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Using artificial intelligence in sustainability teaching and learning

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Abstract

Background The integration of artificial intelligence (AI) in sustainability education (SE) represents a forward-thinking approach to teaching and learning, addressing complex global challenges through innovative technology. The deployment of AI offers promising prospects in SE as a means to enhance learning experiences, foster innovative problem-solving skills, and contribute to the development of sustainable solutions. Despite the potential of AI in sustainability teaching and learning, there is a need for studies that explore several key areas, including how AI may enhance educational outcomes, develop sustainable solutions, and prepare students for future challenges.

Results By means of a set of case studies and a survey from 45 countries, it examines the current use of AI as a tool towards sustainable development identifying some areas where action is needed. The results show that the integration of AI in SE has the potential to significantly enhance the learning experience by providing personalized instruction and facilitating interactive simulations that deepen students' understanding of complex environmental issues. In addition, AI tools can increase student engagement through personalized learning paths and real-time feedback, fostering a more interactive and immersive educational environment that encourages critical thinking and problem-solving.

Conclusions While promising, the use of AI in SE requires ongoing research to explore potential challenges and the ethical implications of AI technologies in educational settings.

Keywords Artificial intelligence, Higher education, Learning, Sustainability, Sustainable development, Sustainability education, Teaching, UN Sustainable Development Goals

Introduction: Artificial intelligence and sustainability education

The potential role of artificial intelligence (AI) in sustainability education (SE) is both transformative and multifaceted. AI can significantly enhance the delivery, personalization, and effectiveness of education focused on sustainability, helping to prepare students, professionals, and the general public to tackle the complex challenges of sustainable development (SD) [27].

Over recent years, modern machine learning methods have evolved significantly, with advancements in algorithms, computational power, and data availability driving innovation across various domains [22, 52]. Among these methods, notable approaches include Deep Learning, Convolutional Neural Networks, Recurrent Neural Networks, Generative Adversarial Networks, Reinforcement Learning, Transfer Learning, Natural Language Processing techniques, Federated Learning, and Neuroevolution, among others. In addition, Explainable AI has been widely used, although it is not a machine learning method in itself. It encompasses methods and techniques

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that aim to make the outcomes of AI solutions interpretable and understandable to human experts [17, 19].

Overall, the use of AI in education can be operationalized through various methods and tools, including personalized learning experiences as discussed in the literature. Alam [4] demonstrated that AI can tailor educational content to individual students' learning styles, needs, and pace. Kuleto et al. [30] noted that by analyzing data on student interactions and performance, AI can modify task difficulty, provide additional resources, or adjust the learning path to enhance students' comprehension of sustainability concepts. McGovern et al. [38] introduced a second approach, highlighting the use of AI-powered technologies such as Virtual Reality and Augmented Reality to create interactive and immersive learning experiences, allowing students to engage in simulations of environmental scenarios. These experiences can vividly illustrate the impact of climate change, deforestation, or pollution on ecosystems, making the abstract and distant consequences of unsustainable practices more tangible and immediate [12, 50].

In addition, by means of scalable education and outreach, AI-driven platforms can facilitate massive open online courses (MOOCs) and other online learning tools that reach a wide audience [13]. This scalability ensures that SE is accessible to a global audience, spreading awareness and knowledge beyond traditional classroom settings [61]. Furthermore, by the use of enhanced engagement through gamification, AI can be used to design educational games or gamified learning experiences that make SE more engaging and interactive. These games can simulate real-world sustainability challenges, allowing players to experiment with solutions and understand the complexity of environmental issues [43].

AI can also foster data-driven insights for curriculum development. It can do so by analyzing vast amounts of data from diverse sources to identify trends, gaps, and emerging topics in the field of sustainability. This can inform curriculum developers and educators, helping them to create content that addresses current issues and equips learners with relevant knowledge and skills [3, 57].

By means of automated assessment and feedback, AI can provide real-time feedback and assessments, enabling learners to understand their progress and areas for improvement. In the context of SE, this immediate feedback is helpful in reinforcing concepts and encouraging reflective learning [14]. A further application in AI in SE is the facilitation of collaborative learning [37]. AI systems can connect learners from across the globe, fostering collaborative projects and discussions on sustainability issues. This can lead to a richer learning experience as students share diverse perspectives and solutions to environmental challenges [1]. Finally, AI tools can assist students and researchers in accessing and analyzing vast datasets relevant to sustainability, facilitating research projects and innovations that contribute to Sustainable Development Goals (SDGs) [8, 23].

By harnessing the power of AI, SE can become more accessible, engaging, and effective, empowering individuals and communities to contribute to a more sustainable future [2]. The adaptive and innovative nature of AI offers promising avenues for educating the public on sustainability challenges and solutions, making it an indispensable tool in the global effort to achieve SD [27]. However, even though AI holds significant potential to enhance education, there are several challenges to its effective implementation as demonstrated in Table 1.

Addressing these challenges requires a collaborative effort among educators, policymakers, technologists, and communities. By focusing on equitable access, ethical use, data privacy, and the quality of AI-driven educational content, the potential of AI to enhance SE can be fully realized, contributing to more informed, engaged, and proactive global citizens in the pursuit of SD.

In this context, this paper aims to identify the extent to which AI may transform educational practices, by assessing how it is being used in respect of personalized learning experiences, facilitation of data analysis, and modeling of complex systems. The results of this study seek to illustrate the applications of AI in SE, offering powerful tools for the implementation of the UN SDGs, increasing the potential for SE in the future. The next section presents an overview of the methods used. Section "Results and discussion" presents and discusses the results. Section "Conclusions" provides conclusions and discusses the implications of the paper to theory and practice.

Methods

Seeking to identify how AI can transform educational practices for teaching sustainability, this study is characterized as descriptive research with both quantitative and qualitative approaches, with two complementary sources of data. First, an analysis of a set of case studies at universities worldwide was conducted. Second, a survey with faculty members and administrators who teach in various fields at higher education institutions (HEIs) globally was undertaken. The use of a mixed-methods approach broadens the scope, enhances objectivity, and caters for the methodological rigor of the research.

Case studies

An analysis of a set of 20 case studies involving universities in different global geographical locations was conducted. The goal was to understand, within different realities, how AI is being used for sustainable teaching

Table 1 Some of the challenges associated with the use of AI. Source: The authors

Challenge	Implications	Reference
Access and equity	Despite the global reach of the internet, there is still a significant digital divide, with many regions lacking reliable access to the technology and connectivity required to benefit from AI-enhanced education. This disparity can exacerbate existing inequalities, leaving behind those in low-income countries or rural areas	[21]
Data privacy and security	The use of AI in education involves the collection and analysis of large amounts of personal data, raising concerns about privacy and data security. Ensuring the protection of this data is paramount to maintain trust and the ethical use of AI in educational settings	[36]
Bias and fairness	AI systems can inherit biases present in their training data or in the assumptions of their developers. In the context of SE, this could lead to biased educational content or recommendations, potentially skewing perspectives on sustainability issues and solutions	[9]
Quality and relevance of content	While AI can help customize learning experiences, ensuring the quality and relevance of the content is a challenge. Misinformation or outdated information can mislead learners, undermining the goals of SE	[40]
Technical skills and literacy	Both educators and learners may require additional training to effectively use AI-powered tools. The lack of technical skills can be a barrier to the adoption and effective use of AI in SE	[44]
Dependence on technology	Over-reliance on AI for educational purposes can lead to a reduction in critical thinking and problem-solving skills if not carefully managed. It is essential to maintain a balance between technology-assisted learning and traditional learning methods that promote deep understanding and critical engagement with sustainability issues	[6]
Cost	Developing, implementing, and maintaining AI systems for education can be expensive. This cost barrier can prevent institutions, especially those in less affluent areas, from adopting AI technologies, further widening the educational divide	[41]
Ethical considerations	The use of AI in education raises ethical questions, such as the extent to which AI should influence learning pathways and outcomes. There is also the concern about the potential for AI to make decisions that affect learners' futures based on algorithms that may not fully capture the complexity of human learning and development	[45]
Interdisciplinary integration	SE is inherently interdisciplinary, requiring a broad understanding of social, economic, and environmental issues. Developing AI systems that can effectively integrate these diverse fields into cohesive learning experiences presents a significant challenge	[49]
Sustainability of AI systems	Ironically, the environmental impact of developing and running AI systems themselves, due to the significant energy consumption of data centers and networks, needs to be considered. Ensuring that AI applications in SE are themselves sustainable is an ongoing challenge	[58]

and learning. By targeting universities from across all geographical regions, there is an alignment with general sustainability principles, since global action for SD needs to involve all countries, independent of their sizes. Through a document analysis, the authors verified the various methods and AI tools being used for sustainability teaching activities. According to Leal Filho et al. [34] and Yin [60], an analysis of case studies, based on qualitative methods, allows researchers to understand the phenomenon in depth while strengthening the study's analytical conclusions.

For the analysis of case studies, 20 papers and book chapters concerning AI and SE were selected. The choice of 20 case studies was based on their nature, the international scope of the work done, the diversity of approaches used, and their perspectives. The search for papers was initially conducted using the Web of Science (WoS) because it is one of the most trusted and widely recognized worldwide citation databases containing multi-disciplinary research. 95 peer-reviewed papers were initially returned from the WoS using the following search string within the title: ((“artificial intelligence” OR “AI” OR “machine learning”) AND (“sustainab*”) OR (“sustainable development”) OR (“SDG*”) AND (“higher education” OR “HEI*” OR “universit*”) AND (“case stud*”)). The publication years were filtered to 2018–2024; the language was set to English; and the document type was filtered to article, book chapter, and book. As the result, 61 papers were yielded, and two papers were selected as case studies that fit this study. The selection criteria were case studies of actual course implementation considering various AI applications, disciplines, and geographical representations. Next, a search using Scopus was conducted due to its comprehensive scope on peer-reviewed publications in international outlets in the English language [32]. The same search string and criteria for filters were used. The search returned 93 papers, and five papers were selected as suitable case studies using the same selection criteria as that of the WoS search. Next, a series of Google Scholar searches were conducted, yielding seven case studies. The same criteria were used. The small return of case studies of actual course implementation reveals that this topic is emerging, although HEIs have begun incorporating AI tools into their curriculum

in various disciplines, published case studies on AI in SE in peer-reviewed academic journals or books indexed in WoS, Scopus, and Google Scholar are rare. The limited presence shows that the topic is in its infancy, and there is a need for more exploration.

The authors initially planned to select 20 real-world examples of AI use implemented in courses offered at HEIs worldwide; however, they could find only 14 of them suitable. Therefore, the authors included six additional papers from the initial lists, broadening the criteria; for example, papers on AI in SE using students' communications on their perceptions and experience in sustainability learning were used because they help uncover the practical implications of the applications. The selection process of 20 case studies is illustrated in the flow diagram in Fig. 1.

The 20 papers and book chapters were analyzed and synthesized to examine the trends of the applications of AI, which adds qualitative depth to the study, providing real-world examples of courses and applications of AI in SE in HEIs in different global geographical locations.

Survey

In order to discern the challenges, experiences, and trends faced by education professionals when utilizing AI for teaching sustainability, we collected data through a written survey to engage experts from various areas to ask them how they are currently using AI for sustainability teaching and facilitating learning [51, 56]. Surveys are investigations that gather data from representative samples of a specific population, aiming to describe and analytically explain findings that can be generalized to the entire population universe [7]. Furthermore, the application of a survey can be seen as a solution for identifying the demands and preferences of a specific population [42, 46].

The questionnaire consisted of 20 questions (multiple-choice, Likert scale, and open-ended) divided into four sections. They were (1) participants' background information, (2) AI awareness and adoption, (3) impact of AI on teaching, and (4) impact of AI on sustainability teaching/education. The instrument used was adapted from Leal Filho et al.'s study [31], which was previously validated and had its reliability tested. It was also subject to peer review in the context of the paper where it was documented. It was acknowledged as being an instrument suitable to be used in the study. Following a comprehensive review by all authors, a pre-test was conducted with five experts in sustainability. They assessed both the content of the questions and the format in which they were presented. This process led to the final version of the instrument being dispatched to the target audience.

The sampling used was a convenience one. The final version of the questionnaire was distributed via Google

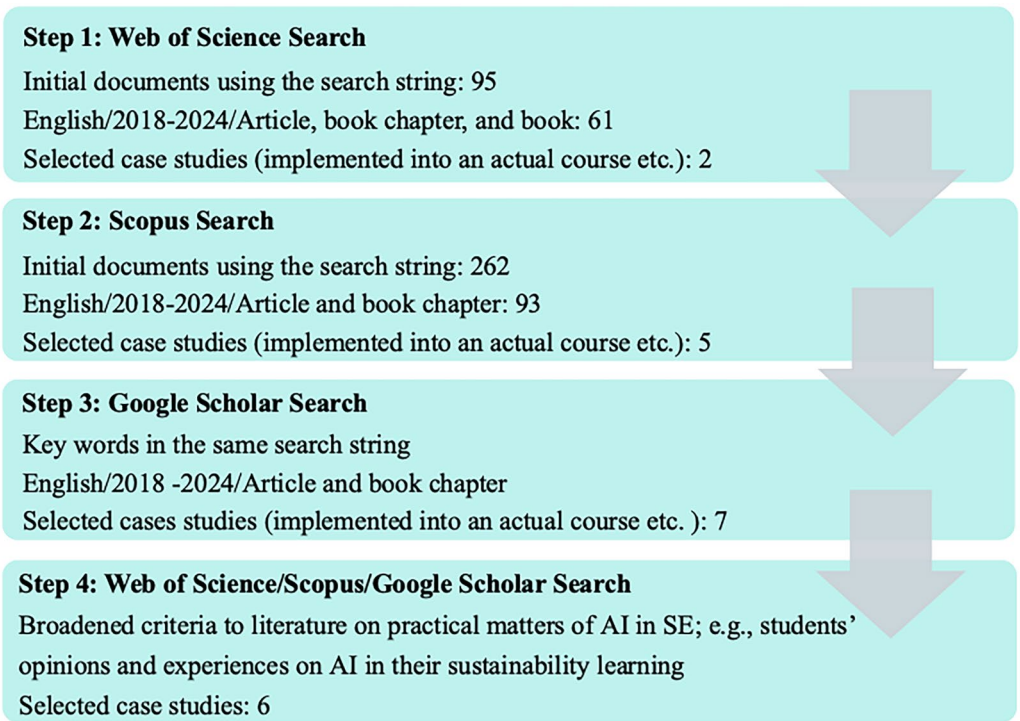

Fig. 1 Selection process for 20 case studies. Source: The authors

Forms and disseminated through email, newsletters, websites, and LinkedIn to academic and professional networks that might be familiar with AI in a SE context. Participation in the study was voluntary, and those interested took part in the study. Various reminders were sent. This approach garnered 101 responses from 45 countries between May and July 2024. The low response rate reflects the fact that not many colleagues felt encouraged to provide a response. The small size of the sample was listed as one of the limitations of the study. In line with German rules, an ethical approval was not required for the survey since it entails no personal or critical data. Informed consent was obtained from all individual participants included in the study. Data analysis involved descriptive statistics and text-mining tools for the open questions.

Results and discussion

This section presents an analysis of a set of 20 cases retrieved from literature. Following this, the results of the survey are presented, which involved 101 educational professionals from 45 different countries. The findings are consistent between the two methods, but the results are more robust because they are combined.

Artificial intelligence and sustainability case studies

In this section, the results of the literature analysis and 20 case studies on AI and sustainability teaching and learning in higher education are presented, including 15 papers published in peer-reviewed journals and five peer-reviewed book chapters. There are also 14 case studies of courses offered and projects conducted in HEIs worldwide, whereas six papers are on AI and SE. The six papers are not case studies in the narrow sense; rather, they consist of literature reviews on practical matters of AI in SE, such as analyses of college students' opinions and experiences on AI in their sustainability learning. They are included in the selection because this type of research also uncovers practical issues of AI in sustainability teaching and learning. The details of the research on the case studies, including titles, focuses, and references, are presented in Table 2.

By enhancing their curriculum and infrastructure, HEIs may play a more important role in preparing future professionals, providing the advanced skills demanded by the ever-evolving industry 4.0. In recent years, the integration of AI into education has been recognized as a transformative force with great implications. Judijanto et al. [26] suggested the potential of AI in revolutionizing educational paradigms to solve social and environmental problems, providing an understanding of the complex dynamics and impacts of leveraging AI in SD education. Jokhan et al. [25] also argued that in the context of SDG 4, offering equitable quality education, AI is gaining interest in assessing student behavior and performance.

In a study at Jouf University in Saudi Arabia, Kamruzzaman et al. [28] found that integrating AI and the IoT into SE can revolutionize learning by providing students with personalized, engaging, and adaptive learning experiences and real-time support. AI-powered algorithms can analyze student data, offering students tailored content, assessments, and feedback for their unique learning style and pace. IoT-enabled devices can be used to collect student work, allowing for automatic grading and assessing student assignments.

Despite many benefits, Elimadi et al.'s case study [18] at the University Hassan II in Morocco analyzed the complexity of integrating AI into digital learning environments. Forty students from the Faculty of Sciences participated in an online questionnaire and the majority of them were optimistic about AI's potential to improve student learning outcomes through flexible and individualized learning experiences; however, they offered caution for the need for accountable and transparent use of AI. Alamäki et al. [5] conducted an empirical study with undergraduate business administration students in Finland to map the capabilities and perceptions of students about AI and its potential to facilitate a sustainable transition in society. The findings revealed that the students had difficulties in solving the actual problem due to their lack of knowledge of the basics of AI and SD. Leal Filho et al.'s study [33] that highlighted optimism with caution, such as ethics and authenticity in assessment and the lack of training on the software and information technology.

Concerning the integration of AI techniques in educational instruction and learning processes, Kondoyanni et al. [29] presented recent machine-learning techniques applied to agricultural engineering students in Greece to tackle the challenge of water resource preservation. Innovative, cost-effective software and hardware components were incorporated to monitor the operation of agricultural equipment, and relevant educational activities were developed. The findings indicated that students' familiarity with emerging technologies enhanced their capacity for innovation and collaborative engagement. Božić [10] explored the incorporation of AI into nursing education, and the outcomes included students' enhanced critical thinking, decision-making, and data analysis skills in the context of AI in healthcare despite certain challenges such as data privacy, algorithm transparency, and potential biases in AI algorithms.

Researchers explored the integration of various AI tools to enhance SD education [1, 47]. AI and machine-learning approaches offer rapid solutions with high accuracy [25]. Jokhan et al. [25] used an AI-based analytics tool to predict student performance in a first-year

Table 2 Case studies on using AI in sustainability teaching and learning. Source: The authors

Case	The title of the paper	The focus	The reference
1	Using artificial intelligence to implement the UN Sustainable Development Goals at higher education institutions	Investigates the connections between AI and the implementation of the UN SDGs at HEIs	Leal Filho et al. [33]
2	Artificial Intelligence in the context of digital learning environments (DLEs): towards adaptive learning	Analyzes the complexity of integrating AI into digital learning environments at the University Hassan II in Morocco	Elimadi et al. [18]
3	A methodology for evaluating and reporting the integration of artificial intelligence for sustainability in higher education: New insights and opportunities	Provides insights into the assessment approaches for the incorporation of AI technologies	Chemlal and Azzouazi [11]
4	AI- and IoT-assisted sustainable education systems during pandemics, such as COVID-19, for smart cities	Investigates how AI and the IoT can be integrated into SE in order to provide students with personalized and immersive learning experiences for smart cities at Jouf University in Saudi Arabia	Kamruzzaman et al. [28]
5	Educational revolution through studying the potential of artificial intelligence in sustainable development	Explores the potential of AI in revolutionizing educational paradigms to address socio-environmental challenges	Judijanto et al. [26]
6	Assessing education for sustainable development in engineering study programs: A case of AI ecosystem creation	Evaluates the level of sustainability education in engineering studies at a technological university in Lithuania and proposes criteria to ensure the SDGs in IT/AI study programs	Paulauskaite-Taraseviciene et al. [48]
7	Artificial intelligence literacy in sustainable development: A learning experiment in higher education	Examines the capabilities and perceptions of undergraduate business administration students in Finland on AI and its potential for sustainable transition	Alamäki et al. [5]
8	Artificial intelligence in nurse education	Explores the integration of AI in nursing education, highlighting its importance, current practices, potential benefits, and challenges	Božić [10]
9	Case studies on artificial intelligence for sustainable education in 21st Century	Showcases various applications of AI technologies in education to enhance sustainability, efficiency, and inclusivity in India	Patil and Kumar [47]
10	Increased digital resource consumption in higher educational institutions and the artificial intelligence role in informing decisions related to student performance	Presents an AI-based analytics tool created to predict student performance in a first-year information technology literacy course at the University of the South Pacific in Fiji	Jokhan et al. [25]
11	Navigating the confluence of artificial intelligence and education for sustainable development in the era of Industry 4.0: challenges, opportunities, and ethical dimensions	Examines the integration of AI tools, with a specific emphasis on ChatGPT, in sustainable development education	Abulibdeh et al. [1]
12	Streamlining student support: Enhancing administrative assistance and interaction through a Chatbot solution	Explores the benefits and challenges of integrating a chatbot solution in education to streamline administrative processes and provide timely support to students	Mohamed et al. [39]
13	A meta-analysis and systematic review of the effect of Chatbot technology use in sustainable education	Investigates the effect of Chatbot-assisted learning on various components and how different moderator variables influence the effectiveness	Deng and Yu [15]
14	Adding machine-learning functionality to real equipment for water preservation: An evaluation case study in higher education	Presents activities assisting engineering students to utilize recent machine-learning techniques for tackling the challenge of water resource preservation in Greece	Kondoyanni et al. [29]
15	Evaluation of UN SDG-related formal learning activities in a university common core curriculum	Explores how common core courses can be classified by machine-learning approach according to the SDGs at a university in Hong Kong	Lei et al. [35]
16	Blockchain technology and artificial intelligence for smart education: State of art, challenges and solutions	Covers the main advantages of Blockchain technology and AI illustrates how they may be used in education	Ettaoufik et al. [20]
17	Creation of an artificial neural network to predict the behavior of MOOC platforms on the 2030 agenda and the sustainable development goals	Discusses the creation of an artificial neural network as the future of MOOC courses related to the 2030 Agenda at the National University of Distance Education in Spain	Hueso Romero [24]

Table 2 (continued)

Case	The title of the paper	The focus	The reference
18	Evaluating sustainability of mobile learning framework for higher education: a machine learning approach	Presents a novel machine-learning approach and technique to evaluate sustainability of the proposed mobile learning framework in Sri Lanka	Dolawattha et al. [18]
19	SeisTutor: A custom-tailored intelligent tutoring system and sustainable education	Evaluates SeisTutor, which mimics human tutor cognitive intelligence offering quality education for the SDG 4	Singh et al. [55]
20	Artificial intelligence enabled sustainable education system using Vedic Scripture and Cyber Security	Explores the potential of an AI-enabled sustainable education system that incorporates Vedic scripture and cybersecurity measures	Sharma et al. [54]

Information Technology Literacy course at the University of the South Pacific in Fiji. The developed classification model predicted student performance in Week 6, allowing for early intervention. Lei et al. [35] explored how common core courses could be classified by a machine-learning approach according to SDGs at a university in Hong Kong. In this report, the authors used machine-learning techniques to tag the 166 common core courses with SDGs, and the results indicated that the approach significantly accelerated the process. Dolawattha et al. [16] examined a novel machine-learning technique and approach for evaluating sustainability of the proposed mobile learning framework. They distributed a questionnaire that represented 20 sustainable factors in five sustainability dimensions (social, economic, political, pedagogical, and technological) to 150 students and 150 instructors in the university community in Sri Lanka. The results showed that the proposed system achieved economic and pedagogical sustainability, whereas there was a need to improve on social, political, and technological sustainability. Singh et al.'s study [55] concerning SeisTutor, which mimics the cognitive intelligence of a human tutor, revealed that intelligence-incorporated SeisTutor improved student learning. Intelligent systems assisted SE with various benefits, including a personalized learning environment and exclusive curriculum.

Recently, AI Chatbots such as ChatGPT have gained widespread attention with the potential to revolutionize education. Deng and Yu's study [15] study revealed that Chatbot technology exerted a medium-to-high effect on overall learning outcomes. In terms of learning components, Chatbots could significantly enhance learning interest, explicit reasoning, learning achievement, and knowledge retention. However, the integration requires the effective integration of AI tools, curriculum redesign, continuous learning, and raising potential ethical concerns [1]. Additionally, Mohamed et al. [39] found that the integration of a Chatbot provided timely support to students and facilitated administrative processes, such as enrollment procedures.

Finally, in his study of artificial neural networks conducted at the National University of Distance Education in Spain, Hueso Romero [24] analyzed MOOC platforms using the 2030 Agenda and SDGs as frameworks. As a result, he created an artificial neural network that predicts future MOOC courses related to the 2030 Agenda and suggested the implementation of new specialized platforms in this type of course.

These case studies illustrate a wide range of applications of AI in SE at HEIs, which includes personalized learning, virtual simulation, assessment, data analysis and modeling of complex systems, intelligent tutoring systems, and smart/accessible classrooms. Unlike the others, case studies 1, 5, 7, and 20 are comprehensive literature concerning AI in SE. Table 3 below shows the analysis of the 20 case studies by AI use.

AI offers powerful tools to accelerate the implementation of the UN SDGs with the potential to address complex sustainability challenges in education and across various sectors [33]. Researchers forecast that despite some cautions and challenges, AI use is likely to increase in SE in the future.

Survey analysis

Background information

The sample comprised 101 education professionals, with 60.4% of participants aged between 36 and 55 and an almost equal gender distribution among men and women. Figure 2 shows the geographical representation of the countries which took part in the survey. Although the main represented country is the US (38.6%), answers were obtained from experts from 45 countries. This makes this study one of the most comprehensive ones on the subject matter of AI and higher education undertaken to date. The wide geographical coverage caters for a global understanding about the use of AI in sustainability teaching and learning.

Among the respondents, 87.1% hold doctoral degrees, 72.3% are affiliated with public institutions, and 63.4% are engaged in teaching at the undergraduate, master's, and doctoral levels. More background information on the respondents is presented in Table 4.

Considering the main concepts involved in sustainability teaching and learning, the topic of Sustainable Development Goals (SDGs) was the one with highest scores among "great extent" and "very great extent" (over 50%), followed by Diversity/Equity/Inclusion (DEI), with 45.5% of the answers between those categories (see Fig. 3). Circular Economy (CE) and Corporate Social Responsibility (CSR) received the highest scores in "not at all" category (around 30%), indicating that those concepts were not very well presented in the disciplines taught by professionals.

Participants were also invited to answer questions about the main educational and pedagogical methods used in their classes. Different educational methods are being developed and changed by AI, and a greater understanding of the most popular methods can help to map the use of AI and manage the deployment AI for teaching and learning. This adaptive learning approach can enhance student engagement and help to improve learning outcomes.

The methods that yielded the highest responses were lectures (80.2%), case studies (70.3%), and group activities (68.3%). Those methods can be enhanced by AI to assist analysis and use intelligent tutoring systems [30], which

Table 3 Analysis of AI use in the case studies. Source: The authors

AI use	Impact	Case studies
Personalized Learning	More efficient and effective learning by increased engagement and motivation	2-Elimadi et al. [18] 9-Patil and Kumar [47] 11-Abulibdeh et al. [1] 12-Mohamed et al. [39] 13-Deng and Yu [15]
Virtual simulation	Increased engagement and motivation for learning; improved understanding of complex concepts	9-Patil and Kumar [47] 14-Kondoyanni et al. [29]
Assessment	Reduced time and effort required for manual evaluation; reduced human error (consistent and objective evaluations)	3-Chemlal and Azzouazi [11] 6- Paulauskaite-Taraseviciene et al. [48] 9- Patil and Kumar [47] 16- Ettaoufik et al. [20] 18-Dolawattha et al. [16]
Data analysis/modeling	Identifying patterns and trends and forecasting by analyzing vast amounts of data using AI algorithms	8-Božić [10] 9-Patil and Kumar [47] 10-Jokhan et al. [25] 15-Lei et al. [35]
Intelligent tutoring systems	Interactive and intelligent support by answering questions, explaining complex concepts, engaging students in dialogue, and promoting active learning	4-Kamruzzaman et al. [28] 9-Patil and Kumar [47] 19-Singh et al. [55]
Smart/accessible classrooms	Increased ability to monitor and analyze student data; increased engagement and motivation for learning; and improved ability to collaborate and communicate with classmates	4-Kamruzzaman et al. [28] 9- Patil and Kumar [47] 16-Ettaoufik et al. [20] 17-Hueso Romero [24]
Others		1-Leal Filho et al. [33] 5-Judijanto et al. [26] 7-Alamäki et al. [5] 20-Sharma et al. [54]

could greatly change student experience. The methods with the second-highest responses were project-based learning (57.4%), problem-based learning (53.4%), learning through research (51%), and seminars and/or tutorials (48.5%). The next group included dialogue/expositive class (32.7%), laboratory and practical learning (30.7%), challenge-based learning (29.7%), debates (29.7%), field trips (27.7%), and virtual learning environment (25.7%). Lastly, the other answers included creation workshops (12.9%) and other (7.9%). When asked about other methods beyond the options provided, educators cited Gamification, Software Application, and Experiential Simulation.

The adoption and impacts of artificial intelligence on teaching

Regarding AI awareness and adoption, although 91.1% reported being "aware" or "very aware" of trending technologies that use AI, such as ChatGPT, only 25.5% "often" or "always" adopted AI tools in teaching. Moreover, a significant number of educators indicated that they "rarely" (16.8%) or "never" (19.8%) adopted AI tools.

Among the tasks where AI was used illustrated in Fig. 4a, text generation was the highest category, with 64.4% of the answers, followed by image generation (32.7%) and data analysis (26.7%). The tools followed the same pattern as shown in Fig. 3b, with ChatGPT having the highest mention (77.2%), followed by DALL-E (19.8%).

The educators that either do not use AI or do not intend to use AI were invited to write the reasons why. Among the 17 answers received, the main cited reason ($n=8$) was "lack of awareness" or "not familiar" with AI. This relates to the Technical Skills and Literacy challenge previously cited [44] since those educators also expressed difficulties in learning the technical components of AI and, consequently, incorporating AI tools in their teaching practice. The second-most cited reason ($n=7$) was reliability problems, with answers such as "The few times I have used it, things did not turn out the way I liked them" (#77) and "aversion against it, scientifically unreliable, ethical concerns" (#59). Those reasons represent two other challenges presented in the literature: Quality and Relevance of Content [40] and Ethical Considerations [45]. The lack of trust in the AI output may hinder educators from exploring and using AI in their disciplines. Those aspects could be addressed by HEIs to better support their staff, considering that AI can address contemporary challenges and equip learners with relevant knowledge and skills [3, 57].

Considering AI's impact in teaching practice, 40.6% considered that AI tools had significantly changed the

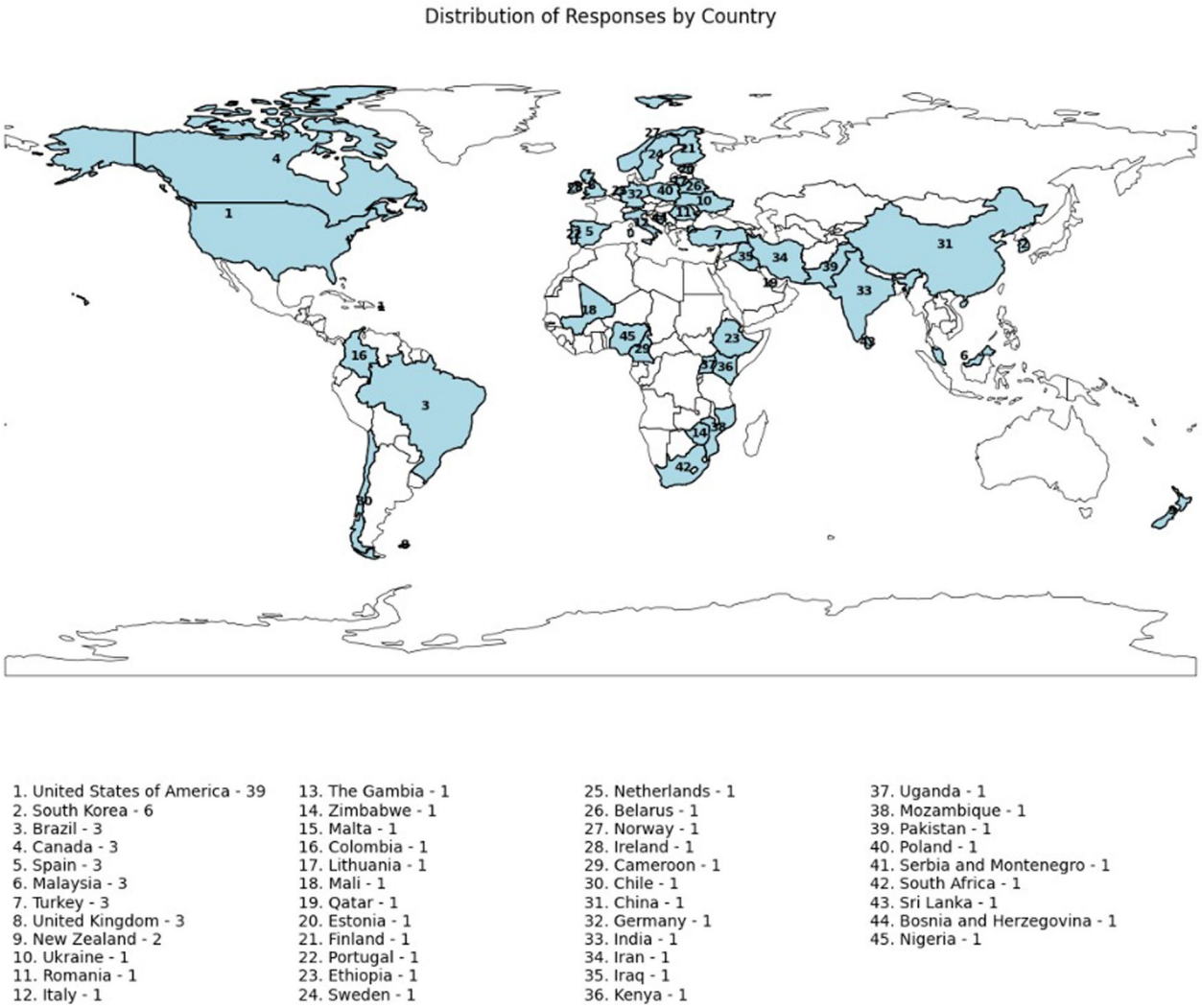

Fig. 2 Distribution of survey responses by country. Source: The authors

way they educate. The educators mentioned the generation of ideas and visuals, and the automation of ordinary tasks such as improving feedback and structuring steps for activities. Among the 34 written comments received, 26 mentioned positive aspects, mainly considering timesaving in content generation and organization for class, which enabled educators to focus on other teaching aspects. As some wrote, "Content generation is easy and thus focus more time on critical reflection with students" (#10) and "I focus more on authentic learning" (#62). Another positive aspect was the use of AI to improve the student's learning process, whether in class ("I have integrated the tool also during classes, it is useful for debates and future narratives" (#30)) or at home ("Encourage the students to do their homework using AI tools" (#18)). It was also mentioned that AI can help in "Getting new ideas for engaging students in active learning. Getting the student to use AI to enrich their learning process" (#20).

Nonetheless, some educators demonstrated concern about the need for critical thinking and suggested that the use of AI tools in teaching is important to make students aware of AI limitations and possibilities. One respondent mentioned:

> *I have always scaffolded work, but I'm leaning more towards using AI to get them started and showing them how it falls short on its own. My fear is that they will rely on it instead of their own critical thinking skills, but I'm always growing and learning with them. (#41)*

Another stated:

> *It is important to teach students how to use a new*

Table 4 Background information on the participants. Source: The authors

Criteria		Percent
Age	26–35 years	7.9%
	36–45 years	29.7%
	46–55 years	30.7%
	56–65 years	23.8%
	More than 65 years	7.9%
Gender	Male	47.5%
	Female	51.5%
	Prefer not to say	1.0%
Highest degree	Doctoral degree	87.1%
	Master's degree	10.9%
	Bachelor's degree	2.0%
Institution	Public	72.3%
	Private	21.8%
	Others	5.9%
Teaching	Undergraduate only	25.7%
	Master's and Doctoral only	10.9%
	All	63.4%
Discipline (select-all-that-apply question)	Social Sciences	30.7%
	Business	22.8%
	Engineering and Technology	21.8%
	Biological, Natural, Agricultural, or Environmental Sciences	20.8%
	Education	19.8%
	Medical and Health Sciences	13.9%
	Humanities	13.9%
	Physical Sciences, Mathematics, and Computer Sciences	7.9%
	Communications, Media, and Public Relations	6.9%
	Arts	5.9%

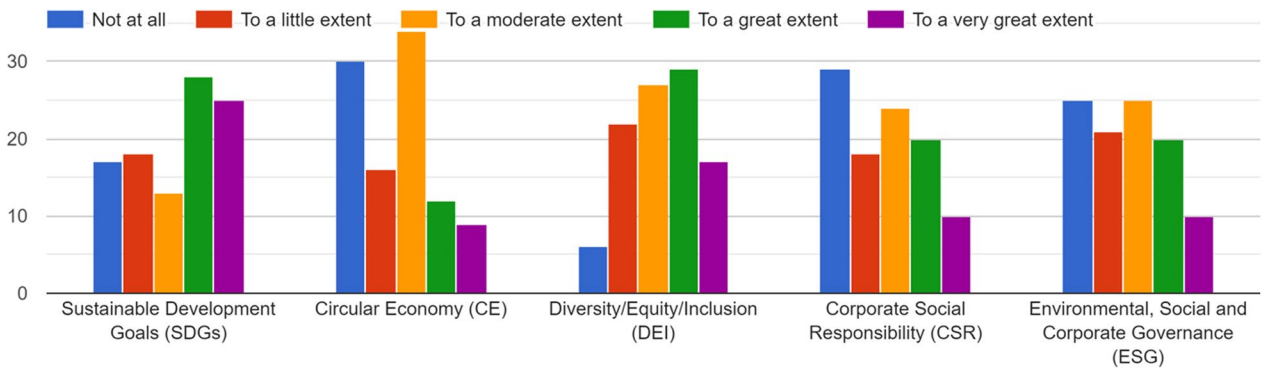

Fig. 3 Main concepts in sustainability teaching and learning. Source: The authors

tool effectively, and discuss its broader ethical implications without stigma. Students do not acknowledge they use it, and in many instances, they do not use it effectively. This also prevents them from engaging with the problems/bias in the system. (#42)

The use of AI in teaching can allow educators to save time with repetitive and mechanical tasks and so focus on developing activities that can enhance critical thinking with students, including about AI tools [6]. However, previous studies mentioned the need for AI literacy [44],

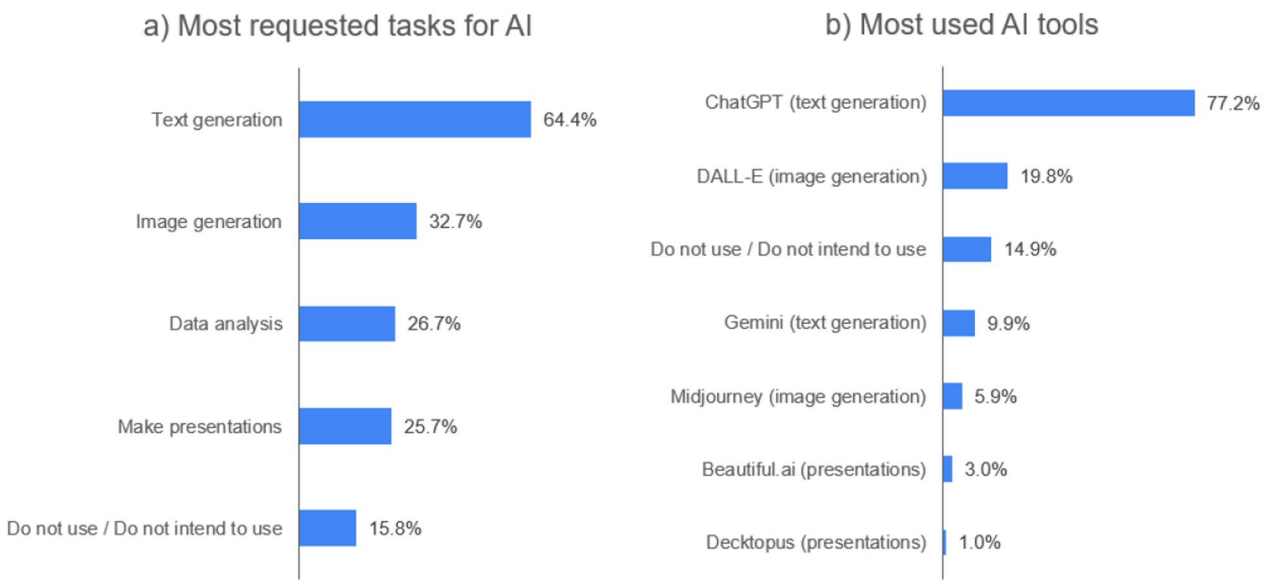

Fig. 4 The adoption of AI in teaching. **a** Most requested tasks. **b** Most used tools. Source: The authors

which can be a barrier to effectively promoting timesaving and critical thinking in the classroom.

The changes that AI had brought were also reflected in evaluation methods, with 46.5% stating that there was a significant impact in assessments. Most of the educators mentioned that the assessments should be made considering that students have AI tools available to answer the questions, so it is important to "try to make sure that not all answers are generated by AI" (#66). As previous studies have shown [45], the need to check plagiarism, fraud, and cheating increased, and new assessment designs must be developed by educators. In this sense, the educators have developed some strategies: according to a respondent (#2), "I always see the specific lexics of ChatGPT and revert the submission for students' revision." Another (#39) mentioned, "When assigning graded math problems, I specifically find questions that ChatGPT does incorrectly so that students do not rely on it to see all of the work and solutions." Another (#23) said, "I pay more attention to developing assignments that cannot be created with AI, such as asking questions about specific things I mentioned in lectures or labs. I also consider using oral exams in the future."

Although AI might have created the need to innovate in assessment design, some educators mentioned the use of AI tools for solving this issue, being used as a tool for test generation and rubric development as well as the object of the learning evaluation: one respondent (#20) mentioned, "Generating new ideas for new and authentic assessments, helping with assessment rubrics development." Another (#45) illustrated, "My evaluation of student learning includes them using AI to generate text and images to demonstrate mastery of current tools" and "I try to follow their process and how they are employing the AI tools." (#33)

Learning can have different outcomes, so educators were asked to answer regarding the use of AI tools to assess different learning outcomes. The outcomes were categorized as cognitive (knowledge and intellectual development, e.g., essays), skill-based (technical skills, e.g., test), and affective (attitudes toward the learning process, e.g., satisfaction) [59]. Most of the educators were conservative, indicating that AI might moderately be applied. Cognitive and skill-based learning outcomes seem to be more appropriate for evaluation with AI, unlike affective ones (see Fig. 5).

When asked about the teaching methods that can be supported by AI and to what extent, the average answer to different options was "Moderately" (from 39 to 18%) supported. Considering the "Very" and "Extremely" votes that each method received, virtual learning environments and lectures stand out (44.5%), followed by case studies (40.6%), learning through research, and project-based learning (39.6% each). On the other hand, field trips and dialogue/expositive classes were considered the methods that can be slightly supported or even cannot be supported at all by AI.

About how the AI tools can be used, educators mentioned code support and data analysis as well as improving writing skills as a drafting tool. Personalized and enhanced learning was also mentioned as a way that AI tools support the teaching methods. As mentioned by

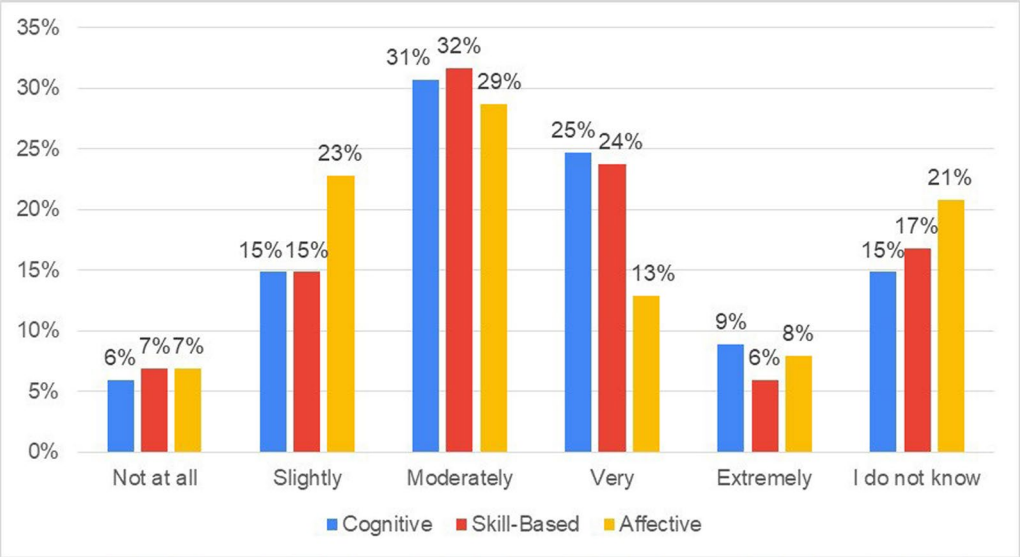

Fig. 5 Use of AI tools for assessing learning outcomes. Source: The authors

one educator (#81), "Each student is on an individual mission, and this can help them fulfill that mission."

When asked about the challenges and limitations of AI and teaching, it is possible to see three groups of concerns (see Fig. 6). First, plagiarism (91%) and hallucination (82%) were the educator's main concern, cited by most of them. A second group of challenges includes data privacy (64%), bias (56%), and hindering learning (51%). Finally, the third group of concerns involve mainly external impacts of AI in teaching, such as social connection (48%), digital divide (34%), and environmental costs of model training (33%). Those three groups are in line with worldwide concerns [45] and might indicate priorities that should be addressed when adopting AI in teaching.

The impacts of artificial intelligence on sustainability teaching and education

Sustainability teaching might have to face additional barriers than teaching traditional disciplines does, especially in the climate change scenario the world faces today. AI

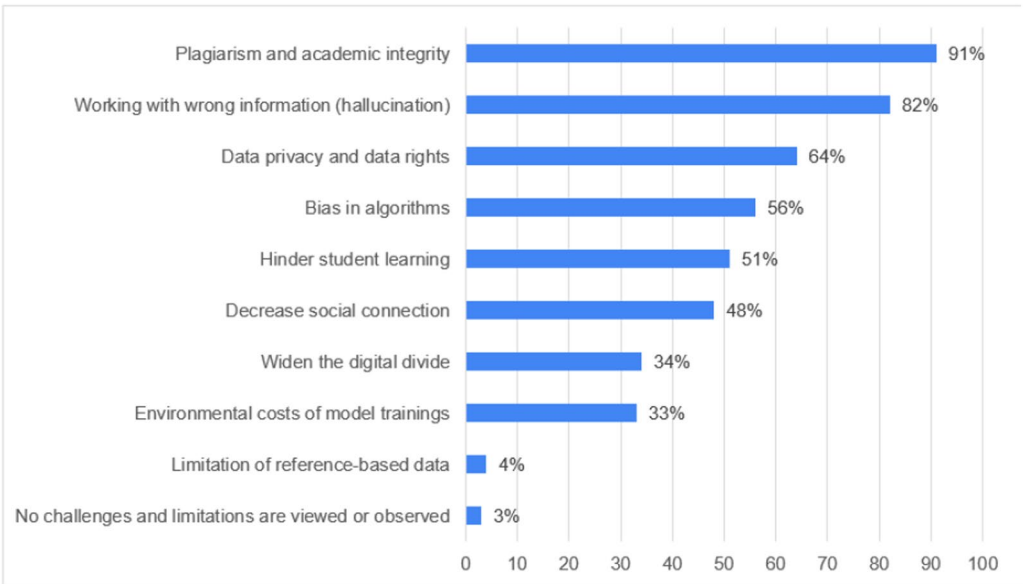

Fig. 6 Challenges and limitations most associated with the use of AI. Source: The authors

has the potential to help with this challenge [30]. However, many educators do not seem confident that AI tools will be protagonists from this movement. When asked to what extent SE can benefit from AI, the answers "Very" and "Extremely" together (41.58%) were slightly less than the "Moderately" category alone (42.57%) (see Fig. 7a). In addition, over 45% indicated they "Neither Agree or Disagree" about the capacity of AI tools to develop better pedagogical approaches in implementing SD aspects such as SDGs and Environmental, Social, and Governance (ESG) (see Fig. 7b) although 42.6% indicated "Agree" or "Strongly Agree."

Among those who believe AI can help sustainability teaching and education, the examples provided included "remove information asymmetries and language barriers" (#34) and "It will help me to access the resources of any subject related to the SDGs and well-structure those resources" (#54). One respondent even mentioned and example of an in-class activity regarding sustainability teaching assisted by AI:

> *AI makes generation of texts and images very easy to do; and also facilitates basic personal research by students. Thus, pedagogy can include practice with real-time basic research. Example: Please use your phones (and AI) to find out which country has the largest known fossil fuel reserves. How much is it? Next do the same for the next nine of the top ten countries. Now work in groups to develop a diplomatic scenario wherein these ten countries create a treaty to limit fossil fuel use. (#45)*

In addition, over 88% indicated that the implementation of AI tools is likely to increase, looking towards 2030. Those results are consistent with previous research that indicated that the potential of AI for sustainable teaching has not yet been fully explored by educators [1].

Considering the potential drivers for the use of AI for SE, the personalized learning experience was the most indicated (over 57%), closely followed by the potential to manage work more effectively (56%) and student access to materials outside the classroom (56%) (see Fig. 8). Although some drivers were more popular than others, there were still some respondents who indicated none of them (almost 8%). Combined with the skepticism regarding the extent that SE can benefit from AI, educators might have more difficulty seeing AI for sustainability teaching and learning, which might be related to AI training levels, or with some kind of user resistance [8, 23].

When asked if AI in SE can enhance educational outcomes, develop sustainable solutions, and prepare students for future challenges, educators from different disciplines had distinct perspectives. Business faculty respondents expressed predominant optimism about AI's potential in these domains. Conversely, arts and communications educators acknowledged possible benefits while highlighting persistent implementation challenges. Natural and health sciences faculty emphasized the need for further longitudinal research to validate AI's efficacy, whereas engineering and mathematics instructors demonstrated the most robust confidence in AI's tangible benefits for SE. These findings underscore that while AI adoption holds cross-disciplinary promise, its integration requires field-specific approaches to address pedagogical and operational considerations.

Although most of the educators could not provide an example of successful SE using AI, 23 answers were received with different implemented projects, and they are compiled into five categories in Table 5. This diverse sample demonstrates the several ways that AI can be applied for SE as well as the exploratory nature of most

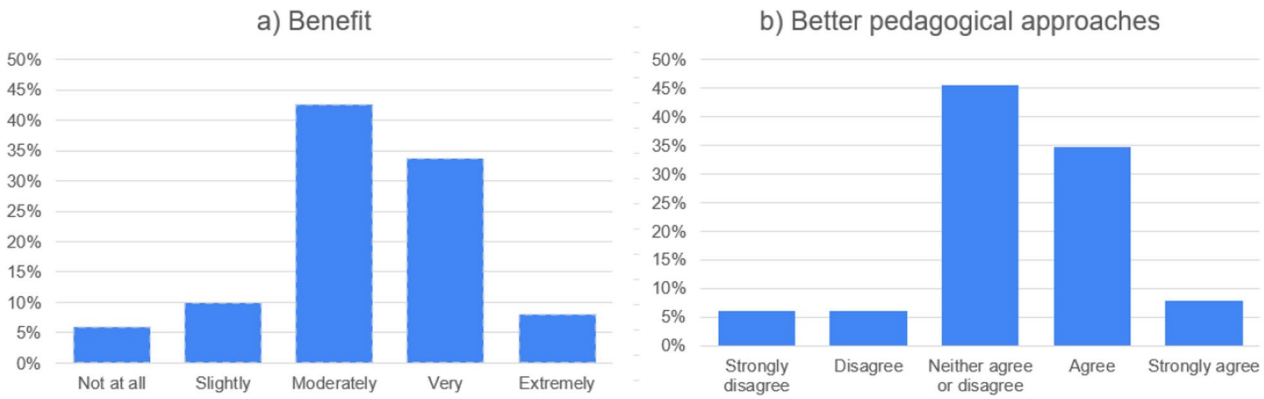

Fig. 7 The impacts of AI on sustainability teaching and education. **a** The benefit. **b** Development of better pedagogical approaches. Source: The authors

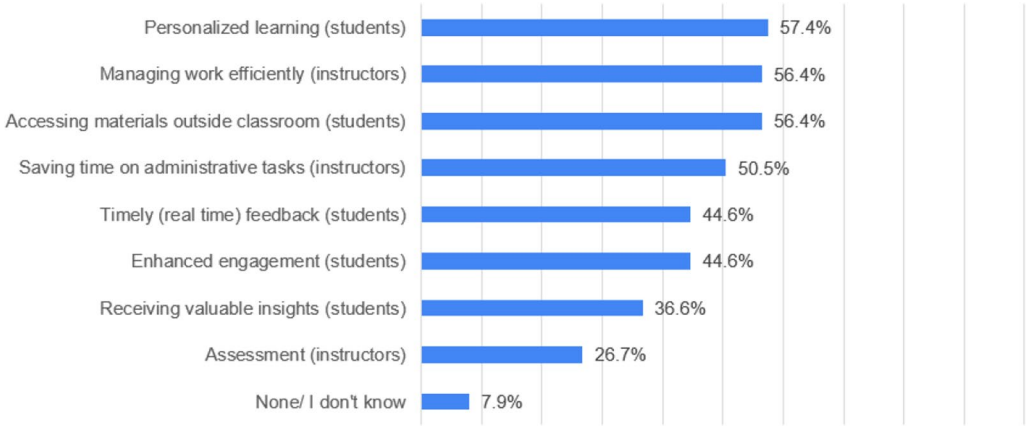

Fig. 8 Potential drivers for AI in sustainable education in HEIs. Source: The authors

Table 5 Examples of sustainable education with AI Source: The authors

Categories	Examples
Content review and generation	Case studies elaboration; create assessment exercises; design posters
Robots	Social robots that interact with students asking questions about sustainability; robots fighting challenge; conversational robot that answers student's questions
Data analysis	Modeling results from studies; learning spatial data analysis
Sustainable data monitoring	Tracking environmental footprint of modern life; AI applications in monitoring water quality; AI-powered energy management to analyze usage, predict consumption, and optimize distribution
Discussion of AI role	Assigned large case studies with short notice for skill development and discussion about the limitations; compare AI and traditional search methods for debate preparation

initiatives that might be related to the novelty and the ongoing adoption by institutions and educators.

Lastly, the educators were invited to share some comments, insights, or ideas about teaching sustainability using AI. Most of them cited the novelty and the ongoing phenomenon that is AI, emphasizing that more training is still needed to uncover its full potential. Among the comments, there were some excited opinions that consider AI "the future of learning" that "offer immersive learning" and that "there should be collaboration between those working with AI, those interested in sustainability, and those skilled in education." Nevertheless, some educators demonstrated skepticism and even pessimism with AI, considering "the worries for the intellectual properties of the shared knowledge" and are "fearful that AI will lead to a further erosion of critical thinking." Even so, one educator translated the mixed feelings, saying "the train has left the station, and we have to help our students find a way to use it."

Although it might seem misplaced to analyze a technology that is rapidly changing with a variety of tools being developed, it is believed that presenting and discussing the suggestions and the ideas that are being explored in different countries might contribute to a foundation for more adequate and secure application development [53].

Conclusions

This paper aimed to explore how AI can transform educational practices, particularly its role in personalized learning experiences, data analysis, and modeling complex systems. To achieve this, a mixed-methods approach, combining quantitative and qualitative methods, was employed. First, an analysis of 20 case studies from universities worldwide were chosen to examine trends in AI applications. Additionally, to identify the challenges, experiences, and trends faced by educators in using AI to teach sustainability, a survey was conducted with 101 educators from various disciplines in HEIs globally.

The results of the case study analysis revealed AI's significant role in education for SD from multiple perspectives. Researchers highlighted the importance of machine learning in providing fast, accurate solutions for assessing student behavior and performance [25] as well as its potential to revolutionize educational paradigms in addressing social and environmental issues [26]. However, the study also underscored the complexity of

integrating AI into digital learning environments, emphasizing the need for responsible and transparent use [18].

Regarding the survey of HEI faculty, the findings indicated that educators were not entirely confident that AI tools would play a central role in this transformation. In fact, over 45% expressed indifference when asked about AI's ability to enhance pedagogical approaches related to SD, such as the SDGs and Environmental, Social, and Governance (ESG). Nonetheless, many educators acknowledged AI's potential to assist students in real-time research and improve sustainable teaching by 2030, aligning with findings from other studies [1]. Despite its growing usage, the researchers stressed that further training is needed to fully harness AI's potential in education.

Another relevant finding of the survey was that although most educators were unable to provide an example of successful SE using AI, 23 responses were identified with different projects implemented and were structured into five categories: Content Review and Generation, Robots, Data Analysis, Sustainable Data Monitoring, and Discussion of AI's Role. This sample demonstrates the various ways in which AI can be applied to SE as well as the exploratory nature of most initiatives. This may be related to the novelty and continued adoption by institutions and educators.

Similar to other research, this paper has certain limitations, particularly regarding the selection of case studies (which may not be fully representative) and the small sample of survey respondents (also not entirely representative). In addition, a further limitation is posed by the restrictions in the validity due to non-probabilistic sampling and a certain level of bias in the case study due to the need to focus on some key areas. Also, the limited duration of the data collection in the survey is a further limitation. In a rapidly evolving field like AI, the paper reflects the situation at the time the research was conducted, in the first half of 2024, and cannot account for any developments that have occurred since.

Despite these limitations, the paper offers relevant contributions and analysis on the use of AI in SE and its application to personalized learning experiences in HEIs. Also, the fact that it has involved respondents from 45 countries makes this study one of the most comprehensive ones on the subject matter of AI and higher education undertaken to date. Moreover, it presents the perspectives of education professionals on the role of AI in teaching and learning, highlighting its potential as a powerful tool for implementing the UN SDGs and enhancing SE in the future.

Overall, the integration of AI in SE has the potential to enhance the learning experience by providing personalized instruction, facilitating interactive simulations, and enabling data-driven insights that deepen students' understanding of complex environmental issues. In addition, AI tools can increase student engagement and motivation through personalized learning paths and real-time feedback, fostering a more interactive and immersive educational environment that encourages critical thinking and problem-solving.

While promising, the use of AI in SE requires ongoing research to explore best practices, potential challenges, and the ethical implications of AI technologies in educational settings. The integration of AI in SE presents ethical challenges that need to be addressed. One major concern is data privacy as AI systems collect and analyze vast amounts of student data, raising risks of misuse or breaches. Transparency is another issue—AI-driven tools often operate as "black boxes," making it difficult for educators and learners to understand decision-making processes, which can undermine trust. Bias in AI algorithms is a further key issue. If AI models are trained on biased data, they may reinforce stereotypes or exclude marginalized perspectives in sustainability discussions. Additionally, over-reliance on AI could reduce critical thinking and human interaction, essential for holistic SE. There are also concerns about accessibility and equity, as AI-powered tools may favor privileged institutions, widening the digital divide. Furthermore, the environmental cost of running large AI models contradicts sustainability goals unless powered by renewable energy. To mitigate these issues, educators must ensure ethical AI use by prioritizing transparency, inclusivity, and accountability. Policies should mandate unbiased algorithms, data protection, and equitable access, ensuring AI enhances—rather than undermines—SE. Future research should also explore how AI technologies may contribute to making SE more accessible to diverse populations, addressing barriers for students with disabilities and creating equitable learning opportunities for all.

Abbreviations

AI	Artificial intelligence
SE	Sustainability education
SD	Sustainable development
MOOCs	Massive open online courses
SDGs	Sustainable Development Goals
HEIs	Higher education institutions
WoS	Web of Science
DEI	Diversity, equity, and inclusion
CE	Circular economy
CSR	Corporate social responsibility
ESG	Environmental, social, and governance
PRME	Principles for Responsible Management Education

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Author contributions
Walter Leal Filho: conceptualization, methodology, writing—original draft, writing—review and editing, supervision. Eundeok Kim: investigation, formal analysis, visualization, writing—original draft, writing—review and editing, project management. Jaluza Maria Lima Silva Borsatto: conceptualization, investigation, formal analysis, writing—original draft, writing—review and editing. Carla Bonato Marcolin: data curation, investigation, formal analysis, visualization, writing—original draft, writing—review and editing.

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Data availability
The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
In line with German rules, an ethical approval was not required for the survey, since it entails no personal or critical data. Informed consent was obtained from all individual participants included in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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