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Enhancing STEM Education Through AI-Driven Service-Learning: Fostering Student Understanding Of Nanotechnology-Based Green Materials For Sustainability

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Abstract
This study examined STEM students' understanding, perceptions, attitudes, and engagement in AI-driven service-learning experiences related to nanotechnology-based green materials for sustainability education. Anchored in Constructivist Learning Theory and the Technological Pedagogical Content Knowledge (TPACK) Framework, the study explored how integrating emerging technologies into service-learning can enhance students' environmental awareness and motivation to address real-world challenges. A descriptive survey design was employed, involving 302 senior secondary school students from purposively selected ICT-enabled schools in the Nsukka Education Zone of Enugu State, Nigeria. Data were collected using a structured questionnaire titled Students' Experiences with AI-Driven Service-Learning for Sustainability Education Questionnaire (SEASLEQ), with a reliability index of 0.87 (Cronbach's alpha). The data were analysed using SPSS version 28, and mean and standard deviation were used to address the research questions. Findings revealed that students had limited understanding of nanotechnology-based green materials and their relevance to sustainability, despite some awareness of practical applications and exposure in school settings. Students generally held positive perceptions of AI integration in service-learning, particularly its usefulness in enhancing STEM learning and promoting creativity. They also expressed positive attitudes toward sustainability and the use of emerging technologies in addressing environmental challenges. However, their engagement and motivation in AI-driven service-learning activities were relatively low, indicating limited participation and classroom involvement. These findings underscore the need for more intentional and engaging integration of sustainability topics and emerging technologies into STEM curricula to enhance student understanding, participation, and motivation.
Keywords: *AI-driven learning, service-learning, sustainability education, STEM students, nanotechnology, environmental literacy*

INTRODUCTION

Science, Technology, Engineering, and Mathematics (STEM) education plays a pivotal role in equipping future generations with the knowledge, skills, and problem-solving capacities needed to address pressing global challenges, particularly those related to sustainability. One emerging frontier in this space is the application of nanotechnology-based green materials, which offer innovative solutions for energy efficiency, pollution reduction, and environmentally friendly manufacturing. Despite their growing relevance, these topics remain largely underrepresented in formal STEM curricula, especially in developing countries, due to their perceived complexity and a lack of pedagogical strategies that effectively connect them to students' lived experiences and local environmental issues.

Education is widely acknowledged as a powerful instrument for personal development, societal advancement, and sustainable global progress (Egara & Mosimege, 2023b; Okeke et al., 2025). Through structured curricula and innovative pedagogies, it equips learners with the capacity to address complex issues such as climate change and resource depletion (Begum et al., 2021; Kizildeniz & Bozkurt, 2024; Zhang et al., 2022). However, performance in science- and environment-related subjects has remained suboptimal, especially in many developing regions (Adedara, 2021; Egara & Mosimege, 2023a; Mosia et al., 2025). One contributing factor is the continued reliance on traditional instruction methods that fail to foster active engagement or link learning to real-world environmental challenges (Okeke et al., 2023; Osakwe et al., 2022).

Environmental education, particularly when delivered through interdisciplinary STEM content, holds the potential to foster ecological literacy and promote sustainable behaviour (Gupta et al., 2024). In this context, service-learning has gained prominence as a transformative pedagogy that combines academic instruction with community engagement and reflective practice (Alalade, 2023). When implemented effectively, service-learning enables students to participate in meaningful, real-life projects, such as waste management, afforestation, or clean-energy demonstrations, that reinforce classroom concepts and cultivate a sense of environmental responsibility (Samino, 2023).

In parallel, advancements in artificial intelligence (AI) are reshaping educational practice. AI-powered tools can personalize instruction, support inquiry-based learning, and offer real-time, data-informed feedback to students and educators (Mohamed et al., 2022). When integrated into service-learning environments, AI can enhance project planning, facilitate collaboration, and promote deeper engagement by aligning students' activities with their individual learning needs and community contexts.

Given these developments, there is a growing need to explore how AI-enhanced service-learning can support STEM students in understanding the scientific and societal dimensions of nanotechnology-based green materials. Although both AI and service-learning have been shown to improve engagement and learning outcomes, few studies have examined their combined effect on students' knowledge of cutting-edge sustainable technologies. This study addresses that gap by investigating how AI-supported service-learning influences students' conceptual understanding, engagement, and perceptions of nanotechnology-driven sustainability solutions.

Theoretical Framework

This study is anchored in Constructivist Learning Theory (Vygotsky, 1978) and the Technological Pedagogical Content Knowledge (TPACK) Framework (Mishra & Koehler, 2006), which together offer a foundation for understanding how students form knowledge and attitudes in technology-enhanced, context-driven learning environments, particularly within STEM education. Constructivist Learning Theory posits that knowledge is not passively absorbed but actively constructed by learners through experiences, prior knowledge, and contextual interactions (Vygotsky, 1978). Even in the absence of formal instruction, students' understanding of complex topics, such as nanotechnology-based green materials, is shaped by how they engage with related concepts in their academic and social environments. In this study, constructivism helps interpret how students' experiences with service-learning activities and environmental issues influence their current knowledge and awareness of sustainable innovations.

The TPACK Framework complements this by emphasizing the intersection of technological, pedagogical, and content knowledge in educational settings. While the current study does not implement an intervention, it explores how exposure to or awareness of AI-supported service-learning (technological and pedagogical components) aligns with students' understanding of STEM concepts (content). TPACK thus provides a conceptual lens for analysing whether students perceive a meaningful connection between AI tools, service-oriented projects, and the STEM content of sustainability and nanotechnology. Together, these frameworks support the survey's investigation of how knowledge and perceptions develop in environments where technology and community engagement intersect, even informally. They also inform the study's focus on identifying educational implications for designing more effective, engaging, and contextually relevant STEM instruction.

LITERATURE REVIEW

This section reviews empirical studies related to students' exposure to artificial intelligence (AI) in education, their engagement with service-learning initiatives, and their understanding of sustainability and nanotechnology-based green innovations. These studies provide context for evaluating how AI-enhanced service-learning can shape students' knowledge and attitudes within STEM education.

Recent studies have shown increasing student awareness and appreciation of AI tools in enhancing learning experiences, especially in STEM contexts. For instance, Holmes et al. (2019) conducted a cross-national survey investigating students' perceptions of AI tools in science classrooms. Their findings revealed that personalized feedback and interactive simulations from AI-driven platforms supported students' comprehension of complex scientific concepts.

In a Nigerian context, Egara et al. (2025) explored secondary school students' awareness and perceptions of AI-based tools like ChatGPT in mathematics instruction. Students acknowledged the usefulness of these tools for improving their conceptual understanding and reported heightened motivation and engagement. Similarly, Egara and Mosimege (2024) assessed mathematics teachers' perspectives on AI integration and found that while AI tools hold potential to support student learning, challenges such as training and curriculum alignment must be addressed to optimize their effectiveness. These studies affirm the positive orientation toward AI in education but also highlight the importance of contextually grounded strategies to maximize its benefits for student learning.

Service-learning has emerged as an impactful pedagogical model that combines academic content with community service to promote civic engagement and real-world learning. Studies have increasingly recognized its value in sustainability education. For example, Adedara (2021) examined service-learning in Nigerian secondary schools and found it improved students' knowledge of social issues. However, the study did not examine the integration of emerging technologies such as AI, nor did it assess students' knowledge of scientific innovations like green materials.

International studies further underscore the benefits of service-learning. Zahedi et al. (2023), in a pilot study in Indian middle schools, found that service-learning boosted civic engagement and awareness of community well-being, essential components of sustainability. Komalasari and Saripudin (2019) similarly reported that service-learning enhanced students' social and environmental consciousness in Indonesian schools. Filges et al. (2022), through a review of 37 service-learning studies, called for more empirical research beyond Western contexts and encouraged the integration of digital technologies to enrich learning outcomes. Our study builds on these findings by examining the potential of AI-enhanced service-learning to not only engage students but also deepen their understanding of complex scientific topics such as nanotechnology-based green materials, addressing a critical gap in the literature.

Empirical evidence reveals that students' understanding of green technologies remains uneven, often depending on access to quality instruction and environmental education resources. Olajire (2020) conducted a comparative study among junior secondary school students in Southwest Nigeria and found that students from private schools exhibited higher levels of environmental literacy than their public-school peers, largely due to better instructional materials and structured environmental programs. However, knowledge of specific sustainable technologies, such as nanotechnology-based green materials, was generally low across both groups.

Further, Egbezor and Brisk-Elemele (2016) observed that while exposure to environmental education positively influenced pro-environmental behaviours among students in Port Harcourt, sustained practice required reinforcement through school and community partnerships. Mahinay et al. (2023), in the Philippines, reported similar findings, students demonstrated general environmental awareness but lacked consistent engagement in sustainable practices. These studies highlight the need for holistic, experiential, and technology-integrated models to transform environmental literacy into action.

While emerging studies have explored the integration of AI tools in educational contexts and the value of service-learning for promoting sustainability awareness, few have investigated how these two innovations intersect in STEM education, particularly from the learners' perspective. Most existing research emphasizes teacher implementation strategies or outcome-based experimental designs, with limited attention to students' prior knowledge, experiences, and perceptions, especially regarding the use of AI tools in service-learning environments focused on sustainability.

Furthermore, the literature reveals a significant gap in understanding how students in sub-Saharan African contexts, such as Nigeria, perceive and understand nanotechnology-based green innovations, especially when taught through AI-supported approaches. There is also minimal empirical research capturing students' attitudes toward using AI in civic-oriented science education, such as environmental sustainability. These gaps are more pronounced in survey-based research, which is critical for collecting large-scale, generalizable insights into students' readiness, awareness, and engagement. This study addresses these gaps by employing a survey approach to gather data on students' understanding of nanotechnology-related green materials, their perceptions of AI-integrated service-learning, and their motivational engagement with STEM content related to sustainability. Therefore, the study aims to examine STEM students' knowledge, perceptions, and engagement levels regarding AI-enhanced service-learning focused on nanotechnology-based green materials for sustainability education.

Research Questions

This study seeks to address the following questions:

1. What is the level of students' understanding of nanotechnology-based green materials and their relevance to sustainability?
2. What are students' perceptions of the integration of AI tools in service-learning activities aimed at enhancing STEM learning?
3. What are students' attitudes toward sustainability and the use of emerging technologies like AI in addressing real-world environmental challenges?
4. To what extent do AI-driven service-learning experiences influence students' motivation and engagement in learning STEM concepts related to sustainability?

METHODS

Research Design

This study adopts a descriptive survey design to investigate STEM students' understanding, perceptions, attitudes, and engagement related to AI-driven service-learning experiences focused on nanotechnology-based green materials for sustainability. The survey approach enables the collection of quantitative data from a large number of participants to gain insights into their educational experiences and views (Creswell & Creswell, 2018).

Population and Sample

The target population comprised all senior secondary school STEM students in selected schools within the Nsukka Education Zone of Enugu State, Nigeria. The study focused on students who had been exposed to environmental and sustainability-related topics through subjects such as Biology, Chemistry, Agricultural Science, Geography, Mathematics, and ICT/Computer Studies, where concepts of scientific innovation, environmental awareness, and digital literacy are typically emphasized. A total of 302 students participated in the study. Using purposive sampling, six secondary schools were selected based on the availability of adequate ICT facilities, access to AI-integrated learning platforms, and a stable electricity supply. These criteria ensured that participants had the necessary exposure to AI-driven learning environments and school-based service-learning projects related to sustainability.

Instrumentation

Data were collected using a structured questionnaire titled Students' Experiences with AI-Driven Service-Learning for Sustainability Education Questionnaire (SEASLEQ). The instrument consisted of five sections. Section A gathered demographic information such as gender, age, grade level, and school type. Section B assessed students' knowledge of nanotechnology and sustainability concepts using multiple-choice and Likert-scale items adapted from Shepardson et al. (2011) and Yacoubian (2015). Section C examined perceptions of AI integration in service-learning, with items adapted from Holmes et al. (2019) and Egara & Mosimege (2024). Section D measured students' attitudes toward sustainability and technology use based on the Environmental Attitudes Inventory (Milfont & Duckitt, 2010). Section E evaluated engagement and motivation during AI-driven service-learning tasks using items from Fredricks et al. (2004) and Reeve and Tseng (2011). All items in the questionnaire were measured using a 4-point Likert scale: Strongly Agree (4), Agree (3), Disagree (2), and Strongly Disagree (1). This format was chosen to encourage decisive responses and avoid neutrality. The questionnaire was reviewed by experts in science education, educational technology, and environmental sustainability to ensure content validity. A pilot test was conducted with 30 students outside the study sample to assess reliability. The instrument demonstrated high internal consistency with a Cronbach's alpha coefficient of 0.84.

Data Collection Procedure

Prior to data collection, ethical approval was obtained, and informed consent was secured from school administrators, participating students, and their parents or guardians. All members of the research team were directly involved in administering the questionnaire to ensure consistency and ethical adherence throughout the process. During administration, the researchers provided clarifications to students where necessary without influencing their responses. A total of 302 questionnaires were distributed and all were duly completed and returned, yielding a 100% response rate.

Method of Data Analysis

Data collected were analysed using the Statistical Package for the Social Sciences (SPSS) version 28. Descriptive statistics, specifically mean and standard deviation, were used to answer the research questions. To ensure consistency in interpreting responses from the Likert-type items, cut-off mean scores were established across the different constructs assessed. These cut-off points were defined as follows: scores ranging from 3.50 to 4.00 indicated Very High Understanding/Perception/Attitude/Engagement (VHU/VHP/VHA/VHE); scores from 2.50 to 3.49 were categorized as High Understanding/Perception/Attitude/Engagement (HU/HP/HA/HE); scores between 1.50 and 2.49 reflected Low Understanding/Perception/Attitude/Engagement (LU/LP/LA/LE); and scores from 1.00 to 1.49 denoted Very Low Understanding/Perception/Attitude/Engagement (VLU/VLP/VLA/VLE).

RESULT

This section presents the results in line with the research questions as shown below.

Research Question 1:

What is the level of students' understanding of nanotechnology-based green materials and their relevance to sustainability?

Table 1 Students' Understanding of Nanotechnology-Based Green Materials and Sustainability

S/N	Item	M	SD	Decision
1	I understand what nanotechnology means and how it is used in creating green materials.	2.21	1.09	LU
2	I am aware of examples of nanotechnology-based materials used in everyday products (e.g., clothes that don't get dirty easily, sunscreen, mobile phone screens, water-repellent shoes).	2.54	1.09	HU
3	I know how green materials contribute to solving environmental problems like pollution and waste.	2.31	.92	LU
4	I can explain how nanotechnology helps in promoting environmental sustainability.	2.18	.96	LU
5	I have learned about nanotechnology in my science or technology-related subjects at school.	2.56	1.13	HU
	Grand Mean	**2.36**	**1.04**	**LU**

The results in Table 1 shows that students demonstrated generally low understanding of nanotechnology-based green materials and their relevance to sustainability, as indicated by a grand mean of 2.36 with a standard deviation of 1.04. Although students showed moderate awareness of practical examples of nanotechnology applications (M = 2.54) and exposure in school subjects (M = 2.56), they reported limited conceptual understanding of nanotechnology itself (M = 2.21), its role in solving environmental problems (M = 2.31), and its contribution to sustainability (M = 2.18). This suggests that while students may encounter nanotechnology concepts superficially in their curriculum or daily life, deeper knowledge and understanding remain limited, highlighting a need for improved integration of these topics in STEM education.

Research Question 2

What are students' perceptions of the integration of AI tools in service-learning activities aimed at enhancing STEM learning?

Table 2 Students' Perceptions of AI Integration in Service-Learning

S/N	Item	M	SD	Decision
6	AI tools like chatbots or smart learning apps help me understand STEM concepts better.	2.78	1.18	PP
7	AI-based learning activities in school are easy to use and engaging.	2.73	1.04	PP
8	I have participated in learning projects where AI tools were used to solve real-world problems.	2.35	.86	NP
9	Service-learning projects that use AI tools are more interesting than regular classroom lessons.	2.12	1.08	NP
10	AI tools have helped me become more creative in solving sustainability-related challenges.	2.88	1.15	PP
	Grand Mean	**2.57**	**1.06**	**PP**

The overall grand mean of 2.57 (SD = 1.06) as shown in Table 2 suggests that students generally held positive perceptions of the integration of AI tools in service-learning activities. They found AI helpful in enhancing their understanding of STEM concepts (M = 2.78), encouraging creativity in solving real-world challenges (M = 2.88), and engaging to use (M = 2.73). However, fewer students reported firsthand experience with AI-driven service-learning projects (M = 2.35) or found them consistently more interesting than traditional classroom lessons (M = 2.12). These findings indicate a generally favourable attitude toward AI in STEM education, though actual involvement in AI-driven projects may still be limited and needs further encouragement in school programmes.

Research Question 3:

What are students' attitudes toward sustainability and the use of emerging technologies like AI in addressing real-world environmental challenges?

Table 3 Students' Attitudes Toward Sustainability and Technology Use

S/N	Item	M	SD	Decision
11	I believe it is important to use technology to protect the environment.	2.66	.10	PA
12	I am interested in learning more about sustainability issues.	2.61	1.04	PA
13	I support using green technologies like solar energy and biodegradable products in schools.	2.96	1.03	PA
14	I think students should be involved in solving environmental problems through school projects.	2.72	1.09	PA
15	I enjoy using AI tools to explore ideas related to the environment and sustainability.	2.61	1.01	PA
	Grand Mean	**2.71**	**.85**	**PA**

From Table 3, the grand mean of 2.71 (SD = 0.85) reveals that students exhibited a generally positive attitude toward the integration of sustainability and technology. The strongest support was shown for green technologies in schools (M = 2.96), followed by a belief in student involvement in solving environmental problems (M = 2.72). Students also expressed interest in learning more about sustainability (M = 2.61) and showed a willingness to engage with AI tools to explore environmental ideas (M = 2.61). Overall, these findings suggest that students are not only aware of environmental issues but are also inclined to adopt technological tools, especially AI, to address such challenges through meaningful school initiatives.

Research Question 4:

To what extent do AI-driven service-learning experiences influence students' motivation and engagement in learning STEM concepts related to sustainability?

Table 4 Engagement and Motivation in AI-Driven Service-Learning

S/N	Item	M	SD	Decision
16	I feel more motivated to learn STEM topics when they are linked to real-life problems.	2.81	1.07	HE
17	I actively participated in group projects involving sustainability and AI tools.	2.25	.96	LE
18	I felt a sense of responsibility while working on environmental service-learning tasks.	2.30	.91	LE
19	I was more engaged in class when AI tools were used to explore sustainability topics.	2.17	.95	LE
20	Service-learning projects involving AI made STEM learning more enjoyable for me.	2.51	1.03	HE
	Grand Mean	**2.41**	**.98**	**LE**

As observed in Table 2, the grand mean of 2.41 (SD = 0.98) indicates a generally low level of engagement and motivation among students in AI-driven service-learning activities. Although students reported feeling more motivated when STEM topics were connected to real-life issues (M = 2.81) and found such learning more enjoyable (M = 2.51), they were less likely to report active participation (M = 2.25), responsibility (M = 2.30), or increased classroom engagement when AI tools were involved (M = 2.17). These findings suggest that while students appreciate the relevance of real-life connections in STEM learning, the current implementation of AI-driven service-learning may not be fully effective in fostering active and sustained engagement.

DISCUSSION

The findings from this study provide critical perspectives into students' understanding, perceptions, attitudes, and engagement regarding the integration of nanotechnology-based green materials, AI, and sustainability within STEM education. Despite growing exposure to environmental themes and AI in educational settings, students demonstrated limited conceptual understanding of nanotechnology and its role in sustainability. This low level of understanding may be attributed to the relatively minimal presence of nanotechnology content in the secondary school science curriculum, as well as insufficient opportunities for experiential learning that bridges abstract scientific concepts with real-world applications.

These findings are consistent with earlier research, such as that by Olajire (2020), which showed that environmental literacy among Nigerian secondary students is uneven and strongly influenced by access to quality instruction and resources. Furthermore, although students showed moderate awareness of practical examples of nanotechnology in everyday life, this awareness did not translate into a deeper comprehension of its environmental significance. This outcome supports the interpretation through Constructivist Learning Theory, which asserts that meaningful understanding is constructed through authentic learning experiences. The current curriculum may lack sufficient scaffolding and contextual relevance to support the construction of such knowledge.

Students' generally positive perceptions of AI tools in service-learning activities reflect growing familiarity with digital platforms and a willingness to adopt emerging technologies in learning contexts. This aligns with findings from Holmes et al. (2019) and Egara et al. (2025), where students appreciated AI tools for enhancing comprehension and motivation in STEM subjects. However, the limited direct participation in AI-integrated service-learning projects suggests a gap between positive perceptions and practical engagement. This discrepancy may stem from infrastructural constraints, lack of teacher training, or the absence of structured opportunities for students to apply AI in meaningful, service-oriented contexts. The TPACK Framework helps explain this gap by highlighting the need for balanced and well-integrated technological, pedagogical, and content knowledge in classroom implementation. Without adequate teacher preparedness and curriculum support, the potential of AI-enhanced learning remains underutilized.

In terms of attitudes, students expressed a clear interest in sustainability and the use of technology to address environmental challenges, echoing findings from studies by Egbezor and Brisk-Elemele (2016), as well as Mahinay et al. (2023). These attitudes suggest a readiness among students to engage with sustainability topics, particularly when paired with technological innovation. The enthusiasm for green technologies and AI reflects a favourable disposition that educators and policymakers can leverage. However, interest alone is not sufficient to drive long-term behavioural change or deep engagement with scientific content, especially when the learning environment does not support consistent practice or project-based exploration.

Regarding motivation and engagement, the findings revealed a mixed picture. While students appreciated the real-life relevance of sustainability-themed STEM lessons and found AI-enhanced activities more enjoyable, their overall participation and sustained engagement in AI-driven service-learning projects were low. This echoes the concerns raised by Filges et al. (2022), who emphasized the need for more empirical research and practical frameworks for integrating digital technologies into service-learning models, especially outside of Western contexts. The limited engagement observed in this study may be attributed to a lack of hands-on opportunities, insufficient collaboration with community partners, or superficial integration of AI tools that fails to foster ownership and responsibility among learners.

These results underscore the importance of moving beyond awareness and passive exposure to emerging technologies and sustainability themes. Effective learning in this domain requires intentional, experiential pedagogies that combine content knowledge, digital innovation, and real-world problem-solving. This study supports the call by Zahedi et al. (2023) and Komalasari and Saripudin (2019) for embedding sustainability education within community-based and technology-enriched learning contexts to cultivate both cognitive understanding and civic engagement.

CONCLUSION

This study explored secondary school students' understanding, perceptions, attitudes, and engagement with nanotechnology-based green materials, artificial intelligence, and sustainability themes within STEM education. The findings underscore several critical gaps in conceptual understanding, practical engagement, and pedagogical support for integrating emerging technologies and sustainability into the classroom. While students demonstrated interest in sustainability and positive perceptions of AI-enhanced learning, their limited conceptual grasp of nanotechnology and low participation in service-learning activities reveal a disconnect between curricular exposure and experiential learning opportunities. These gaps reflect broader challenges in aligning technological innovation with pedagogical practices and contextual realities, particularly in resource-constrained educational environments.

Educational Implications

The results of this study hold important implications for STEM education, curriculum design, teacher preparation, and policy development, particularly in contexts aiming to integrate sustainability and emerging technologies like nanotechnology and artificial intelligence. First, the limited understanding students demonstrated regarding nanotechnology-based green materials suggests the need for curriculum enrichment. Educational planners could incorporate relevant and age-appropriate content on nanotechnology and green innovation into science lessons. This would help learners develop a foundational understanding of modern scientific developments that have direct implications for environmental sustainability. In addition, the low levels of student engagement in AI-integrated service-learning activities point to the need for experiential and project-based pedagogies. Schools could adopt service-learning approaches that connect classroom instruction with real-world environmental challenges in students' communities. Such approaches could provide meaningful contexts for applying STEM knowledge while fostering a sense of civic responsibility and agency among learners.

Moreover, the successful implementation of AI-supported learning depends largely on teachers' capacity to design and facilitate technologically enriched lessons. This highlights the importance of continuous professional development focused on strengthening teachers' Technological Pedagogical Content Knowledge. Through targeted training, educators could be better equipped to incorporate AI tools effectively into interdisciplinary learning experiences that emphasize both conceptual understanding and practical application. The study also underscores the critical role of infrastructure and access. Although students reported positive perceptions of AI tools, their limited participation in AI-supported projects suggests that barriers such as poor internet connectivity, limited digital resources, and inadequate school infrastructure might be hindering engagement. Addressing these barriers is essential to ensure that the benefits of technology integration are equitably realized across diverse educational settings.

Furthermore, students' positive attitudes toward sustainability and their openness to using technology for environmental problem-solving present a promising foundation for developing environmental and technological literacy. Educators should build on this enthusiasm by creating interdisciplinary opportunities for students to explore sustainability challenges and innovate solutions using digital tools. Finally, the findings point to the need for supportive educational policies that promote innovation in STEM teaching and learning. Policymakers could consider frameworks that encourage curriculum reform, teacher capacity-building, and investment in digital infrastructure. Partnerships between governments, educational institutions, and private sector actors may also be instrumental in scaling effective practices and ensuring that students are well-prepared for the demands of a technology-driven and sustainability-focused future.

Limitations

This study has several limitations. It was conducted in a specific geographic area, limiting the generalizability of the findings. Data were based on self-reported responses, which may not accurately reflect actual understanding or engagement. The study did not assess the long-term impact of AI-integrated service-learning on academic performance or civic involvement. Additionally, limited curriculum integration of nanotechnology and AI may have influenced students' exposure and responses. These factors should be considered when interpreting the results.

Recommendations

Based on the findings of this study, the following recommendations are proposed to enhance students' understanding, engagement, and application of nanotechnology-based green materials, AI integration, and sustainability within STEM education:

1. Educational policymakers should incorporate nanotechnology and sustainability more explicitly into the secondary school science curriculum. This includes contextualizing abstract scientific concepts with real-world examples to promote deeper understanding.

2. Ministries of education and teacher development agencies should provide targeted professional development programmes on the effective integration of AI tools and service-learning pedagogies. This will strengthen teachers' Technological, Pedagogical, and Content Knowledge.
3. Governments and school authorities should invest in the technological infrastructure required to support AI-enhanced learning environments, especially in underserved areas. This includes access to digital devices, reliable internet connectivity, and updated software tools.
4. Schools should design and implement structured, hands-on service-learning projects that involve students in solving real community-based environmental problems using technology.
5. Educational institutions should collaborate with industry experts, non-governmental organizations (NGOs), and local communities to co-create relevant service-learning opportunities that link STEM knowledge with societal needs.
6. Teachers should adopt learner-centred approaches that promote autonomy, collaboration, and reflection. These approaches are more likely to sustain motivation and increase student engagement in STEM-related service-learning.

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