.

However, this study has significant limitations. Saudi universities' findings may not apply to other countries or institutions. In contrast to cross-sectional studies, longitudinal studies may offer a more dynamic view. Self-reported statistics may be biased by social desirability. While sample size standards were followed, a larger, more diverse sample could improve generalizability. However, self-reported surveys and Likert-scale interpretations may reduce data precision despite proven assessment procedures. Only a little was done to examine economic or policy factors that affected the observed connections. Interpreting and applying the study's conclusions to sustainable higher education requires acknowledging these limitations.

Disclosure statement
There is no potential conflict of interest.

Data Availability Statement
The statistical data used in this research has been shared with the research as a supplementary file.

Declaration
No funding was received.

7. References

Abdelhakim, M., Abdeldayem, M. M., & Aldulaimi, S. H. (2022). Information technology adoption barriers in public sector. *2022 ASU International Conference in Emerging Technologies for Sustainability and Intelligent Systems, ICETSIS 2022*. https://doi.org/10.1109/ICETSIS55481.2022.9888805

Abidi, S., & Faisal AU Khan, S. M. (2018). Factors effecting performance of women entrepreneurship: An empirical study in Saudi Arabia. *Review of Professional Management- A Journal of New Delhi Institute of Management*, *16*(1). https://doi.org/10.20968/rpm/2018/v16/i1/129256

Akudugu, M. A., & Ogwu, M. C. (2024). Sustainable development policies and interventions: A bibliometric analysis of the contributions of the academic community. *Journal of Cleaner Production*, *434*. https://doi.org/10.1016/j.jclepro.2023.139919

Alharthi, S., Alharthi, A., & Alharthi, M. (2019). Sustainable development goals in the Kingdom of Saudi Arabia's 2030 vision. *WIT Transactions on Ecology and the Environment*, *238*. https://doi.org/10.2495/SC190401

Allwood, C. M. (2012). The distinction between qualitative and quantitative research methods is problematic. *Quality and Quantity*, *46*(5). https://doi.org/10.1007/s11135-011-9455-8

Alsaati, T., El-Nakla, S., & El-Nakla, D. (2020). Level of sustainability awareness among university students in the Eastern province of Saudi Arabia. *Sustainability (Switzerland)*, *12*(8). https://doi.org/10.3390/SU12083159

AlShamsi, A., & Quirke, P. (2023). Stakeholders' perspectives of early childhood education language and literacy laboratories in the United Arab Emirates. *International Journal of Learning, Teaching and Educational Research*, *22*(7). https://doi.org/10.26803/ijlter.22.7.6

Alshuaibi, A. (2017). Technology as an Important role in the implementation of Saudi Arabia's Vision 2030. *International Journal of Business*, *7*(2).

Amato, V. (2021). The Sustainable development goals: A framework for business. In *Management for Professionals: Vol. Part F445*. https://doi.org/10.1007/978-3-030-56344-8_2

Ashraf Alwy Balabel, & Hamad Raja Almujibah. (2022). Towards sustainable transportation: The development of hyperloop technology in Saudi Arabia. *World Journal of Engineering and Technology Research*, *2*(1). https://doi.org/10.53346/wjetr.2022.2.1.0032

Avendano, R., Jütting, J., & Kuhm, M. (2020). Counting the invisible: The challenges and opportunities of the SDG indicator framework for statistical capacity development. In *The Palgrave Handbook of Development Cooperation for Achieving the 2030 Agenda: Contested Collaboration*. https://doi.org/10.1007/978-3-030-57938-8_15

Balwant, P. T., Mohammed, R., & Singh, R. (2020). Transformational leadership and employee engagement in Trinidad's service sector: The role of job resources. *International Journal of Emerging Markets*, *15*(4). https://doi.org/10.1108/IJOEM-01-2019-0026

Bamaga, A., Terzis, S., & Zafar, B. (2024). Quality factors impacting e-learning within the mobile environment in Saudi Arabia universities: An interview study. *International Journal of Data and Network Science*, *8*(1), 269–288. https://doi.org/10.5267/j.ijdns.2023.9.025

Banerjee, A., Murphy, E., & Walsh, P. P. (2020). Perceptions of multistakeholder partnerships for the sustainable development goals: A case study of Irish non-state actors. *Sustainability (Switzerland)*, *12*(21). https://doi.org/10.3390/su12218872

Barroso, C., Carrión, G. C., & Roldán, J. L. (2010). Applying maximum likelihood and PLS on different sample sizes: Studies on SERVQUAL model and employee behavior model. In *Handbook of Partial Least Squares*. https://doi.org/10.1007/978-3-540-32827-8_20

Bass, B. M. (1985). *Leadership and performance beyond expectations.* Free Press.

Bennich, T., Weitz, N., & Carlsen, H. (2020). Deciphering the scientific literature on SDG interactions: A review and reading guide. In *Science of the Total Environment* (Vol. 728). https://doi.org/10.1016/j.scitotenv.2020.138405

Benzidia, S., Makaoui, N., & Bentahar, O. (2021). The impact of big data analytics and artificial intelligence on green supply chain process integration and hospital environmental performance. *Technological Forecasting and Social Change*, *165*. https://doi.org/10.1016/j.techfore.2020.120557

Berawi, M. A. (2016). Accelerating sustainable infrastructure development: Assuring well-being and ensuring environmental sustainability. *International Journal of Technology*, *7*(4). https://doi.org/10.14716/ijtech.v7i4.3829

Cayabas, J. P., Codod, C. L. C., Sumeg-Ang, D. A., & Lacaben, E. P. (2023). Contributions and partnership strategies of external stakeholders in the implementation of the alternative learning system in Bontoc District: Insights from teachers. *International Journal of Learning, Teaching and Educational Research*, *22*(7). https://doi.org/10.26803/ijlter.22.7.24

Chaiyasit, W., Chomsuwan, K., & Chanchalor, S. (2023). Hybrid Teaching using problem-based learning to promote self-directed learning abilities of students during the COVID-19 pandemic. *International Journal of Learning, Teaching and Educational Research*, *22*(8). https://doi.org/10.26803/IJLTER.22.8.1

Chumnumporn, K., Jeenanunta, C., Simpan, S., Srivat, K., & Sanprasert, V. (2022). The role of a leader and the effect of a customer's smart factory investment on a firm's Industry 4.0 technology adoption in Thailand. *International Journal of Technology*, *13*(1). https://doi.org/10.14716/ijtech.v13i1.4814

Douven, I. (2018). A Bayesian perspective on Likert scales and central tendency. *Psychonomic Bulletin and Review*, *25*(3). https://doi.org/10.3758/s13423-017-1344-2

El-Haddadeh, R., Osmani, M., Hindi, N., & Fadlalla, A. (2021). Value creation for realising the sustainable development goals: Fostering organisational adoption of big data analytics. *Journal of Business Research*, *131*. https://doi.org/10.1016/j.jbusres.2020.10.066

Erin, O. A., Bamigboye, O. A., & Oyewo, B. (2022). Sustainable development goals (SDG) reporting: an analysis of disclosure. *Journal of Accounting in Emerging Economies*. https://doi.org/10.1108/JAEE-02-2020-0037

Ermawati, A. (2018). Discriminant validity, convergent validity, composite realiability. *Jurnal Agora*, *6*(2).

Fazlagić, J., & Skikiewicz, R. (2019). Measuring sustainable development - the creative economy perspective. *International Journal of Sustainable Development and World Ecology*, *26*(7). https://doi.org/10.1080/13504509.2019.1651418

Gerard, L., McMillan, J., & D'Annunzio-Green, N. (2017). Conceptualising sustainable leadership. *Industrial and Commercial Training*, *49*(3). https://doi.org/10.1108/ICT-12-2016-0079

González-Campo, C. H., Ico-Brath, D., & Murillo-Vargas, G. (2022). Integrating sustainable development goals (SDG) for the fulfilment of the 2030 agenda in Colombian public universities. *Formacion Universitaria*, *15*(2). https://doi.org/10.4067/S0718-50062022000200053

Gonzalez-Torres, P., Cabrera-Solano, P., & Castillo-Cuesta, L. (2023). Stakeholders' perceptions of teaching and technological skills in EFL vocabulary instruction: Implications for remote learning. *International Journal of Learning, Teaching and Educational Research*, *22*(7). https://doi.org/10.26803/ijlter.22.7.10

Hair, J. F. (2023). *SmartPLS*. https://www.smartpls.com/

Hair, J. F., Howard, M. C., & Nitzl, C. (2020). Assessing measurement model quality in PLS-SEM using confirmatory composite analysis. *Journal of Business Research*, *109*. https://doi.org/10.1016/j.jbusres.2019.11.069

Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). When to use and how to report the results of PLS-SEM. In *European Business Review* (Vol. 31, Issue 1). https://doi.org/10.1108/EBR-11-2018-0203

Hajikhani, A., & Suominen, A. (2022). Mapping the sustainable development goals (SDGs) in science, technology and innovation: application of machine learning in SDG-oriented artefact detection. *Scientometrics*, *127*(11). https://doi.org/10.1007/s11192-022-04358-x

Hakami, T. A., Al-Shargabi, B., Sabri, O., & Khan, S. M. F. A. (2023). Impact of blackboard technology acceptance on students learning in Saudi Arabia. *Journal of Educators Online*, *20*(3). https://doi.org/10.9743/JEO.2023.20.3.13

Ibrahim, M. Y., Muis, M. A., Bakar, M. H., Zainal, M. A., Hashim, M. J., & Jusoh, M. H. (2024). Factors on political involvement among university students in Malaysia. *Multidisciplinary Science Journal*, *6*(5). https://doi.org/10.31893/multiscience.2024060

Islam, M. M., Murad, M. W., McMurray, A. J., & Abalala, T. S. (2017). Aspects of sustainable procurement practices by public and private organisations in Saudi Arabia: an empirical study. *International Journal of Sustainable Development and World Ecology*, *24*(4). https://doi.org/10.1080/13504509.2016.1209794

Islam, Q., & Ali Khan, S. M. (2024a). Assessing consumer behavior in sustainable product markets: A structural equation modeling approach with partial least squares analysis. In *Sustainability* (Vol. 16, Issue 8). https://doi.org/10.3390/su16083400

Islam, Q., & Ali Khan, S. M. F. (2024b). Sustainability-infused learning environments: Investigating the role of digital technology and motivation for sustainability in achieving quality education. *International Journal of Learning, Teaching and Educational Research*, *23*(1). https://doi.org/10.26803/ijlter.23.1.25

Islam, Q., & Faisal Ali Khan, S. M. (2023). Integrating IT and sustainability in higher education infrastructure: Impacts on quality, innovation and research. *International Journal of Learning, Teaching and Educational Research*, *22*(12), 210–236. https://doi.org/10.26803/ijlter.22.12.11

Kearns, A. (2011). Climate adaptation engineering: A new direction for environmental science, engineering and technology in urban environments. *International Journal of Sustainable Development and World Ecology*, *18*(3). https://doi.org/10.1080/13504509.2011.574740

Khan, M., & Chawla, C. (2015). Impact of Age on purchase decision from organized & unorganized retail stores – A research report in Indian Context. *IRACST – International Journal of Commerce, Business and Management*, *4*(2).

Khan, S. M. F. A., & Damanhouri, A. M. S. (2017). Store patronage and buying behavior of consumer - A case study of organized retail stores of Jazan. *International Journal of Applied Business and Economic Research*, *15*(16).

Krishnamurthy, R., & Sahay, G. (2023). Higher education for sustainable development goals: Bridging the global north and south. In *Higher Education for the Sustainable Development Goals: Bridging the Global North and South* (pp. 57–75). https://doi.org/10.1108/978-1-80382-525-020231004

Lateef, K. F. (2023). *How to Start Data Analysis using SMART-PLS - ResearchWithFawad*. Join the ResearchWithFawad Social Media Platforms. https://researchwithfawad.com/index.php/lp-courses/basic-and-advance-data-analysis-using-smart-pls/how-to-start-data-analysis-using-smart-pls/

Leguina, A. (2015). A primer on partial least squares structural equation modeling (PLS-SEM). *International Journal of Research & Method in Education*, *38*(2). https://doi.org/10.1080/1743727x.2015.1005806

Leiva-Brondo, M., Lajara-Camilleri, N., Vidal-Meló, A., Atarés, A., & Lull, C. (2022). Spanish university students' awareness and perception of sustainable development goals and sustainability literacy. *Sustainability (Switzerland)*, *14*(8). https://doi.org/10.3390/su14084552

Liu, J., Zheng, X., Tong, Q., Li, W., Wang, B., Sutter, K., Trilling, M., Lu, M., Dittmer, U., & Yang, D. (2020). Overlapping and discrete aspects of the pathology and pathogenesis of the emerging human pathogenic coronaviruses SARS-CoV, MERS-CoV, and 2019-nCoV. In *Journal of Medical Virology* (Vol. 92, Issue 5). https://doi.org/10.1002/jmv.25709

Medabesh, A., & Khan, S. M. F. A. (2020). Sustainability management among enterprises in the United Kingdom and Saudi Arabia. *Academy of Strategic Management Journal*, *19*(2). https://doi.org/10.1002/9781118100509.ch@

Mishra, P., Pandey, C. M., Singh, U., Gupta, A., Sahu, C., & Keshri, A. (2019). Descriptive statistics and normality tests for statistical data. *Annals of Cardiac Anaesthesia*, *22*(1). https://doi.org/10.4103/aca.ACA_157_18

Mulyani, S. (2024). The effect of environmentally oriented leadership and public sector management quality on supply chain performance: The moderating role of public sector environmental policy. *Uncertain Supply Chain Management*, *12*(1), 471–480. https://doi.org/10.5267/j.uscm.2023.9.005

Muralidharan, E., & Pathak, S. (2018). Sustainability, transformational leadership, and social entrepreneurship. *Sustainability (Switzerland)*, *10*(2). https://doi.org/10.3390/su10020567

Najjar, M., Alsurakji, I. H., El-Qanni, A., & Nour, A. I. (2023). The role of blockchain technology in the integration of sustainability practices across multi-tier supply networks: implications and potential complexities. *Journal of Sustainable Finance and Investment*, *13*(1). https://doi.org/10.1080/20430795.2022.2030663

Nathaniel, S. P., Solomon, C. J., Ajide, K. B., Ahmed, Z., & Fakher, H. A. (2023). Striving towards carbon neutrality in emerging markets: the combined influence of international tourism and eco-friendly technology. *International Journal of Sustainable Development and World Ecology*, *30*(7). https://doi.org/10.1080/13504509.2023.2195831

O'Shea, A., Boaz, A., Hanney, S., Kok, M., Borst, R., Pokhrel, S., & Jones, T. (2021). Expect the unexpected? Challenges of prospectively exploring stakeholder engagement in research. *Humanities and Social Sciences Communications*, *8*(1). https://doi.org/10.1057/s41599-021-00770-5

Philips, Z., Claxton, K., & Palmer, S. (2008). The half-life of truth: What are appropriate time horizons for research decisions? In *Medical Decision Making* (Vol. 28, Issue 3). https://doi.org/10.1177/0272989X07312724

Piwowar-Sulej, K., & Iqbal, Q. (2023). Leadership styles and sustainable performance: A systematic literature review. *Journal of Cleaner Production*, *382*. https://doi.org/10.1016/j.jclepro.2022.134600

Purbiyantari, W., Zauhar, S., Suryadi, Hermawan, R., & Riyadi, B. S. (2023). Transformational leadership, technology adoption, and public service towards job competency. *International Journal of Membrane Science and Technology*, *10*(2). https://doi.org/10.15379/ijmst.v10i2.1389

Quinonez-Beltran, A., Cabrera-Solano, P., & Castillo-Cuesta, L. (2023). Implementing active reading strategies in virtual settings: High school students' experience during remote learning. *International Journal of Learning, Teaching and Educational Research*, *22*(8). https://doi.org/10.26803/IJLTER.22.8.10

Rada, V. D. de. (2019). Influence of the questionnaire design in self-administered surveys. *Sociology International Journal*, *3*(1). https://doi.org/10.15406/sij.2019.03.00163

Sand, A. (2022). Inferential statistics is an unfit tool for interpreting data. *Applied Sciences (Switzerland)*, *12*(15). https://doi.org/10.3390/app12157691

Saratun, M. (2016). Performance management to enhance employee engagement for corporate sustainability. In *Asia-Pacific Journal of Business Administration* (Vol. 8, Issue 1). https://doi.org/10.1108/APJBA-07-2015-0064

Sathorar, H., Geduld, D., Moeng, M., Mapasa, T., & Oosthuizen, H. (2023). Leading for Sustainability and empowerment: Reflecting on the power of collaboration and humanising pedagogy. *Educational Research for Social Change*, *12*(2), 78–95. https://doi.org/10.17159/2221-4070/2023/v12i2a6

Schwindenhammer, S., & Gonglach, D. (2021). SDG implementation through technology? Governing food-water-technology nexus challenges in urban agriculture. *Politics and Governance*, *9*(1). https://doi.org/10.17645/pag.v9i1.3590

Shehawy, Y. M., & Ali Khan, S. M. F. (2024). Consumer readiness for green consumption: The role of green awareness as a moderator of the relationship between green attitudes and purchase intentions. *Journal of Retailing and Consumer Services*, *78*, 103739. https://doi.org/https://doi.org/10.1016/j.jretconser.2024.103739

Shishakly, R., Almaiah, M. A., Lutfi, A., & Alrawad, M. (2024). The influence of using smart technologies for sustainable development in higher education institutions. *International Journal of Data and Network Science*, *8*(1), 77–90. https://doi.org/10.5267/j.ijdns.2023.10.015

Shobande, O. A., & Ogbeifun, L. (2022). Has information and communication technology improved environmental quality in the OECD? —a dynamic panel analysis. *International Journal of Sustainable Development and World Ecology*, *29*(1). https://doi.org/10.1080/13504509.2021.1909172

Shuib, L., Yadegaridehkordi, E., & Ainin, S. (2019). Malaysian urban poor adoption of e-government applications and their satisfaction. *Cogent Social Sciences*, *5*(1). https://doi.org/10.1080/23311886.2019.1565293

Siangchokyoo, N., Klinger, R. L., & Campion, E. D. (2020). Follower transformation as the linchpin of transformational leadership theory: A systematic review and future research agenda. *Leadership Quarterly*, *31*(1). https://doi.org/10.1016/j.leaqua.2019.101341

Solano-Olivares, K., Santoyo, E., & Santoyo-Castelazo, E. (2024). Integrated sustainability assessment framework for geothermal energy technologies: A literature review and a new proposal of sustainability indicators for Mexico. *Renewable and Sustainable Energy Reviews*, *192*. https://doi.org/10.1016/j.rser.2023.114231

Suhluli, S. A., & Ali Khan, S. M. F. (2022). Determinants of user acceptance of wearable IoT devices. *Cogent Engineering*, *9*(1), 2087456. https://doi.org/10.1080/23311916.2022.2087456

Tang, Y., Chen, Y. J., Shao, Y. F., & Cao, Q. (2022). The impact of sustainable transformational leadership on sustainable innovation ambidexterity: Empirical evidence from green building industries of China. *Frontiers in Public Health*, *10*. https://doi.org/10.3389/fpubh.2022.814690

United Nations Organization. (2015). *The 17 goals*. Retrieved September 29, 2023, from https://sdgs.un.org/goals

Vargas-Merino, J. A., Rios-Lama, C. A., & Panez-Bendezú, M. H. (2024). Critical implications of education for sustainable development in HEIs - A systematic review through the lens of the business science literature. *International Journal of Management Education*, *22*(1). https://doi.org/10.1016/j.ijme.2023.100904

Zangirolami-Raimundo, J., Echeimberg, J. de O., & Leone, C. (2018). Research methodology topics: Cross-sectional studies. *Journal of Human Growth and Development*, *28*(3). https://doi.org/10.7322/jhgd.152198

Zekaj, R. (2023). AI language models as educational allies: Enhancing instructional support in higher education. *International Journal of Learning, Teaching and Educational Research*, *22*(8). https://doi.org/10.26803/IJLTER.22.8.7

Zhou, G., Liu, L., & Luo, S. (2022). Sustainable development, ESG performance and company market value: Mediating effect of financial performance. *Business Strategy and the Environment*, *31*(7). https://doi.org/10.1002/bse.3089