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Harnessing outdoor learning in primary science education: impact on developing technological innovations for waste management and sustainability awareness

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Sustainability education in primary schools is often dominated by classroom-based and theoretical instruction, which limits students' sustainability awareness and their ability to develop practical technological solutions to real-world environmental problems, particularly in waste management. This study explores the impact of outdoor learning programs in fostering sustainability awareness and encouraging technological innovations in waste management among elementary school students. Conducted at a "Self-managed Waste Village," the research integrates experiential learning with problem-based activities, focusing on students' direct engagement with authentic environmental challenges. Using a quantitative research design, data were collected from 299 students through sustainability awareness questionnaires and rubrics for evaluating technological products. Structural Equation Modeling (SEM) was employed to examine direct and mediating relationships among outdoor learning, sustainability awareness, and technological innovation. The results indicate that outdoor learning is positively associated with students' sustainability awareness and shows a significant relationship with their technological innovation outcomes. Sustainability awareness is also significantly related to students' ability to design innovative waste management solutions, with outdoor learning acting as a mediating factor in this relationship. These findings highlight the potential role of outdoor learning as a pedagogical approach associated with the development of sustainability awareness and technological creativity in primary science education.

KEYWORDS

outdoor learning, primary science education, sustainability awareness, technological innovation, waste management

1 Introduction

In the global context, sustainability awareness has become a crucial element in ensuring the continuity of human life and the environment (Urbaniak et al., 2024; Saraiva et al., 2019). Sustainability awareness not only encompasses an understanding of the importance of preserving natural resources but also includes the moral and intellectual drive to take concrete actions in addressing environmental challenges (Howell, 2021). In the context of waste management in primary education, sustainability awareness can be understood through three interrelated dimensions: knowledge, attitudes, and behavior. Knowledge enables students to recognize waste-related problems and understand basic principles such as waste reduction, reuse, and recycling; attitudes reflect students' sense of responsibility and concern toward environmental issues; while behavioral tendencies relate to students' willingness to engage in concrete actions, such as waste sorting and participation in local waste management practices. Education serves as one of the primary instruments for fostering this awareness, with the hope that the younger generation will not merely be spectators in environmental issues but active agents of change (Mahariya et al., 2023). Ideally, students should understand their responsibility in sustainability, possess the skills to create innovations, and be willing to take on roles in seeking solutions.

However, the reality on the ground reveals significant barriers. Studies indicate that students' level of sustainability awareness remains at a concerning level (Huckle and Wals, 2015). Many students have a superficial understanding of environmental issues, lacking the ability to analyze problems in depth or develop relevant solutions. Furthermore, the teaching methods employed in schools are often theoretical and fail to provide space for exploration and practical application. Preliminary studies in several elementary schools show that lessons on waste issues are often limited to classroom discussions without direct implementation (Brotosusilo et al., 2022; Cheng et al., 2022; Gugssa, 2023; O'Malley and Pierce, 2023). Recent empirical studies have similarly reported limited student engagement in authentic waste management practices, particularly in primary education settings where hands-on and community-based learning opportunities remain scarce (Valenzuela et al., 2018; Lloyd and Gray, 2014). As a result, students do not perceive the relevance of the learning to real-life situations, let alone develop the skills to create technological innovations as solutions. This problem becomes even more complex in areas with chronic waste management issues, such as regions lacking adequate waste management infrastructure. On the other hand, the potential for student involvement in creating technology-based solutions is often overlooked. Yet, technological innovations developed by students, even if simple, can have a significant environmental and social impact (Cui et al., 2022). For instance, a simple waste sorting tool or a locally-based waste reporting application can serve as an innovative solution while also empowering the community.

To address this issue, this research proposes an outdoor learning program at "A Self-managed Waste Village." It refers to a community-driven initiative where local residents take responsibility for the management of waste within their region. This program is designed to integrate direct learning experiences with efforts to develop technological innovations relevant to local problems. In this program, students are actively involved in the entire process, from problem identification and context analysis to the development of technological prototypes. This process aims not only to enhance students' sustainability awareness but also to encourage them to produce tangible solutions such as organic waste-to-energy conversion tools or simple IoT-based waste monitoring systems. This program offers several advantages that other learning approaches do not. First, this approach positions students as the main actors in the learning process, thereby increasing their sense of responsibility and engagement. Second, the program provides students with opportunities to create and innovate using technology, making learning more relevant to contemporary needs. Third, direct involvement in waste management at this village provides a profound contextual experience, enabling students to see the direct impact of the solutions they create. This is highly relevant in building strong, action-based sustainability awareness (Assaraf and Orion, 2010). While "A Self-managed Waste Village" represents a locally developed and community-driven initiative, it should not be viewed as an isolated or exceptional case. Rather, it reflects a model of grassroots waste management that can be found in various urban and semi-urban contexts, particularly in regions with limited formal waste management infrastructure. Although specific practices may vary across locations, the core principles of community participation, contextual learning, and localized problem-solving are transferable to other educational settings. Therefore, the findings of this study emphasize conceptual transferability rather than statistical generalization.

Previous studies have demonstrated the relevance of outdoor learning in enhancing students' understanding of environmental issues. Rickinson et al. (2004) found that outdoor learning deepens students' understanding of environmental issues through direct experiences that cannot be obtained in the classroom. Kelley and Knowles (2016) highlighted that student involvement in technological development enhances their critical and innovative skills. Additionally, research by Ballard et al. (2024) emphasized that community-based learning approaches can strengthen students' environmental awareness by providing real-world context to their learning. However, few studies have integrated outdoor learning approaches with the development of technology specifically aimed at addressing sustainability issues. Most outdoor learning research tends to focus on cognitive or attitudinal outcomes without examining how experiential learning translates into students' capacity to design concrete technological solutions. Conversely, studies on sustainability-oriented technological innovation often emphasize product outcomes without situating these innovations within authentic, community-based learning environments. As a result, the interaction between outdoor learning, sustainability awareness, and students' technological innovation, particularly in primary education and waste management contexts, remains underexplored. This study identifies a gap in the existing literature. While many studies have discussed the benefits of outdoor learning in enhancing environmental understanding or explored technological innovations for sustainability, few have connected both elements within a single integrated framework. This research seeks to answer the question of how students can use context-based outdoor learning to create technological solutions relevant to local environmental challenges, particularly in waste management. This gap is crucial to address because linking practical experiences with students' innovative abilities can create a greater impact on their sustainability awareness and actions. This gap is crucial to address because existing studies predominantly focus on conceptual understanding or attitudinal outcomes, while empirical evidence linking students' hands-on technological product development with their innovative capabilities and sustainability-oriented actions remains limited. By explicitly connecting practical engineering design experiences with innovation and sustainability awareness, this study offers a novel perspective that extends current research on sustainability education.

This study aims to answer the central question: How can the outdoor learning program enhance students' sustainability awareness through the development of technological innovations relevant to waste management issues? The primary aim of this research is theory testing through model validation, examining the structural relationships among outdoor learning, sustainability awareness, and technological innovation using Structural Equation Modeling (SEM), rather than evaluating the effectiveness of a specific program intervention. Based on the assumptions and exposition presented earlier, this study focuses its investigation on "Harnessing Outdoor Learning in Primary Science Education: Impact on Developing Technological Innovations for Waste Management and Sustainability Awareness".

2 Critical literature analysis

2.1 The linkage between outdoor learning program and sustainability awareness

Sustainability awareness is a critical aspect of 21st-century education, emphasizing the relationship between humans and the environment in the context of ecological, economic, and social sustainability. Outdoor learning programs have proven to be an effective approach in enhancing this awareness through direct and context-based experiences. According to Hills et al. (2024), outdoor learning helps learners understand the relationship between human actions and their environmental impacts, strengthens emotional engagement with ecological issues, and encourages critical reflection. In outdoor learning, students are encouraged to interact directly with natural or constructed environments that represent sustainability challenges. This interaction allows them to experience the dynamics of systems firsthand, such as the water cycle, resource management, and the effects of pollution. Research by Hulaikah et al. (2020) indicates that this experiential approach not only increases ecological awareness but also strengthens sustainability values, including empathy for nature and environmental responsibility. Moreover, outdoor learning is often collaborative, which, according to Zamora-Polo and Sánchez-Martín (2019), fosters the development of sharing attitudes and social solidarity in addressing sustainability issues. This supports the view that experiential learning can cultivate a systemic mindset, an essential element in education for sustainability (UNESCO, 2017b).

> *H1:* Outdoor learning programs have a significant positive direct relationship with the enhancement of students' sustainability awareness.

2.2 The linkage between outdoor learning program and technology innovation for waste management

Technological innovation in waste management is a key solution to addressing environmental problems caused by high waste volumes and low recycling rates. Outdoor learning significantly contributes to stimulating technological innovation through problem-based approaches and creative collaboration. According to Kolb (1984), experiential learning allows students to identify real-world problems in their environment and design innovative solutions through cycles of reflection and active experimentation. Research by Zandvliet (2012) shows that outdoor learning provides a real-world context that encourages students to develop critical and creative thinking skills, both of which are essential in the process of technological innovation. Direct interaction with waste management issues, such as unprocessed waste piles or limited recycling facilities, motivates students to create relevant technology-based solutions, such as waste monitoring applications or Internet of Things (IoT)-based management systems. Furthermore, project-based approaches in outdoor learning facilitate technological mastery, as students are often required to use tools or technological devices in the problem-solving process. McCormick (2004) emphasizes that project-based learning strengthens the integration of interdisciplinary knowledge, which is essential in the development of technological innovations for waste management.

> *H2:* Outdoor learning programs have a significant positive direct relationship with the technological innovations for waste management developed by students.

2.3 The linkage between sustainable awareness and technology innovation for waste management

Sustainability awareness is a key factor in driving the adoption and development of technological innovations for waste management. This awareness encompasses a deep understanding of the environmental impact of human activities and the importance of taking actions that support ecological, social, and economic sustainability (UNESCO, 2017b). In the context of waste management, individuals and communities with high sustainability awareness are more likely to be open to using and developing technologies that support efficient and environmentally friendly waste management. Research by Barth and Michelsen (2013) shows that sustainability awareness motivates the development of innovative technology solutions, such as automated recycling systems, biotechnology for organic waste processing, and digital applications for waste management. Individuals or organizations with sustainability awareness not only understand the need for such technologies but also have the capacity to integrate sustainability principles into their design. Furthermore, Schaltegger and Wagner (2011) assert that sustainability awareness creates market demand that drives technological innovation. For example, growing concern about the impact of single-use plastics has spurred the development of substitute technologies, such as biodegradable materials or more efficient chemical recycling. This research indicates a causal relationship between sustainability awareness and the adoption of technology in waste management. Additionally, the systems-based approach in sustainability literature (Reid, 2019). Technologies designed with sustainability principles can transform how society views and manages waste, thereby promoting more inclusive, efficient, and sustainable management systems (Ajibike et al., 2023).

> *H3:* Sustainability awareness has a significant positive direct relationship with technological innovations for waste management.

2.4 Relationship among outdoor learning program, technology innovation for waste management, and sustainability awareness

The relationship between outdoor learning, sustainability awareness, and technological innovation represents a critical pathway in education for sustainability. Outdoor learning provides students with direct and meaningful experiences in real environmental contexts, allowing them to develop a deeper understanding of sustainability issues related to waste management. Through these experiential learning processes, students' sustainability awareness, encompassing knowledge, attitudes, and behavioral orientations, can be strengthened (Escrig-Olmedo et al., 2019). This heightened sustainability awareness then plays a key role in supporting students' capacity to design and develop technological innovations that address environmental challenges. Previous studies have shown that experiential and project-based learning approaches enhance students' environmental understanding, which subsequently informs their ability to create contextually relevant technological solutions (Wulf, 2010; Karaarslan Semiz and Teksöz, 2024).

> *H4:* Sustainability awareness mediates the relationship between outdoor learning and technological innovations for waste management developed by students.

2.5 The hypothesis model

Keeping in view the literature cited and hypotheses developed in the light of current literature analysis, a research framework was proposed shown in Figure 1.

3 Materials and method

3.1 Research design

This study employs a quantitative design with a cross-sectional approach (Aboussalah et al., 2022). The aim of this research is to determine the impact of the outdoor learning program on sustainability awareness and technological innovation, as well as to examine whether the outdoor learning program can mediate the relationship between sustainability awareness and technological innovation, and to understand the relationships among the variables involved. The primary aim of this research is to examine the structural relationships among outdoor learning, sustainability awareness, and technological innovation in waste management, as well as to test the mediating role of sustainability awareness within this framework. A cross-sectional design was selected because it allows for efficient data collection within a limited timeframe and provides a snapshot of the relationships among the study variables. Prior to data collection, expert validation of the outdoor learning program was conducted to ensure the relevance and clarity of the learning activities and measurement instruments. Following this validation process, Structural Equation Modeling (SEM) was employed to analyze the relationships among outdoor learning, students' sustainability awareness, and technological innovation outcomes. SEM is a multivariate statistical technique that enables the simultaneous examination of relationships among multiple latent and observed variables. However, due to the cross-sectional nature of the data and the absence of temporal sequencing or control groups, the findings of this study should be interpreted as associative rather than causal relationships.

3.2 Sampling

The sample for this study consists of 299 elementary school students who have participated in an outdoor learning program based on technological innovations for waste management. The selection of schools was purposively done, considering several criteria: (1) schools with a high level of student participation in environmental activities, and (2) schools located in areas with significant waste management issues. The study locations include elementary schools in both urban and rural areas to obtain a broader comparison. Although students were drawn from multiple schools, the primary unit of analysis in this study was the individual student. School-level clustering effects were not explicitly modeled, as the focus of the analysis was on student-level relationships within a relatively similar program implementation context. Nevertheless, potential clustering effects are acknowledged as

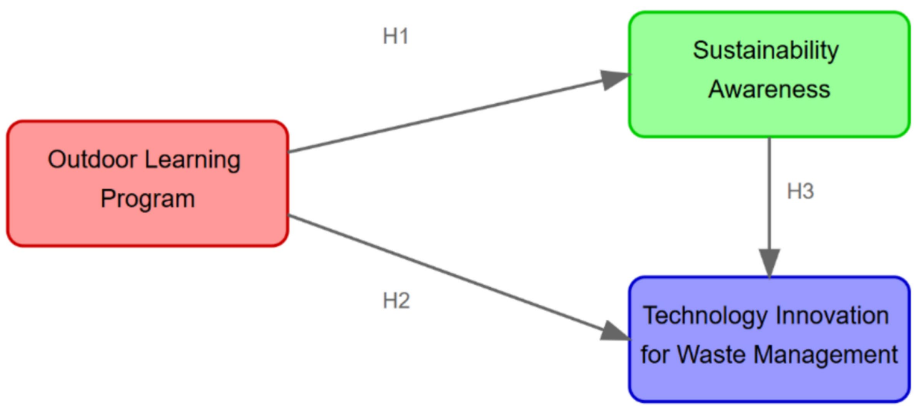

FIGURE 1
The hypothesized model.

a limitation, and future studies are encouraged to apply multilevel or hierarchical modeling to examine school-level influences more explicitly.

3.3 Instruments

The instruments used in this study include a sustainability awareness questionnaire and a rubric for assessing the technological products related to waste management. The sustainability awareness questionnaire consists of 81 statements related to environmental issues and waste management, assessed from the dimensions of knowledge, attitudes, and behaviors. Furthermore, the rubric for assessing technological products is designed to evaluate the outcomes of student projects developed through the outdoor learning process. This instrument aims to assess the quality, innovation, and sustainability of the technological products developed by the students. Assessment is conducted based on predetermined criteria, which are elaborated into specific indicators to ensure objectivity and consistency in evaluation. The aspects and indicators for assessing the waste management technological products are presented in Table 1.

The sustainability awareness questionnaire consists of 81 statements related to waste, pollution, and health, assessed from the aspects and dimensions of sustainability awareness presented in Table 2.

Each sustainability awareness indicator (SA1–SA9) represents a composite score derived from nine questionnaire items. Thus, although the sustainability awareness instrument consists of 81 statements, these items were organized into nine indicator groups based on their conceptual alignment. For the purposes of structural equation modeling (SEM), only the nine aggregated indicators (SA1–SA9) were included in the measurement model. This approach was adopted to reduce model complexity, avoid estimation issues related to an excessive number of indicators, and ensure stable parameter estimation, while still preserving the multidimensional structure of the sustainability awareness construct. The use of composite indicators in SEM is consistent with established methodological

TABLE 1 Technology product innovation construct (T).

No.	Aspect	Indicators
1	Product design	a. Innovation: the extent to which the product demonstrates creative and innovative ideas. b. Aesthetics: assessment of the product's appearance, form, and functionality. c. Practicality: ease of use of the product in the field.
2	Function and effectiveness	a. Functional suitability: the ability of the product to fulfill its primary purpose in waste management. b. Effectiveness: how well the product addresses the identified problem. c. Safety: the product does not pose risks to users or the environment.
3	Sustainability	a. Environmentally friendly materials: use of recyclable or environmentally friendly materials. b. Durability: the product's resilience to long-term use. c. Implementation potential: the possibility of the product being widely adopted in society.
4	Presentation and documentation	a. Communication skills: how students present the ideas, concepts, and advantages of the product. b. Process documentation: completeness and quality of the documentation of the product development process.

Hynes et al. (2011) and UNESCO (2017a).

TABLE 2 Sustainability awareness construct (SA).

Indicator	Indicator description	Dimension	Dimension description
Knowingness	The knowledge possessed by students about environmental, social, and economic dimensions.	Environmental (SA1)	Knowledge possessed by students regarding environmental issues related to waste, pollution, and health.
		Social (SA2)	Knowledge possessed by students regarding social issues related to waste, pollution, and health.
		Economy (SA3)	The knowledge possessed by students regarding economic issues related to waste, pollution, and health.
Attitudes	Positive or negative feelings of students towards the environmental, social, and economic dimensions.	Environmental (SA4)	The positive or negative attitudes held by students toward environmental issues related to waste, pollution, and health.
		Social (SA5)	The positive or negative attitudes held by students toward social issues related to waste, pollution, and health.
		Economy (SA6)	Knowledge possessed by students regarding economic issues related to waste, pollution, and health.
Behavior	The intention or tendency of students to engage in behavior that support or oppose the attitude object in the environmental, social, and economic dimensions.	Environmental (SA7)	Positive or negative feelings students have towards environmental issues related to waste, pollution, and health.
		Social (SA8)	Positive or negative feelings students have towards social issues related to waste, pollution, and health.
		Economy (SA9)	Positive or negative feelings students have towards economic issues related to waste, pollution, and health.

Gericke et al. (2019).

recommendations, particularly when the research focus is on structural relationships rather than item-level measurement.

Outdoor learning (OL) in this study is measured with a focus on the experiential learning method. The outdoor learning variable is assessed using four learning dimensions: concrete experience, reflective observation, abstract conceptualization, and active experimentation.

3.4 Data analysis

Data analysis was conducted using Structural Equation Modeling (SEM) with a covariance-based approach (CB-SEM) to examine the relationships among outdoor learning, sustainability awareness, and technological innovation within the proposed research model. SEM enables the simultaneous examination of measurement models and structural relationships among latent constructs, including both direct and indirect (mediated) effects. The SEM analysis was performed using AMOS software. Model adequacy was evaluated using established goodness-of-fit indices, including the Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA), Goodness-of-Fit Index (GFI), and the chi-square to degrees of freedom ratio (CMIN/df). These indices were used to assess the suitability of both the measurement and structural models prior to hypothesis testing.

The structural model was specified to test the direct effects of outdoor learning on sustainability awareness and technological innovation, as well as the mediating role of sustainability awareness in the relationship between outdoor learning and technological innovation. Mediation effects were examined directly within the SEM framework through the significance of indirect paths, in line with contemporary SEM practices. In addition to SEM, linear regression analyses were conducted as supplementary analyses to provide additional descriptive insights into the relationships among variables and to support the robustness of the SEM findings. Simple regression was used to examine the association between outdoor learning and sustainability awareness, while multiple regression was applied to explore the combined association of outdoor learning and sustainability awareness with technological innovation. These regression analyses were not intended to establish causal inference but to offer results that may be more readily interpretable for educational practitioners.

The quality of technological products was assessed at the group level using a rubric-based evaluation. Products with higher scores were further examined descriptively to identify characteristics associated with innovation quality and sustainability orientation.

4 Results

4.1 Outdoor learning scenario

The outdoor learning scenario was designed as an integrated pedagogical sequence aimed at strengthening students' scientific understanding, technological creativity, and sustainability awareness. The learning flow consists of ten interconnected stages, each contributing to the development of system thinking, sustainability awareness, and the ability to design appropriate waste-management technologies, as seen at Figure 2.

Based on the Figure 2, the learning process began by orienting students to the basic concepts of ESD, providing them with the foundational understanding necessary to interpret environmental phenomena through a sustainability lens. This conceptual grounding was followed by structured thinking exercises that activated prior knowledge, stimulated analytical reasoning, and prepared students to engage more critically with the environmental contexts they would later observe.

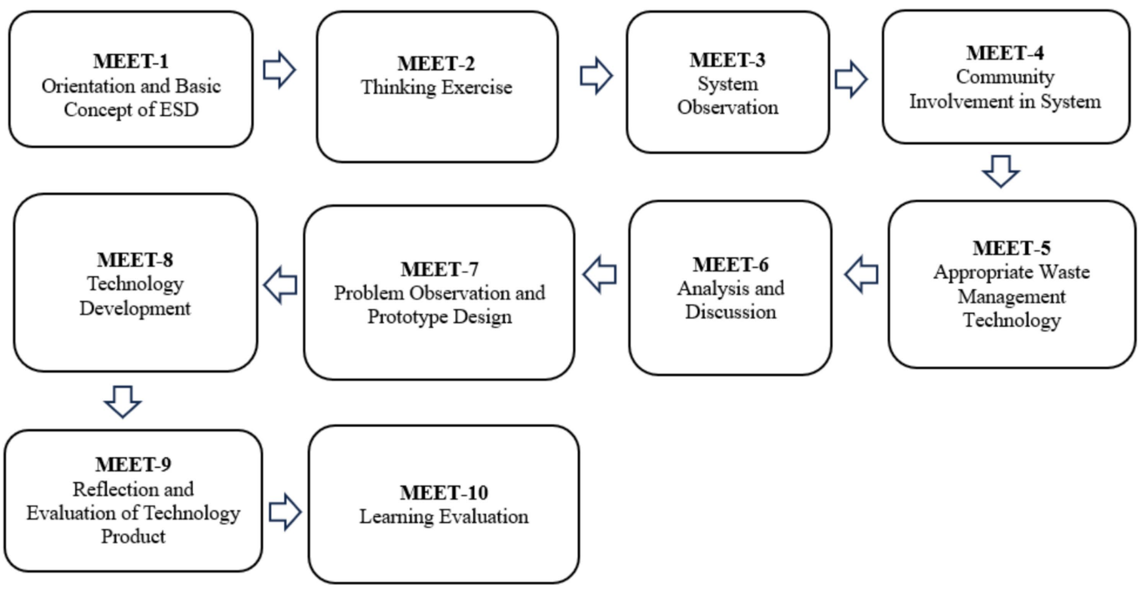

FIGURE 2
The outdoor learning scenario.

After establishing this cognitive readiness, students moved into direct system observation in their surrounding environment. Through this outdoor engagement, they examined real ecological and human systems, identifying components, interactions, and dynamic relationships that shape local waste-flow patterns. Their observations were further enriched through deliberate involvement with community members, enabling students to situate environmental issues within broader social practices and to recognize how collective behaviors influence system dynamics. Exposure to appropriate and context-specific waste-management technologies further increased their awareness of practical solutions available within the community, offering concrete examples that bridged theoretical learning with real-world technological applications.

The insights gathered from the field were then brought into structured classroom discussions, where students analyzed the data they had collected, synthesized their observations, and articulated emerging environmental problems. This analytical phase equipped them with the conceptual clarity needed to proceed to problem-focused observation and prototype design. Building on authentic environmental challenges, students collaboratively conceptualized technological solutions aligned with sustainability principles and local needs. They subsequently developed these ideas into tangible prototypes, engaging in hands-on technological creation that required applying scientific knowledge, creativity, and engineering design skills.

Upon completing their technological products, students reflected on the functionality, feasibility, and environmental relevance of their innovations. This reflective evaluation deepened their metacognitive awareness and encouraged critical appraisal of their own technological thinking. The learning sequence concluded with a comprehensive evaluation of students' conceptual, analytical, and technological competencies, ensuring that the outdoor learning experience not only strengthened their understanding of environmental systems but also enhanced their capacity to generate meaningful contributions to waste management and sustainability awareness. The outdoor learning program was implemented over a period of six weeks, consisting of ten learning sessions. Each session lasted approximately 120 min and was conducted at the Self-managed Waste Village site. The learning activities were facilitated by classroom teachers in collaboration with researchers and local waste management practitioners, who acted as field facilitators. Teachers were responsible for guiding conceptual understanding and reflection activities, while facilitators supported students during field observation, problem identification, and prototype development. This structured implementation ensured consistency across groups while allowing flexibility for contextual exploration. All participating student groups followed the same learning sequence and assessment criteria to ensure comparability of outcomes.

4.2 Descriptive analysis

In a sample of 299 students from various educational levels and schools, the survey was distributed. Regarding the age of the respondents, the majority of the participants were in the early age group, accounting for 53.68%. The exact percentage of each group is shown in Table 3. In terms of school conditions, 65.67% of the respondents attended schools with significant waste management issues.

TABLE 3 Demographic characteristics of the sample.

Characteristic	Frequency	Percentage
Age		
9–10 year	161	53.84
11—12 years	138	46.16
School location		
Rural	156	52
Urban	143	48
Condition		
Significant waste issue	197	65.89
Moderate waste issue	102	34.11

4.3 Measurement model

To assess the reliability of all constructs and items used in the survey, the researchers calculated Cronbach's alpha values, ranging from 0.91 to 0.77. Hundleby and Nunnally (1968) described that Cronbach's alpha values greater than 0.70 are considered good and are regarded as the standard for measuring reliability. Therefore, all Cronbach's alpha values in this study are considered reliable. Convergent validity and discriminant validity for the research model used were determined through Confirmatory Factor Analysis (CFA). The standard range for factor loadings is described as 0.60 with a p-value less than 0.001. All factor loadings in this study remain above the standard range, and the threshold for Composite Reliability (CR) is described as 0.70. All CR values in this study are well above the standard range. The cutoff point for the Average Variance Extracted (AVE) is described as 0.50, and all AVE values in this study are well above the cutoff point. The means, standard deviations, items, constructs, factor loadings, AVE, CR, and Cα for the survey instrument are provided in Table 4.

Subsequently, the Fornell and Larcker (2012) measurement was adopted to assess the AVE values and evaluate discriminant validity. The square root of the AVE for each construct was calculated and presented in italics in Table 5. Table 5 indicates that all constructs (OL, SA, and T) exhibit good convergent and discriminant validity. Additionally, the relationships between the variables show moderate to strong positive correlations, supporting the notion that these three variables are interrelated yet conceptually distinct.

Table 5 shows that the correlation between OL and SA is 0.65, indicating a strong positive relationship between Outdoor Learning and Sustainable Awareness. The correlation between OL and T is 0.60, indicating a fairly strong positive relationship between Outdoor Learning and Technological Innovation. The correlation between SA and T is 0.70, indicating a very strong positive relationship between Sustainable Awareness and Technological Innovation (see Table 6).

The current study used tools like Root-mean-square error of approximation (RMSEA), goodness-of-fit index (GFI), and Chi-square minimum/df (CMIN/df) to measure the fitness of the model. The comparative fit index (CFI), the adjusted goodness of fit index (AGFI), and the normed fit index (NFI) were also employed as appropriate supplementary measures. Additionally, the study used Parsimonious-fit measures like parsimony goodness of fit index

TABLE 4 Measurement model.

Construct	Mean	SD	Item	Loading	AVE	CR	C∝
OL	3.65	0.55	OL1	0.85**	0.62	0.85	0.88
			OL2	0.89**			
			OL3	0.83**			
			OL4	0.87**			
SA	3.72	0.60	SA1	0.88**	0.68	0.89	0.91
			SA2	0.84**			
			SA3	0.79**			
			SA4	0.81**			
			SA5	0.86**			
			SA6	0.82**			
			SA7	0.90**			
			SA8	0.87**			
			SA9	0.83**			
T	3.58	0.50	T1	0.91**	0.64	0.87	0.89
			T2	0.88**			
			T3	0.85**			
			T4	0.87**			

The double asterisk (**) attached to the factor loading values indicates that the coefficients are presented with two digits after the decimal point for consistency and readability. This notation does not represent a significance level, but merely reflects the rounding convention used in reporting the results.

TABLE 5 The average variance extracted (AVE) and correlation.

Construct	OL	SA	T
OL	0.79	0.65	0.60
SA		0.82	0.70
T			0.80

TABLE 6 Fit index of the confirmatory factor analysis (CFA) model.

Fit index	Score	Recommended threshold value
Absolute fit measures		
CMIN/df	2.12	≤ 3.0
GFI	0.92	≥ 0.90
RMSEA	0.045	≤ 0.06
Incremental fit measures		
NFI	0.94	≥ 0.90
AGFI	0.90	≥ 0.90
CFI	0.96	≥ 0.95
Parsimonious fit measures		
PGFI	0.75	≥ 0.50
PNFI	0.78	≥ 0.50

(PGFI) and parsimony normed fit index (PNFI). The values given in Table 7 for all the fitness indicators used to measure the reliability and validity of the model used in the current study demonstrates that these values lie in an acceptable range, and the fitness indicators meet the required standards.

4.4 Structural model

In this phase, we assessed the procedure by determining how to measure the results of an inner structural model. The proposed hypotheses of the current study were tested through SEM technique. The findings of the study were presented in Table 7 and Figure 3.

Overall, the results of the structural equation modelling provide strong empirical support for the proposed model. All hypotheses formulated in this study were confirmed with p-values < 0.001, indicating that the relationships among the variables are both statistically significant and theoretically meaningful. The magnitude of the path coefficients presented in Table 7 and illustrated in Figure 2 offers a clear depiction of the strength and direction of the effects within the structural model.

First, Outdoor Learning (OL) demonstrates a strong positive effect on Sustainability Awareness (SA) ($\beta = 0.710$; $p < 0.001$). This finding suggests that students' engagement in outdoor, experiential learning activities significantly enhances their awareness of

TABLE 7 Structural equation modelling (SEM) results.

Hypotheses	Relationship	Impact	Estimate	Value	Result
H-1	OL → SA	+	0.710	<0.001	Confirmed
H-2	OL → T	+	0.640	<0.001	Confirmed
H-3	SA → T	+	0.520	<0.001	Confirmed
H-4	OL → SA → T	+	0.180	<0.001	Confirmed

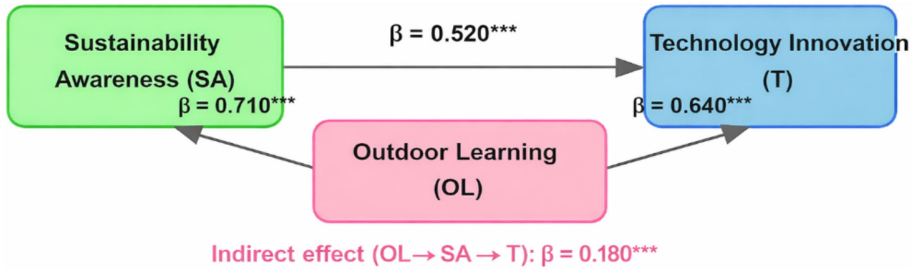

FIGURE 3
Structural model path coefficients.

sustainability principles. This aligns with previous studies emphasizing that direct interaction with real environmental contexts deepens ecological understanding, fosters emotional connection with nature, and strengthens students' ability to link environmental issues with sustainable practices.

Second, Outdoor Learning also exerts a positive influence on Technology Innovation (T) ($\beta = 0.640$; $p < 0.001$). This result indicates that contextual, exploratory, and hands-on learning in outdoor settings not only broadens students' environmental awareness but also stimulates their capacity to generate technology-based solutions. Such a finding underscores the pedagogical value of outdoor learning in promoting creativity, problem-solving, and systems thinking—skills essential for developing simple yet meaningful technological products that respond to real-world needs.

Third, Sustainability Awareness has a positive and statistically significant effect on Technology Innovation ($\beta = 0.520$; $p < 0.001$). This demonstrates that students who possess higher levels of sustainability awareness are more likely to develop innovative technologies that are environmentally relevant. Sustainability awareness thus serves as a cognitive and value-oriented foundation guiding students toward designing technologies that are not only inventive but also aligned with long-term ecological solutions.

Furthermore, the mediation analysis indicates that Outdoor Learning is indirectly associated with Technological Innovation through Sustainability Awareness ($\beta = 0.180$; $p < 0.001$). This finding suggests that the relationship between Outdoor Learning and students' technological innovation outcomes operates through the development of sustainability awareness. In other words, outdoor learning experiences are more strongly associated with technological innovation when they contribute to students' understanding and internalization of sustainability values, which function as a key mediating mechanism. This result supports the hypothesized mediation structure in which sustainability awareness serves as an explanatory pathway linking outdoor learning experiences to students' technological innovation performance.

Taken together, the SEM results affirm that the conceptual model developed in this study is both statistically robust and theoretically sound. Outdoor Learning emerges as a pedagogical mechanism that facilitates authentic learning experiences while strengthening students' cognitive competencies and sustainability-oriented attitudes. These competencies, in turn, contribute significantly to their ability to create environmentally responsible technological products. The findings reinforce the importance of integrating Education for Sustainable Development (ESD) into elementary education through experiential, problem-based outdoor learning approaches.

4.5 Evaluation of student-developed technological products

To strengthen the interpretation of technological innovation outcomes, descriptive statistics were calculated based on the product evaluation rubric. Each technological product developed by students during the outdoor learning program was assessed across four dimensions: product design, function and effectiveness, sustainability, and presentation and documentation. The results indicate that the overall quality of student-developed technological products was at a moderate to high level. The highest mean score was observed in the function and effectiveness dimension ($M = 3.84$, $SD = 0.56$), suggesting that most products were able to address waste-management problems effectively and operate according to their intended purposes. The product design dimension also demonstrated a relatively high mean score ($M = 3.71$, $SD = 0.61$), indicating that students were able to incorporate creative and practical elements into their technological solutions.

In terms of sustainability, the mean score was slightly lower but remained within an acceptable range ($M = 3.52$, $SD = 0.63$). This finding suggests that while students demonstrated awareness of environmentally friendly materials and long-term use, the integration of sustainability principles into technological design varied across groups. The presentation and documentation dimension showed a mean score of 3.68 ($SD = 0.58$), reflecting students' ability to communicate ideas and document the development process adequately.

Overall, these descriptive results indicate that the outdoor learning program facilitated the development of technological products that were not only functional and innovative but also reflected varying degrees of sustainability awareness. These findings provide empirical support for the role of sustainability awareness as an important mechanism through which outdoor learning contributes to technological innovation.

5 Discussion

The results of the Structural Equation Modelling (SEM) analysis reveal a significant relationship between the outdoor learning program, sustainable awareness, and technological innovation. Specifically, the outdoor learning program exerts a direct, positive, and significant influence on students' sustainable awareness, with an estimate of 0.710 ($p < 0.001$). furthermore, the simple regression analysis revealed that the Outdoor Learning (OL) variable had a significant effect on Sustainability Awareness (SA), with a standardized regression coefficient of $\beta = 0.710$ and an R^2 value of 0.50. This indicates that 50% of the variance in sustainability awareness can be explained by students' participation in the outdoor learning program. This finding underscores that learning approaches involving direct engagement with the natural environment can enhance students' understanding of sustainability issues. Outdoor learning programs provide contextual and relevant learning experiences, enabling students to observe and comprehend environmental challenges firsthand. These results align with prior research emphasizing that experiential learning strengthens students' awareness of the importance of sustainability (Ely, 2018).

Besides, the outdoor learning program also has a significant direct effect on students' technological innovation, with an estimate of 0.640 ($p < 0.001$). OL was also found to significantly influence Technological Innovation (T), with a coefficient of $\beta = 0.640$ and $R^2 = 0.41$, suggesting that field-based experiences play a substantial role in shaping students' technological innovation abilities. This indicates that field-based experiences not only enhance sustainable awareness but also encourage students to develop innovative solutions, such as waste management technologies. Students' interactions with real-world environmental issues, such as waste management, facilitate critical and creative thinking processes, ultimately leading to the development of practical and innovative ideas. These findings are consistent with the literature suggesting that project-based and experiential learning approaches can foster creativity and technological innovation (Marquez et al., 2023). The research findings on student-developed waste management technology products reveal a strong potential for innovation and practical application in addressing environmental challenges. These products showcase diverse creative solutions such as sensor-based bins, portable composters, and manual waste sorters. The creative designs, such as sensor-based bins and portable composters, reflect the effectiveness of hands-on learning environments in nurturing problem-solving skills. This aligns with the work of Kolb (1984), which emphasizes the role of experiential learning in enhancing creativity and innovation. Similarly, recent studies (Braßler and Schultze, 2021) have highlighted how integrating STEM education with sustainability projects can significantly improve students' critical thinking and design capabilities. Functionally, the majority of the student-developed technologies met their intended objectives, such as improving waste segregation and reducing organic waste. This success supports findings by Jackson (2015), who noted that project-based learning enables learners to apply theoretical knowledge to real-world problems effectively. However, challenges in durability suggest the need for iterative design processes, as recommended by Traifeh and Meinel (2018) in the context of design thinking frameworks. Sustainability aspects were particularly strong, with over 90% of the products utilizing recycled materials. This aligns with the principles of the circular economy, as outlined by Lin and Ardoin (2023), which emphasize designing for resource efficiency and minimal environmental impact. However, scalability remains a challenge, reflecting findings by Keränen et al. (2023), who noted that sustainable innovations often face barriers in transitioning from prototypes to large-scale implementation.

A significant positive relationship was also identified between sustainable awareness and technological innovation, with an estimated coefficient of 0.520 ($p < 0.001$). Another simple regression showed that SA had a significant effect on T, with $\beta = 0.520$ and $R^2 = 0.27$, reinforcing the notion that sustainability awareness serves as a critical foundation for fostering innovation. High levels of sustainable awareness enable students to better understand the complexity of environmental challenges and the importance of efficient resource management. This understanding forms the foundation for students to develop technologies that provide practical solutions to environmental issues, such as waste management technologies. These findings align with the perspective that sustainable awareness is a critical element in fostering innovation aimed at creating positive environmental impacts (Cebrián et al., 2020).

Furthermore, the results indicate that sustainability awareness plays a significant mediating role in the relationship between outdoor learning and technological innovation, with an indirect effect coefficient of 0.180 ($p < 0.001$). This finding suggests that outdoor learning is associated with students' technological innovation outcomes primarily through its influence on the development of sustainability awareness. In this context, outdoor learning experiences contribute to enhancing students' understanding of sustainability values, which in turn supports their ability to design and develop technological solutions for waste management. These results highlight that experiential and contextual learning environments do not merely expose students to real-world problems but also facilitate the internalization of sustainability principles that act as a key mechanism linking learning experiences to technological innovation. Thus, sustainability awareness functions as an explanatory pathway through which outdoor learning is associated with students' practical innovation performance.

The multiple regression analysis examining the combined effects of OL and SA on T yielded an R^2 value of 0.56, with relative contributions of β (OL) = 0.43 and β (SA) = 0.39, both statistically significant ($p < 0.001$). This finding corroborates the SEM results, demonstrating that both variables simultaneously contribute to the development of innovation. The results of the multiple linear regression analysis, indicating that Outdoor Learning (OL) and Sustainability Awareness (SA) jointly explained 56% of the variance in Technological Innovation (T) ($R^2 = 0.56$), provide compelling evidence of the integrated contribution of both experiential and cognitive dimensions in fostering innovation. The relative standardized coefficients, $\beta = 0.43$ for OL and $\beta = 0.39$ for SA, demonstrate that both predictors significantly influence students' capacity to develop technological solutions, with outdoor learning slightly outweighing sustainability awareness in predictive strength. These findings support and extend the conclusions drawn from the SEM, which also confirmed that both OL and SA had significant direct effects on technological innovation. The alignment between regression and SEM results strengthens the validity of the model and suggests a robust interplay between pedagogical strategy and student values in shaping innovation outcomes. From a pedagogical standpoint, the relatively strong predictive power of Outdoor Learning reinforces the value of experiential and context-based education in stimulating students' creative and technical capacities (Kolb, 1984; Zandvliet, 2012). Through direct exposure to real-world problems, such as community-based waste management, students are more likely to develop functional and original technological prototypes, as learning becomes situated within meaningful, tangible challenges (Rickinson et al., 2004; Kelley and Knowles, 2016). Meanwhile, the significance of

Sustainability Awareness as a predictor affirms that students' understanding of environmental, social, and economic dimensions contributes to their motivation and ability to design appropriate and responsible innovations (Barth and Michelsen, 2013; Cebrián et al., 2020). When learners internalize sustainability principles, they are more inclined to pursue technology not only for functionality, but also for social and ecological impact, aligning with the broader goals of Education for Sustainable Development (UNESCO, 2017b). The joint influence of OL and SA suggests that innovation in environmental education is not solely a result of technical skill-building, but emerges from the integration of hands-on experiences and critical awareness. This corresponds with (Wulf, 2010) call for education that transcends cognitive knowledge, incorporating systemic thinking and practical engagement. The implication is clear: effective sustainability education must balance experiential learning with value-based content to achieve transformative outcomes.

Besides, the descriptive evaluation of student-developed technological products indicates that the outdoor learning program successfully supported the development of functional, innovative, and sustainability-oriented technological solutions for waste management. The moderate to high rubric scores across product design, functionality, sustainability, and presentation suggest that students were able to translate their learning experiences into tangible technological outcomes. These findings align with prior research emphasizing that authentic, context-based learning environments enhance students' capacity to apply scientific knowledge to real-world technological challenges (Pimthong and Williams, 2020; Ballard et al., 2024). Notably, the highest scores were observed in the dimension of function and effectiveness, indicating that students demonstrated a strong ability to design technologies that addressed waste-management problems in practical and operational ways. This result supports the argument that hands-on engagement with real environmental contexts encourages solution-oriented thinking and strengthens students' technological problem-solving skills (Cui et al., 2022). When students interact directly with waste systems and community practices, technological innovation becomes grounded in actual needs rather than abstract concepts. The sustainability dimension, although slightly lower than other aspects, still achieved satisfactory levels, suggesting that students incorporated environmental considerations such as material selection, durability, and implementation potential into their designs. This variation reflects developmental differences in students' sustainability awareness, reinforcing the role of sustainability awareness as a mediating factor between outdoor learning and technological innovation. As indicated by the SEM results, outdoor learning contributes to technological innovation primarily by fostering sustainability awareness, which then guides students' technological decision-making processes. This finding is consistent with studies asserting that sustainability-oriented innovation emerges when learners internalize sustainability values and integrate ecological, social, and economic considerations into design practices (Escrig-Olmedo et al., 2019; Howell, 2021). The mediation effect of sustainability awareness further highlights that technological innovation in primary education is not merely a product of technical skill acquisition but also of value-based learning. Outdoor learning experiences promote students' awareness of environmental responsibility, which functions as a cognitive and affective bridge connecting experiential learning with innovative technological outcomes. This supports the view of education for sustainable development (ESD) as a transformative process that links knowledge, attitudes, and behavior to concrete action (Mahariya et al., 2023). These findings demonstrate that the strength and sustainability of students' technological innovations are closely associated with the level of sustainability awareness cultivated through outdoor learning. By positioning sustainability awareness as a central mechanism in the innovation process, this study extends previous outdoor learning and sustainability research by empirically showing how contextual learning environments contribute to meaningful technological innovation in waste management. This contribution is particularly relevant for primary science education, where early exposure to sustainability-oriented innovation can foster long-term environmental responsibility and creative problem-solving capacities.

Overall, the results of this study demonstrate that the outdoor learning program is an effective approach for enhancing sustainable awareness and fostering technological innovation. By providing contextual and relevant learning experiences, students not only grasp the importance of sustainability but are also motivated to develop innovative solutions to environmental challenges. These findings have significant implications for sustainability-based education, particularly in promoting innovations that support the Sustainable Development Goals (SDGs). For schools with limited access to community-based waste management facilities, the findings of this study suggest several actionable strategies. First, outdoor learning can be implemented through school-based waste projects, such as composting organic waste, simple waste sorting stations, or recycling corners managed by students. Second, partnerships do not necessarily require formal waste villages; schools may collaborate with local households, small community groups, or municipal sanitation units to provide contextual learning experiences. Third, when direct field access is constrained, simulated outdoor learning using school yards, nearby neighborhoods, or project-based assignments supported by digital resources can still foster sustainability awareness and technological creativity. These approaches enable schools with limited infrastructure to adapt outdoor learning principles while maintaining meaningful engagement with real environmental problems.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Postgraduate School of Universitas Pendidikan Indonesia. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

DW: Conceptualization, Methodology, Writing – original draft, Visualization, Investigation, Project administration. AW: Methodology, Writing – review & editing, Validation,

Supervision. ES: Investigation, Writing – review & editing, Conceptualization. Muslim: Validation, Writing – review & editing, Data curation, Formal analysis.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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