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Exploring sustainability accounting education in the digital era with sustainability leadership as a moderating factor using a two-stage approach PLS-SEM–ANN

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Abstract
This study aims to investigate the interrelationships among digital literacy, AI adoption, institutional image, social innovation, and sustainability accounting education in Chinese higher education institutions. Study's framework was developed by integrating Technology Acceptance Model (TAM), Diffusion of Innovations (DOI) theory, and the Institutional Theory to guide analysing research factors. Two-stage analytical approach was employed - Partial Least Squares Structural Equation Modelling (PLS-SEM) followed by Artificial Neural Network (ANN) approach. Research data were collected through distributing 500 questionnaires, of which 375 valid responses, comprising 75% response. Findings revealed that digital literacy promotes critical connection with sustainability challenges, AI adoption improves personalized learning opportunities and access to real-time environmental data. Universities with a sustainability-oriented image are more likely to entrench sustainability principles into their curricula. Social innovation, promoting collaboration and participatory learning, is perceived as a key player in facilitating sustainability education. Moreover, sustainability leadership is a significant competency that aids in facilitating the responsible integration of technology with sustainability principles. This study provides both theoretical and practical insights for Higher Education Institutions seeking to enhance sustainability education, in addition it contributes to further technological and institutional environment knowledge to shape sustainability education.

Keywords Sustainability accounting education, Digital literacy, AI adoption, Institutional image, Social innovation, Least squares structural equation, Artificial neural approach

Discover

1 Introduction

Due to the Fervent trends towards sustainability, CSR and ESG, a paradigm shifts within the accounting education domain became evident [1, 2]. An increasing demand for sustainability professionals is obvious as businesses and financial institutions have incorporated sustainability throughout various aspects of their operations. This indicates the edge to shift current accounting education towards digital literacy competency, artificial intelligence (AI) adoption, institutionalizing the image and related social innovation that are key in reshaping the current educational regimes [3, 4]. notes that currently the obstacle holding students back from adopting digitalisation in institutions is the lack of effective incorporation of the evolving sustainability accounting context throughout teaching delivery and assessment process, systems should be more reductive, not particularly reductive rather than collaboratively sustaining students in the portability and flexibility of their delivery through scholarships and engaging research [5].

In spite of the increased recognition regarding the need for digital transformation, still various significant gaps exist. First, thorough research in the context of digital literacy and AI adoption in the sustainability accounting education field has to be conducted, with taking into consideration sustainably training a technology-savvy workforce, fulfilling financial sector's current demands [6, 7]. Second, Universities and educational institutions image is increasingly acknowledged as a major factor in driving students' interest and trust in sustainability-oriented curricula [8], yet an evident absence of empirical studies assessing the relationship between institutional perception and positive sustainability education-related outcomes exist [9]. Thirdly, although a detailed exploration throughout the business and management literature regarding the social innovation and institution's ability to generate novel solutions to sustainability problems exist, its influence on sustainability education practices remains significantly unaddressed [10, 11].

Additionally, sustainability leadership plays a critical role in promoting and sustaining learning environments that leads to developing a sustainability-oriented learning outcome [12]. However, an evident insufficiency in examining the moderating effect of sustainability leadership on integrating digital competencies into sustainability accounting education exist. Unlike researches pertaining leadership effects on the level of faculty engagement, and curriculum integration for digital learning tools reactive students, yet limited empirical studies investigated the moderations of leadership in regards to digital literacy with AI adoption, Institutional image along with the social innovation in sustainability education [13].

This study adds up to the literature in several important ways. First, this research integrates digital transformation education with sustainability accounting education through providing a detailed relationships between digital literacy, AI adoption, institutional image, social innovation and learning outcomes. Second, it examines the moderating effect of sustainability leadership on those relationshis with providing an empirical insight into the role of leadership climate in digitalizing the sustainability curricula. Thirdly, applying a two-stage analytical procedure in this research including the partial Least Squares Structural Equation Modelling (PLS-SEM) for hypotheses testing, and Artificial Neural Network (ANN) analysis to conduct predictive modelling. Employing such hybrid method allows both theory testing through PLS-SEM and robust non-linear prediction through ANN providing a deeper understanding of the variable relationships. Lastly, the study delivers actionable insights for policymakers, educators, and industry practitioners, empowering them with means to harmonize sustainability education with digital progress.

This paper is structured in the following sequence: Next section includes a presentation of the theoretical framework and hypothesis development. Followed by the research methodology section describing the data collection process, in addition to a formal explanation of the PLS-SEM and ANN approach. Results and their implications are then discussed, followed by a discussing the theoretical and practical contributions. Finally, recommendations for future research are provided.

2 Literature review and hypothesis development

Examining the role of Digital Literacy and AI Adoption for sustainability education and leadership can be obtained through various theoretical perspectives. Among these theoretical frameworks is the Technology Acceptance Model (TAM) which is used for illustrating the factors that influence the acceptance of new technologies by individuals, and may parallel the paradigm shift in adopting digital tools, including AI-driven applications, for educational purposes [14]. More specifically, this model underlines the significance of both the perceived usefulness and the perceived ease of use, which can influence sustainability leadership meeting the digital literacy. The Technology Acceptance Model (TAM) can be effectively employed for explaining adapting the digital tool micro-processes of education. Both ease of use perception (for example, user-friendly interfaces of the AI) and usefulness perception (for instance, improving teaching outcomes towards sustainability) provide a key role in clarifying digital tools acceptance and utilization by teachers and students in sustainability accounting education. Other theories can also aid in this context, this includes the Diffusion of Innovations (DOI) Theory which provides a multi-level perspective regarding innovation adaptation, including AI adoption [15, 16], DOI (1) explains how such innovations are diffused across organizations and/or communities and (2) examines diffusion mechanisms such as communication channels, social networks, and perceived innovation benefits. Evaluating how AI quality and digital literacy are integrated within the education system to impact sustainability behaviours can be obtained through utilizing this framework. DOI Theory contributes efficiently by framing innovation adaptation on both the systemic and organizational levels. It examines how innovations such digital technologies and AI spread throughout educational institutions along the communication channels, people networks, in addition to the perceived benefits. Framing such diffusion are influenced by the relative benefits of digital technologies and institutional readiness for sustainability literacy. Finally, in reference to the Institutional Theory [17], this research can aid in understanding how a larger institutional environment influences the digital technologies adoption and social innovations in education. Institutional Theory provides a macro perspective, especially emphasising on how adapting digital tools and institutionalizing within education is influenced by institutional regulation, pressures, and norms. Ensure curricula updates by institutions can be obtained through normative pressures to comply with international sustainability goals, for instance, pressures of regulation towards sustainability. Institutional theory provides a framework to explain how AI and digital literacy become institutionalized in educational settings through observing how certain institutions develop their image, and how the pressure of regulations and norms creates a well-established practice. Combining all the motioned provides a multi-dimensional vision about understanding the educational leadership robotics, and the means to utilizing it to get long lasting results. In the following process [18], a link is established among digitalizatio, sustainable outcomes, organizational leadership and cooperation. In this context, sustainability leadership guidance is not limited to internal acceptance, but extends to ensure external world's involvement as well, thereby taking forward institutionalization and effective digital literacy programs in sustainability accounting education.

2.1 Digital literacy and sustainability accounting education

Combining digital literacy with sustainability accounting education, aids in delivering an innovative approach to handle current diverse issues [19]. in this context, digital literacy training enhances people ability and skills in working with and evluating digital resources effectively, yet sustainability accounting education teaches them about environmental stewardship and sustainable behavior [20]. These two domains interact together in creating a comprehinsive framework which enables people to work on emerging digital related sustainability matters [21]. Individuals possessing both digital skills and sustainability knowledge are tend to be more creative in delivering innovative solutions for environmental problems. People skilled with Digital literacy master utilizing new technology, learn data analysis and develop capabilities to handle sustainability-based projects. Recently daily life became dominated by digitalization; hence digital literacy is a key when it comes to taking a meaningful role in societies [22]. Through Digital literacy training people gain the needes capability to move through digital spaces securely, while developing critique and maximizing technology resources for learning and self-improvement purposes [23]. The Diffusion of Innovations (DOI) [24] framework provides aid in analyzing how adapting digital literacy as an innovation of education within the higher education systems, and how it's used to facilitate sustainability education. DOI Theory provides several factors that affects innovations' adoption: knowledge, persuasion, decision, implementation, and confirmation. all mentioned factors depend on communications channels, social systems, and innovation features perception such as their relative advantage, compatibility, and complexity.

Through sustainability accounting education digital literacy provides users with the required capabilities access worldwide sustainability discourse and provides improved information about environmental concerns, while providing digital platforms for sustainable behavior development. Digital literacy functions as an fundamental requirement for improving sustainability education creating environmental awarnace among society [20]. The following set of assumptions emerges from the previously mentioned information.

H1 Digital literacy has a positive effect on sustainability accounting education.

2.2 AI adoption and sustainability accounting education

Among the significant theoretical framework used to understand artificial intelligence technologies adoption in educational environments is the technology acceptance model (TAM) [14]. TAM states two main factors: perceived usefulness and perceived ease of use, which plays the key role in influencing users' behavior towards technology adoption and their usage intention. In sustainability accounting education, artificial intelligence is perceived to be useful as it: facilitates accessing real-time environmental information, aids in modeling sustainable activities (such as energy use and waste management), and encourages diverse backgrounds students' involvement through personalized learning experiences.

Artificial intelligence technology are beneficial to modern schools' as it serves as a tool to changes teaching methods successfully and improves students' achievements [25]. Using artificial intelligence in sustainability accounting education improves students' knowledge and behavior towards environmental matters, as it creates opportunities to add data-based learnings and customized instruction [26]. AI-powered learning systems help educational institutions in educating its students about challenging sustainability topics while providing them with the fundamental thinking methods required in handling environmental and social problems [27]. From different points of view, sustainability accounting education benefits from artificial intelligence integration. AI helps teachers and learners get quick access to environmental data allowing them to discover current trends in designing sustainable solutions [28]. Systems offered by AI such the smart simulation tools and smart tutoring teaches students how to handle climate change and manage resources through implementing practical sustainability methods [26]. AI facilitates sustainability accounting education to provide support to students with diverse backgrounds through personalized learning making these lessons available and enabling more students to engage regardless of their background [29]. Creating sustainable practices in higher educational institutions can be achieved through using AI technology as it aids in optimizing resources usage and running intelligent campus operations. Universities worldwide use AI in designing energy-efficient programs, manage their waste, and build sustainable plans to achieve sustainability targets [27]. The new developments provide evidence on how AI education helps organizations achieve sustainability goals.

H2 AI Adoption has a positive effect on sustainability accounting education.

2.3 Institutional image and sustainability accounting education

Sustainability accounting education advancement in higher education institutions (HEIs) is recently considered significantly important topic. Through conducting research activities alongside teaching functions and institutional practices, higher education institutions act as knowledge hubs and as accelerators of sustainable development [26]. Universities' institutional image which is a component of their reputation along with values and sustainability dedication helps directing educational results through merging sustainability principles with both operational structures and academic courses. University's credibility can be achieved through a strong institutional image, enabling better promotion of sustainability accounting education and successful faculty members recruitment, students as well as relevant stakeholders who support sustainability values [26].

Institutional Theory, as illustrsated by [17], States that normative, mimetic, and coercive pressures of surrounding environment play a role in influencing organizations. In higher education institutions, stakeholders, including government, accreditation agencies, students, faculty, and the public, create a pressure resulting from the increasing demand for visible and legitimate commitments towards sustainability. Foregrounding sustainability allows universities to address and interact with such pressures and demands while garnering the required support for curriculum redesign, cross-disciplinary cooperation, and the adoption of sustainability-oriented pedagogical practices. Organizational perception of ethical and social responsibility activities usually defines institutional image according to [30]. Universities can strengthen their institutional image through promoting sustainability initiatives such as green policy implementations, sustainable research development, and strategic social responsibility objectives [31].

Favorable reputation enables universities implementing sustainability accounting education through both their academic curricula and institutional value system. Such universities seek increased student involvement in sustainability modules, and faculty members adoption of sustainability materials, while obtaining external funding through their positive institutional reputation and image [32]. Universities characterized by strong sustainability-oriented image serve as role models, promoting both academic innovation and broader societal transformation. Institutions pace in adapting sustainability accounting education is mainly determined by stakeholders depending on their perception of genuine sustainable practice commitment at the institution [33]. University with robust sustainability profiles effectively use their sustainable reputation to build new policies while encouraging cross-disciplinary teamwork and redesigning educational practices [31]. Institutions promoting sustainable education tend to extensively leverage their institutional image to shape the way sustainability accounting education is received and put into practice. Therefore, this study hypothesizes that:

H3 Institutional image has a positive effect on sustainability accounting education.

2.4 Social innovation and sustainability accounting education

The key significance of innovation for improving sustainability stands confirmed by current scientific investigations. Educational sustainability development benefits from innovative educational methods, varied learning activities, and modified curriculum designs [34]. Digital storytelling is an educational tool that was established to help students learn digital literacy [35]. local wisdom approaches serve in the favor of educational outcomes benefit through reinforcing innovative teaching methods to create a better adapted learning spaces in their context [36]. Despite the moderating effects of technological resources availability, technology acts as a critical enabler in this process [37].

Sustainability accounting education advancement depends heavily on innovation because it plays a key role in developing students' creative tendencies, along with analytical abilities and problem-solving competencies [38]. Modern innovative changes in educational systems require signeficant modernization of curricula and skills development addressing complex sustainability problems [39]. Sustainability accounting education and innovation covergance relays on two essential matters, maintaining sustainable processes, and applying innovative practices for sustainable educational development [40]. Still higher education literature suffers a scarcity of resources addressing sustainability alternatives through creativity [41]. Nowadays a global understanding regarding the vital role of innovative approaches toward sustainability, resulting in various strategies implementation to merge sustainability into both academic and operational procedures [36]. An essential aspect of sustainability-focused development is social innovation, providing fresh approaches to social processes, collaborative student learning, and local community-based solutions for environmental issues [42]. Social innovation creates environments that support participatory engagement, interdisciplinary collaboration, and knowledge-sharing as it serves as an enabler of successful implementation of sustainability accounting education throughout university curricula [43]. Complying with Institutional Theory, universities are becoming more responsive to both normative and social pressures, requiring teaching programs and business approaches to the include sustainability related matters [17]. Universities can effectively respond to the pressures through applying the social innovation approach through adopting innovative paradigms and pedagogic approaches that respond to the changing environment, in addition to societa and technology requirements. Sustainability discourse in universities can be demonstrated through lecturers adopting a socially innovative teaching methods for dissemination across their curricula [36]. The following hypotheses presented based on the previously mentioned information.

H4 Social innovation has a positive effect on sustainability accounting education.

2.5 The moderating role of sustainability leadership

The leadership approach for sustainability works to reinforce constructive relationships among organizational images, digital capabilities, social development initiatives, and environmental teaching methods. Institutions with strong sustainability leadership show better ability to merge strategic vision and resource allocation decisions along with sustainability objectives which delivers an enhanced institutional image impacting related educational results [25]. Positive institutional representations which emerge through sustainability-focused branding along with ethical operations work to boost stakeholder confidence and attracts valuable sources of resources [44]. Establishing sustainable values that are intrinsic to organizational culture by Sustainability leaders leads institutions to deliver sustainable outcomes [45]. Digital literacy and its aspects is considered a key player in sustainability accounting education because it's the main source that provides students with required technological kills to handle sustainability issues. Digital literacy stands insufficient for successful sustainability accounting education unless schools practice sustainability leadership. Sustainability-emphasizing leaders will guide digital literacy programs to pursue sustainable objectives by guaranteeing effective usage of digital tools for environmental and social issue management [45].

Strategic support of leaders makes AI adoption in education more successful, as such support advocates ethical AI usage while linking technological integration to sustainability targets [46]. Leadership functions to deploy AI tools through equitable distribution so they resolve social and environmental problems and promote educational results [31]. institutions Stance towards sustainability defines how students and other stakeholders view them [47]. Portraying a solid sustainability leads to attracting students who prefer sustainability related studies. strategic alignment between goals and educational outcomes achieved by leadership results in translating of institutional image into a practical learning experience [48]. Sustainability accounting education becomes more powerful when leaders use power to embed such education into their institutional plans.

Nowadays educational curricula incorporate social innovation as an approach to devise new solutions that tackle societal problems [49]. Effective leadership is crucial for sustainable innovation model as such leadership creates a culture of sustainability-oriented innovation as educational success cannot be guaranteed in standalone institutions [32]. Through a robust sustainability leadership approach an assurance can be provided that social innovation projects remain dedicated to supporting sustainable learning initiatives. The positive role of sustainability leadership benefits the relationships between institutional image and digital literacy, in addition to social innovation and sustainability accounting education. Introducing sustainability leaders generates an organizational climate that maximizes the effectiveness of these elements, influencing sustainability accounting education [50]. Figure 1 shows the framework of this study.

For the purpose of explaining the theoretical mechanisms among the relationships between our conceptual framework (Fig. 1), well-known theories were employed throughout the study, the Technology Acceptance Model (TAM), Diffusion of Innovations (DOI) Theory, and Institutional Theory. Among the aspects of sustainability accounting education, digital literacy is considered to be the most fundamental that equips the learners with the ability for critically accessing, processing, and judging digital information on ESG issues. Digital literacy enhances learners' skill in interpreting complex sustainability information in addition to its application within the accounting contexts, resulting in an improved analytical and decision-making judgments. This complies with TAM in which being part of the learning activity and user acceptance relies on the ease of usage and the perceived utility of digital technologies. Additional contributory factor towards sustainability education is AI Utilization, bringing forth the aspects of learning experiences personalization, information real-time analysis inclusion as well as automated feedback loops. AI technologies facilitate learners' access through simulation, as well as scenario-based uses of sustainability accounting, enhancement of high-order thinking and practical problem-solving. According to DOI Theory such innovations tend to get adopted in case they have a relatively high advantages as well as compatible with current systems. Institutional image also determines the extent of sustainability accounting education. Universities with sustainability-oriented image will tend to amalgamate significant sustainability aspect into its academic and administrative systems. According to Institutional Theory, such legitimacy pressures prompt incorporating sustainability education into curricula, conditioning the priorities of the faculty members, in addition to setting learners' expectation. Sustainability accounting

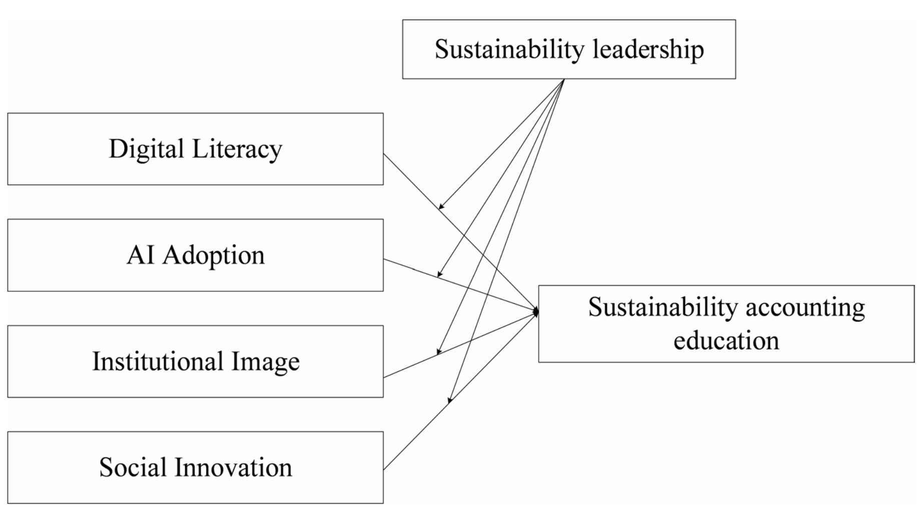

Fig. 1 Framework Proposed

education is facilitated by social innovation, through providing interdisciplinary, participatory, as well as community-centred learning approaches. It smooths collaborative problem-solving, as well as practicality of sustainability topics within accounting programs. Social innovation brings up real life sustainability problems into the classroom, resulting in enhanced course learning outcomes and cultivating social responsibility. Institutional sustainability leadership is a fundamental moderating factor that is expressed in digital literacy levels, AI implementation, institutional brand building, and social innovation. Leadership facilitates aligning strategic learning outcomes with institutional goals and sustainability programs for the purpose of providing stable learning environment for enabling the cultivation of sustainability accounting education. Institutionalizing sustainability within teaching and learning can be achieved through encouraging initiatives, revising resources, and institution building .

3 Methodology

This study employs a quantitative survey approach with a cross-sectional research design for data collection. The sample consists of faculty and staff from higher education institutions (HEIs) in China, encompassing both public and private institutions. As a result of conditions related to accessibility and available participant volition, convenience sampling was implemented. Academic networks and institutional channels were used to distrebute 500 questionnaires, 375 valid responses were received, representing 75% response. Research participants were approached from various Chinese geographical areas, including eastern, central, and western parts, including educational institutions as research universities, teaching colleges, and specialized centers. The relevancy of research scope was achieved through participant selection criteria of faculty members and administrative staff, who functioned among digital transformation and sustainability education programs. Minimal non-response bias was Validated through statistical evaluation as a comparison between early and late respondents on major demographic factors was conducted and indicated no significant differences at a $p > 0.05$. While random sampling was impossible the collected sample data represents a diverse range of China's higher education sector thus providing major findings regarding digital era sustainability accounting education. G*Power software was used to determine the sample size, recommending a minimum sample of 160 participants [51]. Additionally, according to [52], a larger sample size was obtained (384) assuring more accurate representation of the targeted population. As of June 20, 2024, there are 3,117 HEIs in China (excluding Hong Kong, Macau, and Taiwan).

3.1 Instrument development

The measurement instruments applied in this study were adapted from previous research with similar design, related specific items and sources listed in Table 1. This tool includes couple of sections involving demographics questionnaire items and study variables. The demographic part includes respondent background questions inquiring about age, educational attainment, occupational history, and work duration. Research measurement items are in the second part. Sustainability accounting education was obtained from [53], while Digital literacy was obtained from [54]. The measurement items for institution image and social innovation were adapted from [55, 56], respectively. Sustainability leadership items were taken from [55], while artificial intelligence

Table 1 Measurement model results

Variables		FL	CA	CR	AVE
Sustainability accounting education Shwedeh et al., [53]					
1	The institution implements sustainability ideas throughout accounting instruction to improve academic value and student learning achievements.	0.863	0.810	0.837	0.719
2	The educational pathway for accounting at my educational organization establishes both enduring academic results and extended planning capabilities.	0.776			
3	The education funding at my institution works specifically to improve sustainable learning practices in accounting.	0.801			
4	The instructional programming for accounting at my educational establishment features modules about responsible environmental practices as well as sustainable financial operations.	0.826			
5	Accounting courses at the institution dedicate significant focus to sustainability-related matters, including ethical accounting practices and social responsibility.	0.751			
6	Students receive education about financial sustainability from my institution so they can develop responsibility in their decision-making.	0.851			
7	The ethical aspects and sustainability challenges related to our accounting education, along with AI performance risks in financial technologies, have become part of my awareness.	0.876			
Digital literacy Kabakus et al., [54]					
1	My technical knowledge enables me to tackle my own ICT problems.	0.846	0.757	0.881	0.553
2	Learning new digital technologies proves simple for me.	0.816			
3	I maintain active awareness of essential new digital technologies that emerge.	0.874			
4	I have extensive knowledge about numerous digital technologies.	0.831			
5	I have mastered all technical abilities required to work with digital technologies and develop artifacts, including documents, reports, and presentations that reflect my acquired knowledge.	0.801			
6	Applications that display my comprehension of acquired knowledge serve as demonstration tools.	0.859			
Institution Image Kaushal et al., [56]					
1	Students can have a successful education at this institution.	0.804	0.916	0.937	0.749
2	The university provides students with access to numerous educational choices.	0.779			
3	This university has a good atmosphere	0.855			
4	The community views the University positively because of its good reputation.	0.830			
5	The institution presents itself better than all competing educational establishments.	0.753			
Social innovation Eustachio et al., [55]					
1	The educational organization expands community life quality through its provision of social support services.	0.870	0.798	0.851	0.652
2	The educational institution seeks solutions that establish social transformation along with political reforms in society.	0.889			
3	The educational institution creates innovative training methods that facilitate community members' capacity for innovation.	0.874			
4	The educational institution implements modern technologies to address problems and develop social solutions.	0.878			
5	The institutional programs of my higher education facility pursue initiatives for enhancing social participation, together with cultural cooperation in society.	0.882			
6	The educational institution implements fresh concepts that produce societal worth and boosts societal effectiveness.	0.866			
7	The educational institution seeks opportunities to transform social rules and standards.	0.886			
Sustainability Leadership Eustachio et al., [55]					

Table 1 (continued)

Variables		FL	CA	CR	AVE
1	The leadership of my educational institution maintains social responsibility within sustainable practices.	0.811	0.845	0.829	0.712
2	The leadership at my HEI conducts sustainability practices that protect both the environment and society.	0.817			
3	Heat Education Institution achieves sustainability together with ethical responsibility in its leadership efforts.	0.799			
4	The leadership of my HEI bases its decisions on considerations throughout the whole organization.	0.823			
5	Official acknowledgement of sustainability-related mistakes occurs from the management at my HEI.	0.805			
6	The leaders at my HEI show readiness to address sustainability-related mistakes that occur.	0.829			
7	The leadership at my HEI makes efforts to adopt distinct novel approaches.	0.869			
8	The leadership of my HEI institution places organizational purpose above financial benefits and cost reduction measures.	0.835			
9	Your HEI leadership performs a balanced approach that integrates economic and environmental, and social responsibilities.	0.841			
10	The sustainable approach of my HEI leadership includes its continuous operation through every transformational phase.	0.859			
11	Leadership at my HEI actively addresses sustainability issues about staff welfare.	0.847			
12	The leadership at my Higher Education Institution informs every party about sustainability decisions.	0.853			
13	The HEI leadership builds a culture that emphasizes sustainability through active communication methods.	0.865			
AI Adopting Shwedeh et al., [53]					
1	AI technologies integrated in our institution have produced better operational results and administrative processes.	0.789	0.854	0.724	0.630
2	Students found AI-powered chatbots together with virtual assistants helpful for improving their satisfaction regarding administrative support services and student assistance when interacting with administrative staff.	0.741			
3	The implementation of AI technologies shaped your academic achievements and academic achievement results as an educational participant.	0.851			
4	I believe AI-powered predictive analytics was effective in identifying at-risk students and facilitating interventions to improve student retention rates.	0.765			
5	The faculty at my institution shows mastery when applying AI technologies to their academic teaching approaches and educational content development methods.	0.813			
6	I believe that the institution demonstrates ethical concern during both the drafting and implementation phases for AI technologies in the university educational framework.	0.723			
7	The institution provides me with straightforward access to its AI-powered tools that help my learning and research activities	0.832			
8	The university provides instruction about AI technologies and platforms for educational development to its students.				
9	The exposure of staff to AI technologies occurs through training conducted for staff development purposes.				

was adopted from [53]. the questionnaire was examined and improved by five experts, together with three academic managers who ensured research quality, within the given research environment. The pilot study provided results validating the constructs' reliability as Cronbach's alpha values exceeded 0.7. Since the questions were obtained from English studies, translation experts were approached for translating the questions to the Chinese language as a first step. In the second step, the translated questioner was checked by academics to ensure linguistic and academic consistency. Finaly, in order to ensure the accuracy of the translation, back-translation procedure was used to verify survey's linguistic consistency [37]. All constructs were measured using a five-point Likert scale ranging from "strongly disagree" (1) to "strongly agree" (5).

Demographic characteristics of respondents were 53.33% females and 46.67% were males. In terms of age distribution, 19.47% were 25 years old or younger, 43.73% were aged 26–35, 29.07% were aged 36–55, and 7.73% were 55 or above. In terms of occupational roles and academic positions, 20.53% were administrative personnel, 50.67% were lecturers or below, 20.00% were associate professors, and 8.80% were full professors. To test the research hypotheses and examine the causal relationships between independent and dependent variables, this study employs the partial least squares structural equation modeling (PLS-SEM) technique, with all analyses conducted using Smart-PLS 4.0 software.

4 Results and findings

This study employs the PLS-SEM approach and utilizes Smart PLS 4 software for data analysis and further presentation and interpretation of research findings. PLS-SEM is extensively employed in social science research due to its capacity to estimate all model parameters simultaneously, making it especially effective for analyzing complex models [57]. Previous empirical studies that have employed this method typically follow a two-step evaluation process, consisting of measurement model evaluation and structural model evaluation [58, 59]. Examine the reliability and validity of constructs is assessed through the measurement model assessment, whereas the structural model evaluation tests the hypothesized causal relationships between exogenous and endogenous variables [60–62].

4.1 Measurement model analysis

In this study, an evaluation of the measurement model, as a reflective construct, is conducted to ensure data quality and model robustness by assessing indicator reliability, internal consistency reliability, convergent validity, and discriminant validity [62]. Indicator reliability is determined using factor loadings, with a recommended threshold of 0.70, indicating that each indicator adequately represents its respective construct [63]. Internal consistency reliability is assessed through Cronbach's Alpha and Composite Reliability (CR), both of which should exceed 0.70 to demonstrate satisfactory reliability [62]. Convergent validity is evaluated based on the average variance extracted (AVE), where a value greater than 0.50 confirms that each construct explains more than 50% of the variance in its associated indicators, thereby supporting its ability to accurately measure latent variables.

Measurement model evaluation results, presented in Table 1, indicate that all factor loadings exceed the recommended threshold of 0.70, implying strong relationships between indicators and their respective constructs. Additionally, high internal consistency is confirmed as all constructs exhibiting CR values above 0.70, while AVE values exceed 0.50, indicating that each construct captures a substantial proportion of variance in its indicators. Collectively, these findings confirm that the measurement model satisfies the necessary reliability and validity criteria, ensuring its robustness for subsequent structural model analysis.

Table 2 Heterotrait-monotrait ratio (HTMT) result

	AI	DL	II	SI	SE	SL
AI Adopting						
Digital Literacy	0.222					
Institution Image	0.239	0.554				
Social Innovation	0.352	0.609	0.28			
Sustainability Leadership	0.194	0.731	0.307	0.553		
Sustainability accounting education	0.353	0.513	0.366	0.443	0.467	

Table 3 Structural model results

Path	St. Beta	St. Error	T-value	*P*-value	Confidence Interval		VIF	f^2	R^2	Q^2	Result
					LB	UB					
H1) DL > SE	0.245	0.056	4.352	0.000	0.079	0.109	1.215	0.283			Supported
H2) AI > SE	0.103	0.051	2.023	0.044	0.154	0.371	1.659	0.122	0.282	0.228	Supported
H3) II > SE	0.150	0.070	2.141	0.033	0.071	0.328	1.264	0.124			Supported
H4) SI > SE	0.204	0.066	3.099	0.002	0.098	0.295	1.417	0.072			Supported

AI: AI Adopting; DL: Digital Literacy; II: Institution Image; SI: Social Innovation; SE: Sustainability accounting education; SL: Sustainability Leadership; LB: lower of the confidence interval; UB: Upper

Furthermore, discriminant validity is assessed to verify that constructs are conceptually distinct. The heterotrait-monotrait (HTMT) ratio is widely recognized as a more rigorous evaluation criterion, with an acceptable threshold of HTMT < 0.85 [64]. As reported in Table 2, all HTMT values remain below this threshold, further substantiating the distinctiveness of the constructs and validating their appropriateness for structural model evaluation.

4.2 Structural model analysis

After a successful validation of the measurement model, the structural model is assessed through multiple criterias ensuring its robustness and explanatory power. Examining potential collinearity is considered one of the primary evaluations issues using the variance inflation factor (VIF). A VIF value below 3.0 indicates the absence of multicollinearity concerns, ensuring that predictor variables do not exhibit high intercorrelations [62]. Additionally, the effect size (f^2) is evaluated to determine the relative contribution of each predictor variable to the outcome variable in the structural equation model. According to [65], size effects are categorized as small ($0.02 \le f^2 < 0.15$), medium ($0.15 \le f^2 < 0.35$), and large ($f^2 \ge 0.35$).

The results presented in Table 3 confirm that all VIF values are below 3.0, indicating no collinearity issues among predicted variables. AI has a significant positive effect on SE (H1) (St. Beta = 0.103; T = 2.023; $P < 0.05$), with a small effect size ($f^2 = 0.122$). Similarly, DL significantly influences SE (H2) (St. Beta = 0.245; T = 4.352; $P < 0.05$), with a moderate effect size ($f^2 = 0.283$). II also exhibits a significant positive relationship with SE (H3) (St. Beta = 0.150; T = 2.141; $P < 0.05$), with a small effect size ($f^2 = 0.124$), while SI significantly influences SE (H4) (St. Beta = 0.204; T = 3.099; $P < 0.05$), though with a relatively smaller size effect ($f^2 = 0.072$). Moreover, as the confidence intervals for all paths do not include zero, these results confirm that the relationships are statistically significant. Therefore, all direct path hypotheses (H1, H2, H3, and H4) are supported, indicating that AI, DL, II, and SI are key determinants of SE.

To further assess the predictive relevance of the structural model, two key indicators are considered: R^2 and Q^2. R^2 measures the proportion of variance in the endogenous variable explained by exogenous predictors, thereby evaluating the explanatory power of the model. R^2 values of 0.02, 0.13, and 0.26 indicate weak, moderate, and substantial explanatory power [65]. Meanwhile, Q^2 assesses the predictive relevance of the model for endogenous latent variables, with Q^2 values of 0, 0.25, and 0.50 representing small, medium, and large predictive accuracy, respectively [62]. As shown in Table 3, the R^2 value for SE is 0.282, indicating substantial explanatory power, while the Q^2 value of 0.228 reflects moderate predictive relevance.

4.3 Moderation analysis

The moderating effect of SL on the relationships between AI, DL, II, SI, and SE was analyzed using the bootstrapping procedure, as presented in Table 4. The results indicate that SL has a significant moderating effect on most of the hypothesized relationships (H5, H6, and H7), except for the relationship between SI and SE (H8). Specifically, H5 (SL × AI > SE) is supported, with a significant positive interaction effect (St. Beta = 0.152; T = 2.500; $P < 0.05$), suggesting that SL enhances the impact of AI on SE. Similarly, H6 (SL × DL > SE) is supported, demonstrating a positive moderating effect (St. Beta = 0.110; T = 2.326; $P < 0.05$), indicating that SL strengthens the relationship between DL and SE. The findings for H7 (SL × II > SE) also supported (St. Beta = 0.067; T = 2.167; $P < 0.05$), confirming that SL positively moderates the relationship between II and SE. However, for H8 (SL × SI > SE), the results reveal that SL does not significantly moderate the relationship between SI and SE. Although the effect remains positive (St. Beta = 0.043; T = 0.897; $P > 0.05$), it is not statistically significant, leading to the rejection of H8. Moreover, the confidence interval for this relationship includes zero (-0.213 to 0.144), further reinforcing the conclusion that SI does not significantly interact with SL to influence SE. Overall, these findings underscore the pivotal role of SL in moderating the relationships between AI, DL, II, and SE, while indicating that SI does not have a significant moderating effect within the context of sustainability accounting education. The reasons behind that can be referred to the perceived idea that social innovation tend to be fueled by citizen action, collaborations networks, and bottom-up movements. As a moderating influence, leadership is not considered as main factor, being in more institutionalized ventures, digital literacy and the uptake of AI are tended to correspond more to institutional top-down leadership. Social innovation is more tendent to take place naturally in a decentered manner such shift is more driven by people and collective actions, seeming to oppose leadership interventions. In addition, and referring to the most current evidence by [66], that examines the influence of government support on technology-knowledge pathways

Table 4 Moderation analysis results

Hypothesis and path	St. Beta	St. Error	T-value	*P*-value	Confidence Interval		Result
					LB	UB	
H5: SL x DL > SE	0.110	0.047	2.326	0.020	0.132	0.052	Supported
H6: SL x AI > SE	0.152	0.061	2.500	0.013	0.157	0.045	Supported
H7: SL x II > SE	0.067	0.031	2.167	0.031	0.132	0.160	Supported
H8: SL x SI > SE	0.043	0.048	0.897	0.370	-0.213	0.144	Not

AI: AI Adopting; DL: Digital Literacy; II: Institution Image; SI: Social Innovation; SE: Sustainability accounting education; SL: Sustainability Leadership in green entrepreneurial activity, concluding that environment support infrastructure is significant for social innovation success. Drawing on their argument that innovation success is influenced by government or institutional support, proposed that in order to achieve success, other forms of support for social innovation may be required, such include resources from the community, collaborations with outsiders, or institutional arrangements for innovation support in education rather than leadership.

4.4 Artificial neural network (ANN)

Applying Analytical procedure that integrates PLS-SEM and ANN in the study is due to the sustainability accounting education research methodological constraints and theoretical requirements during the recent digital era. Applying PLS-SEM in the first stage as a provider of effective validation for the theoretical constructs, beside identifying the linear relationships within this compensatory model framework. The compensatory model logic behind behavioral analysis is supported in this method as it allows offsetting the construct degrade caused by one of the variables by construct improvement brought by another one [67]. PLS-SEM provides a robust test of causal relationships among the inherent constructs including digital literacy and AI adoption along with sustainability leadership while obtaining the needed theory verification.

Human interaction analysis is required in complex decision-making processes in the field of sustainability accounting education as non-linear and non-compensatory relational patterns are demonstrated by variables. In the second stage ANN becomes part of the analysis to give confidence to the findings obtained through PLS-SEM. Versatility in detecting linear and non-linear relationships is demonstrated through the artificial neural network as it operates data-driven non-parametric operations that mimic human brain neural network processes. Analysis differences between ANN and PLS-SEM is due to the lack of predefined functional structure which permits detecting intricate behavioral relationships.

For the purpose of implementing the ANN model we used the feed-forward back-propagation neural network structure with multilayer perceptron (MLP) topology. A multilayer perceptron consisting of three layers known as input, hidden and output that maintains a network connection between each neuron the operating between adjacent layers. Classification throughout a three layers neural network involves a sigmoid activation function in the hidden section and a linear activation function in the output section, helping to predict continuous values. ANN parameter optimization included a grid search method, utilizing a k-fold cross-validation to find the best combination of learning rate, number of hidden neurons, and optimal epochs to minimize prediction error.

Uncovering models' essential causal relationships and evaluating intricate interactions between factors of sustainability leadership and digital transformation is achieved through the usage of PLS-SEM along with artificial neural networks for theoretical validation, and providing the base for predicting different educational outcomes.

The training process enables ANNs to learn in a similar manner our brain does until information is encoded into synaptic weights [68]. For continuous correction the activation function determines the updated weights and creates a difference between actual output and desired results. ANN technique is applicable in accounting research [69], management research [70], as well as tourism research [71]. ANNs compute neuronal outputs by adding all stimulations produced by the input vector x. Each simple neural network connection receives weight Wji which establishes a relationship between input component i and hidden layer neuron- j while weight Vkj exists to join hidden layer neuron- j to the output layer neuron- k. Each true input value required multiplication between the neuron output and the weight of every input. The weighted calculation that produces the j-th hidden neuron output follows Eq. (1) and Eq. (2).

$$net_j^h = \sum {}_{i=1}^{N} Wjix_i \text{ and } Y_i = f\left(net_j^h\right) \quad (1)$$

For the k-th output neuron:

$$net_k^0 = \sum {}_{j=1}^{J+1} V_{kj}y_j \text{ and } o_k = f\left(net_k^0\right) \quad (2)$$

The sigmoid function responds to the λ , parameter in the third equation for slope control. Under the training procedure the output o_k, emerges as the target value for each neuron d_k when processing particular input patterns. The adjustment of weights will occur after error reduction to move onto the next pattern. Weight adjustment formula Eq. The weight calculation for the output layer weights V occurs in Formula (4) whereas weight adjustment Eq. (5) determines W for the hidden layers. The calculations for weights W at the hidden level will be performed through Eq. (5). The ideal output value that neuron k produces when presented with pattern p is denoted as o_{pk} while the actual output value of neuron k is represented by o_{pk}. This strategy utilizes Eq. The weight adjustment functions run through a continuous process which adjusts all weights to minimize the sum square of error [72].

$$f(\text{ net }) = \frac{1}{1 + e^{-\lambda\, net}} \quad (3)$$

$$V_{kj}(t+1) = v_{kj}(t) + c\lambda\ (d_k - o_k)\, o_k\,(1 - o_k)\, y_i(t) \quad (4)$$

$$W_{ji}(t+1) = W_{ji}(t) + c\lambda^{\,2} y_j\,(1 - y_j)\, x_i(t)\left(\sum {}_{k=1}^{k}\ (d_k - o_k)\, o_k\,(1 - o_k)\, V_{kj}\right) \quad (5)$$

$$SSE = \frac{1}{2P}\sum {}_{p=1}^{p} \sum {}_{k=1}^{k} \left(d_{pk} - o_{pk}\right)^2 \quad (6)$$

The research utilized SPSS v27 version to perform ANN assessment [73]. points out that ANN and PLS-SEM share similar traits because they both remain applicable even when multivariate assumptions of linearity and normality fail to materialize. This study executed its prediction through multilayer perceptron's equipped with "feed-forward back-propagation" algorithm procedures using PLS path analysis significant predictors as its input neural network components. The model serves as the preferred choice due to its worldwide acceptance in research at this level. Both the output and hidden layers utilized the sigmoid activation function during their activation process. Table 5 displays the multiplies ten values of RMSE.

The classification technique provides insight into the relevance of these four attributes being, Digital Literacy, AI Adopting, Institution Image, Social Innovation, in relation to Sustainability Accounting Education, as indicated in Table 6. The findings reveal that Social Innovation is the most influential category and has the highest mean relative importance (0.425) and normalized importance (100%), demonstrating a prominent role in advancing sustainability-oriented education. This means that incorporating

Table 5 Artificial neural network values.

Neural Net Work	Training			Testing			
	N	SSE	RMSE	N	SSE	RMSE	Total (N)
Input: AI adoption, digital literacy, institution image, social innovation							
Output: Sustainability accounting education							
1	338	468.77	0.447	38	59.88	0.58	376
2	338	401.79	0.41	38	50.84	0.53	376
3	332	471.16	0.49	44	62.28	0.48	376
4	327	446.82	0.45	49	76.56	0.57	376
5	341	509.26	0.54	35	47.37	0.43	376
6	334	447.20	0.45	42	69.75	0.48	376
7	339	564.90	0.58	37	62.39	0.62	376
8	331	472.26	0.48	45	62.43	0.47	376
9	339	517.64	0.51	37	60.56	0.51	376
10	335	441.77	0.45	40	57.98	0.45	375

Table 6 Relative importance

Neural net work	Sustainability accounting education			
	Digital Literacy	AI Adopting	Institution Image	Social Innovation
1	0.151	0.279	0.219	0.351
2	0.212	0.227	0.225	0.336
3	0.208	0.242	0.26	0.29
4	0.204	0.217	0.223	0.356
5	0.195	0.22	0.256	0.328
6	0.197	0.191	0.217	0.395
7	0.218	0.306	0.148	0.327
8	0.222	0.209	0.249	0.320
9	0.244	0.167	0.26	0.329
10	0.233	0.215	0.216	0.337
Mean relative importance	0.116	0.192	0.267	0.425
Normalized importance	27.20%	45.10%	62.90%	100.00%

innovative social practices augments the learning framework and is in line with sustainable goals. The next most important predictor is the AI Adopting category, with a mean relative importance of 0.267, meaning 62.90% of normalized importance, highlighting the increasing role AI has played in automating accounting tasks, improving decision-making, and driving digital transformation in education. Digital Literacy stands with 45.10% normalized importance score with a mean relative important score of 0.192, making it of moderate significance in supporting the AI adoption and sustainability practices. The finding mentioned above states that Social Innovation is the most influential, highlights the urge for innovative, socially active, and collaborative means toward sustainability accounting education evolution. Defining social innovation is typically made through terms of participatory processes, locally oriented programs, interdisciplinarity, and pedagogical innovation, all aligning with sustainability education visions. These methods enables an active learner engagement and encourage a practice-oriented learning culture along with local applicability.

However, such relatively low placing indicates that institutional investment in AI driven services may be bridging the gaps in learners' digital literacy. On the other hand, Institution Image having the least impact, with a mean relative importance of 0.116 (27.20% normalized importance). Strong institutional reputation may aid in attracting quality students and faculty, though limited direct impact on sustainability accounting education compared to other factors. Such low significance of institutional Image (27.20%) indicates that regardless of its involvement in institutions' reputation, it may not affect the learning experiences of the sustainability accounting education students directly. Its indirect impact exists, perhaps reflects on the overall institutional policies rather than individual learning outcomes. Curriculum content, teaching methods, and experiential learning demonstrated through variables such as social innovation seems to have more direct involvement. in addition, students may not associate institutional image with taught material in the classrooms, resulting in a decreased perception of its applicability.

Figure 2 shows the ANN independent model of four crucial independent variables (Digital Literacy (DL), AI Adopting (AI), Institution Image (II) and, Social Innovation (SI)) contributing to a dependent variable of Sustainability Accounting Education (SE). The structure has an input layer, a single hidden layer with two neurons (H(1:1) and H(1:2)), and an output layer. Inflation of the input and hidden layers occurs when a bias node is added to improve model generalizability by shifting activation thresholds. A tanh activation function is used for the hidden layer, which transforms the values anywhere between -1 and 1, enabling the model to learn more complex, non-linear relationships between the input factors. Positive and negative synaptic weights (gray and blue) suggest when drivers positively associate with sustainability accounting education and when they could potentially inhibit progress by balancing with other influences. The final output of each neuron is a direct multiplication sum of the hidden layer outputs, because it uses an identity activation function, which is conventional for regression-based ANN models. The established architecture indicates that education of sustainability accounting is affected via direct and indirect relationships, where, the appropriate layer is considered to be hidden to facilitate the impact. These weightings suggest that

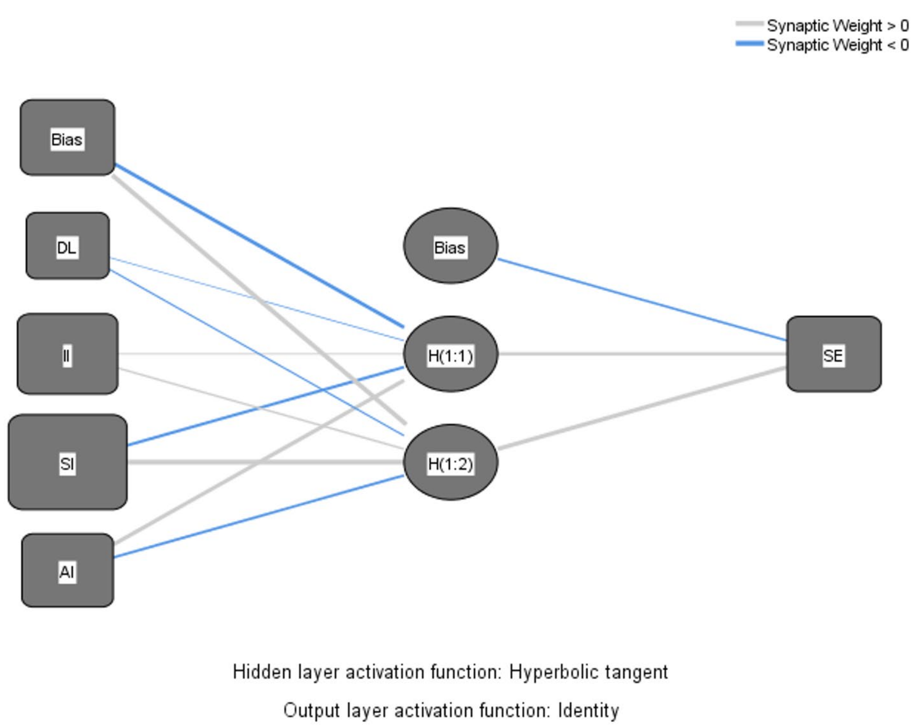

Fig. 2 ANN model

Table 7 Parameter estimates

Predictor		Predicted		
		Hidden Layer 1		Output Layer
		H (1:1)	H (1:2)	Sustainability accounting education
Input Layer	(Bias)	−0.735	1.304	
	Digital Literacy	−0.036	−0.284	
	AI Adopting	0.832	0.480	
	Social Innovation	0.247	0.363	
	Institution Image	−0.535	1.332	
Hidden Layer 1	(Bias)			−0.462
	H (1:1)			0.724
	H (1:2)			1.204

some factors, like social innovation and AI adoption, may be more significant than others. In summary, this ANN model represents the links among technical and institutional factors with regard to education on sustainability.

The parameter estimates of the ANN model predicting Sustainability Accounting Education, as illustrated to be notably influenced by Digital Literacy, AI Adopting, Social Innovation, and Institution Image, with two hidden neurons (H(1:1) and H(1:2)) that ableled adjusting the output based on given inputs which can be connected to the illustrated examples in Table 7. Also, the bias terms at both input(−0.735) and hidden(−0.462) layers are interesting, as such bias for the one in between input(1.304) and hidden layer implies strong encouragement for input with large values. These values point out the essentially required adjustments before learning patterns from the given dataset. Among the input variables AI Adopting shows the most substantial positive contribution (0.832 with respect to H(1:1) and 0.480 for H(1:2)), assuring its strong relevancy in the field of sustainability accounting education. Social Innovation also contributes positively (0.247 and 0.363), emphasizing its significance. On the other hand, Digital Literacy appears to negatively affect both neurons (-0.036 and −0.284), impaling that within the given circumstances it contributes indirectly, or is mediated by other variables. Clearly, Institution Image being negative for H(1:1) (-0.535) implies varied effects as well showing weak negative weight, while showing importance for H(1:2) (1.332) which can be referred to the possibility of interactive role existence that simply cannot be captured using linear impact of institution image. In the output layer, the H(1:1) contribution is 0.724 and that of H(1:2) is 1.204, which indicates capturing higher relationship by the second hidden neuron. These results designate the existence of a significant nonlinear interaction effect, especially between AI adoption and institutions' reputation in addition to campus-based innovation that provides predictions regarding sustainability accounting education. These findings imply that, although AI adoption and social innovation have the key role in this process, a context-relative role is displayed by institutional image, and criticality of digital literacy regardless of not having a significant impact on sustainability education outcomes, in the absence of AI supportive integration.

5 Discussion and implications

Multidimensional Relationships between Digital Literacy, the Adoption of Artificial Intelligence, Institutional Image of Sustainability, and Social Innovation: Findings from Accounting Education. Being significant, these outcomes comply with recognizable theoretical models (e.g., Technology Acceptance Model [TAM], Diffusion of Innovations [DOI] Theory, and Institutional Theory) providing a profound understanding about sustainability education that recently spread among higher education institutions (HEIs).

Our findings contribute to the literature in three ways. Alignment with earlier research findings [19–21] that reinforce the idea that digital literacy promotes a critical view of digital resources, which encourages individuals' participation in sustainability conversation and global sustainability movements. The Technology Acceptance Model (TAM) [14], is a relevant framework for observing this relationship, as both perceived usefulness and perceived ease of using digital tools may influence their adoption for educational purposes. These findings indicate that the integration of digital literacy with sustainability learning outcomes could improve students' potential to engage with environmental issues constructively.

Second, Sustainability accounting education was positively influenced by AI adoption, affirming the previous studies [25, 26]. Leveraging AI, learning systems can be designed to meet personalised educational needs, while real-time access to environmental data fosters and builds sustainable analytical skills. These results are consistent with DOI Theory [24], which describes the diffusion of technological innovations in terms of their perceived benefits, communication channels, and social networks. It is therefore imperative that institutions prioritize ethical and strategic deployment of AI tools to help to enhance sustainability education, and further ensuring that AI adoption is aligned with goals for environmental and social responsibility [27].

Third, as a key aspect in promoting sustainability accounting education, the institutional image was revealed to be significantly important. In this sense, universities with a sustainability-oriented reputation are more likely to integrate sustainability principles into their curricula, which aids in attracting sustainability-conscious stakeholders and implement green policies [26, 32]. Institutional Theory [17] supports these findings, in arguing that institutional legitimacy shapes organizational behaviour. Thus, HEIs should transform their institutional image to provide a robust education on sustainability by incorporating sustainability values to their academic and operational frameworks.

Fourth, similar to [34] and [35], we found that social innovation is a key enabler of sustainability accounting education. Social innovation (SI) promotes inter-disciplinary collaboration, participatory learning, and community-based environmental solutions, which adds up to the impact of sustainability education [42]. Recent innovation and sustainability interaction corresponds to studies that highlight the urge to modernize curricula and adopt innovative learning methods [36, 38]. This is why universities should also developed teaching policies that require faculty members to introduce and engage in innovative teaching methods, and social innovation projects throughout their sustainability education delivery.

Lastly, the moderating role of sustainability leadership moderates the relationships between digital literacy, AI adoption, institutional image, social innovation, and sustainability accounting education. The role of digital capabilities, technology integration, and institutional strategies in sustainability education can be augmented by sustainable leadership [45, 46]. Strong sustainability leadership at institutions will guide strategic efforts to translate the advances provided by AI, promote the importance of digital literacy, and align institutions' operations with sustainability principles [47, 50, 74].

Practically, this research brings forth a range of solid measures that HEIs could adhere to for reinforcing sustainability accounting education. University leaders should adapt a strategic approach towards sustainability education, among such strategies integrating AI technologies into accounting programs is crucial. AI various technologies, for instant AI-powered learning analytics platforms (e.g., IBM Watson Education, Century Tech) can be utilized in personalizing individual students learning experiences, tracking students' sustainability competencies accumulation, with real-time feedback availability throughout the process. Additionally, natural language processing (NLP) tools similar to ChatGPT or Grammarly can be used to aid students in analysing sustainability reports and developing sustainability-related communication skills [75].

Administrators need to inject more investments into education programs related to institutional digital literacy, such investment can guarantee developing the fundamental skills required to effectively work with digital and AI tools among both instructors and learners. Such digital literacy can be attained through either integrating the related education into the general education curricula or by offering it as part of professional development activities. in addition, a well-established institutional sustainability reputation can be realized through green campus projects, sustainability reporting, and high-profile collaborations with sustainable organizations, which will result in attracting environmentally and socially responsible learners and further legitimate stakeholders' institution relationship. Professors are the key plays in pedagogical methods transformation. In order to facilitate experiential learning in sustainability accounting they should adopt AI-powered simulation software such as climate impact simulators, or carbon accounting software. In addition, sustainability accounting education requires faculty members to develop interdisciplinary assignments, through which interdisciplinary collaboration with numerous departments such as environmental science, computer science, or public policy, to point out the intersection between technology and sustainability.

Moreover, encouraging academic staff to amalgamate social innovation projects into sustainability related courses as community green projects or service-learning projects for local sustainability challenges is significant. Not only does this boost students' applied learning process but also contributes to fostering civic action and interdisciplinarity. Staff development initiatives should motivate creative pedagogical methodologies, as well as the establishment of open educational resources that address sustainability challenges, through utalizing digital technologies. Revising and reforming higher education standards used to accrediting educational bodies and institutes to reflect AI and digital skills as a crucial part of sustainability accounting education curricula. Policies should facilitate a national guideline development that will encourage the ethical AI adoption in education that focus on equity, openness, and sustainability goals.

Policymakers should encourage developing collaborative sustainability projects by universities through establishing incentives and financing funds, building sustainability education labs, and reflecting sustainability assessments as a component of the national education assessments. Incentives should also address HEIs and private tech companies' collaborations in co-designing sustainability learning tools and platforms.

Furthermore, Students should be both encouraged and enabled to develop and demonstrate competences in various AI areas and data literacy as a vital part of their core accounting courses. Their exposure to employ Power BI, Tableau, and Python is vital, whether through analysing sustainability information, or learning how to critically evaluate ESG footprints business decisions'. In addition, creating a change-makers mentality among students can be achieved through encouraging them to establish peer-organized sustainability clubs, hackathons, and social media campaigns, that harness various means like social innovations and digital technologies to resolve local or international sustainability challenges. Further mentorship support from tech entrepreneurs or sustainability innovators is substantial for ensuring students' entrepreneurship and activism in the sustainability economy.

6 Conclusion

This study was conducted to investigate the multidimensional associations of digital literacy, AI adoption, institutional image, social innovation, and sustainability accounting education. It aimed to explore the interconnections among these elements for the purpose of providing an insight about how they can operate together to promote sustainability education in Chinees higher education institutions (HEIs). It focused on the influence of digital literacy, AI adoption and institutions' sustainability-oriented image on sustainability education (targeting accounting curricula), and how social innovation can enable this process.

This research found that the students' digital literacy empowered them to address sustainability with all its related aspects more critically. Sustainability education is positively impacted by AI technologies offering the technicalities of personalized learning experiences and facilitating access to real-time environmental data. Moreover, those institutions with high sustainable profiles were more disposed to embracing sustainability principles through their curriculum and attract sustainability-minded members. In addition, social innovation took the key role in facilitating interdisciplinary working and for participatory learning, which are essential for delivering higher education for sustainability. Finally, utilizing sustainability leadership as a moderator among these relationships due to its role in helping institutions to strategically adapt digital tools, AI, and sustainability values into their educational frameworks.

These findings have practical implications for HEIs that intend improving sustainability education. Institutions must focus on digital literacy programs, adopt AI technologies strategically, and bolster their sustainability-oriented image. Furthermore, innovating teaching itself and implementing community projects that foster social innovation will aid in improving sustainability education quality. The significance of the study lies at both theoretical and practical levels, adding to the body of knowledge on sustainability education through highlighting the role of these three factors (adoption of technology, and institutional factors) in determining sustainability education outcomes, as well as providing important insights into how HEIs can harmonize their educational activities with global sustainability objectives.

However, this research also has limitations. Generalizing the findings to other context or field may be bonded as the study was based on a small sample size. Although this article focused on the sustainability education within the accounting discipline, other academic disciplines within HEIs may also have different dynamics. These aspects can be considered in future studies by addressing different schools of study and broaden the sample to encompass a wider mix of institutions. In addition, further research should be directed towards exploring longitudinal designs in an effort to grasp the chronology of digital literacy, the adoption of AI, and institutional practice, and their role in influencing the outcomes of sustainability education. Lastly, the used context-specific sample in this research, which focuses only on Chinese HEIs, limits generalizing the findings towards other areas or education systems. China-specific cultural, institutional, and technological characteristics are peculiar, forming their influence on the observed patterns in ways that might differ in other nations. Future work should aim for cross-cultural or multi-country comparative designs that mitigate such patterns to generalize results across other education and socio-economic contexts.

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Availability of data and materials
Data are available on request due to privacy/ethical restrictions.

Declarations

Ethics approval and consent to participate
This study was conducted according to the guidelines of the Declaration of Helsinki and was approved by the Deanship of Scientific Research Ethical Committee, Middle East University.

Informed consent
All participants involved in this study provided informed consent to participate prior to participation.

Competing interests
The authors declare no competing interests.

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