

Integrating Artificial Intelligence, Robotics, and Extended Reality into Sustainability-Focused STEM Education: A Practice-Based Study

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ABSTRACT

Research Article

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The integration of Artificial Intelligence (AI) and Extended Reality (XR) technologies into educational settings has significantly transformed traditional pedagogical approaches, facilitating immersive and interactive learning experiences. Nevertheless, these technological advancements have raised increasing concerns regarding their environmental impact, particularly in terms of energy consumption, manufacturing processes, and electronic waste. This study seeks to investigate the intersection of digital innovation and sustainability by designing and implementing an AI- and XR-supported educational model that prioritizes eco-friendly practices within STEM education. This study utilized a practice-based, quasi-experimental framework to involve students aged 7–16 in the creation of robotics projects using recycled materials. The participants engaged in programming these projects with AI-supported platforms like PictoBlox and took part in XR simulations to examine environmental scenarios. The instructional design was shaped by Mastery Learning Theory and the Task-Centered Learning (TCL) model, which provided a structured yet experiential framework to promote deep engagement. Both quantitative and qualitative data were obtained through the administration of questionnaires and the use of observational methods to assess shifts in student motivation, environmental consciousness, and interaction with sustainable technologies. The findings reveal that incorporating AI, XR, and robotics into educational modules with an environmental focus not only improves learning outcomes but also cultivates a culture of sustainability, creativity, and responsible innovation. This research contributes to the expanding field of technology-enhanced sustainability education by delivering practical insights into leveraging emerging technologies to cultivate environmental consciousness and accountability in educational environments.

Keywords: artificial intelligence (AI), eco-friendly education, extended reality (XR), recycling practices, sustainability.

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INTRODUCTION

Regarding the increasing use of XR in Education sector, few studies have investigated on how AI-enhanced XR and promotes sustainable, eco-friendly learning environments (Nain & Prasher, 2025). This study bridges this gap by creating intelligent immersive experiences that rely on AI-driven recycling material systems, such as Arduino-based smart bins. Using Artificial Intelligence to recognize waste, automatically sort plastic, glass, and paper recycling paper into cartons, convert plastics into LEGO-like components for STEM kits education. Create glass into decorative jewelry, which offers low-cost, sustainable educational resources while reducing environmental impact and promoting environmental friendliness. This method innovates in the education sector, the new approach focused EdTech frameworks called green digital eco-friendly pedagogy that incorporates AI, XR, and recycling scenario into both physical and virtual education processes(Buriro et al., 2023). In recent years, STEM (science, technology, engineering, and mathematics) education has gained significant attention within the educational community. Students equipped with STEM-related skills are better prepared to analyze, organize, and apply concepts in innovative ways(Sen et al., 2018). The deployment of instructional technologies and interactive materials has increased at a high speed to improve the effectiveness of STEM education. Emerging technologies offer new strength and opportunities to adapt and acquires new skill, knowledge, thus solving long-standing issues in STEM education (Sen et al., 2018). Artificial Intelligence (AI), has founded as the most promising advancements in education technology (Lin et al., 2023). Artificial Intelligence offers global capability applications, such as data analysis, speed and text recognition, automated decision-making, and personalized learning adaptation (Alrawashdeh, 2023). Open Artificial intelligence tools such as Intelligence Tutoring Systems (ITS) provide capability that help personalize learning experiences by evaluating student accomplishments and adaptability based on their interests. These systems offer real-time interaction, suitable assignment, and improved overall learning efficiency of the assistant agent. Also, it provides educational technologies such as: Augmented reality (AR), Extended Reality (XR), virtual reality and mixed reality (MR) (Kamdjou et al.; 2024, Kamdjou et al.,2025).Virtual reality (VR)has been successfully employed in different learning platforms, offering students real-time and flexible engaging experiences that help them to understand the concept of learning. The capability of extended technology to generate immersive virtual reality allows students to explore the subject from different perspectives that may otherwise be costly, toxic, or difficult to experience in the real world. The adoption of Extended Reality Technology in learning sector underlines the potential to improve student skill, performance and increasing engagement, focus and motivation of students (McDonald, 2016; Cornblath et al.,2020). **Figure 1** shows the components, types and subfields of Artificial Intelligent education based.

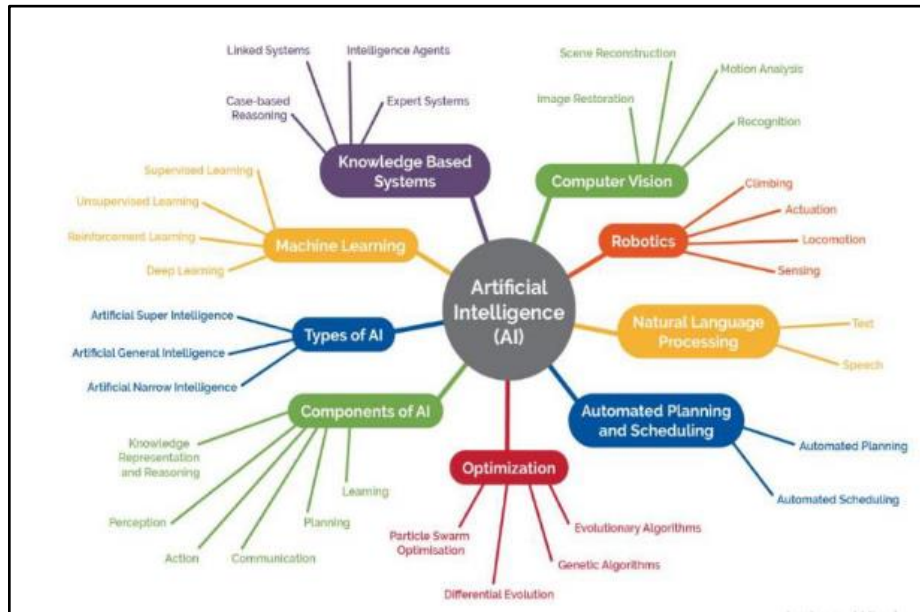


Fig1: Components, types, and subfields of AI education based(Khajeh Naeeni & Nouhi, 2024)

Source(s): Adapted from Khajeh Naeeni & Nouhi, 2024 ; authors' compilation

The growth of digital technology in education as transforming the most innovative techniques and teaching methods, virtual learning, video conferencing systems, and e-learning systems have become essential components of the digital education age due to the COVID-19 pandemic in global public health care, and the use of Extended and Artificial Intelligence technologies during the emerging digital technology has facilitated remote learning and distance education. The Education institutions survived and continuously experiences the education activities by exploring new digital tools, which make learning flexible by maximize the opportunities offer by tools. The combination of AI and XR in education provides new opportunities for novel pedagogical and learning experiences(Lin et al., 2023). Digital transformation in education sector, is essential in tackling the issues in yesterday education concepts(Rosli et al., 2022). Despite their promise, the long-term ramifications of AI and XR in education have been frequently disregarded. The platform impact of Artificial Intelligence and extended reality on education is a significant issue. These technologies require more power supply which consume excessive energy and create electronic waste (Khajeh Naeeni & Nouhi, 2024). The pedagogical value of AI- and XR-based learning environments in boosting student sustainability awareness has not been thoroughly examined. Current research mostly focuses on the technological and engagement aspects of AI and XR, ignoring their potential advantages in sustainability education(Demartini et al., 2024). Furthermore, ethical issues, such as data privacy, algorithmic biases, and institutional resistance to technology adoption, must be addressed to appropriately use AI and XR. AI-powered learning environments can equip students with the skills required to engage in sustainable activities and produce solutions for key environmental issues(Demartini et al., 2024).

This research aims to bridge this gap by investigating the convergence of AI, XR, and sustainability within the educational sector. Specifically, it examines how AI and XR technologies can:

1. Minimize the ecological impact of digital education,
2. Increase student engagement in sustainability-oriented learning activities, and
3. Enhance educational outcomes by using interactive and environmentally sustainable teaching methods.

The study will explore the following research questions to achieve these objectives:

1. What is the effect of AI and XR integration on sustainability education in terms of student engagement and awareness?
2. What are the ecological consequences of using AI and XR technology in educational settings?
3. How do AI- and XR-based educational models compare to traditional teaching methods in developing sustainability?

This research addresses these concerns, aiming to enhance the existing literature on AI and XR in education, and provide insights into their contributions to sustainability, ethical problem reduction, and responsible digital transformation.

LITERATURE REVIEW

The STEM method is essential in teaching students the needs of the 21st-century industry by developing their analytical and problem-solving abilities (Cvejic et al., 2018). The implementation of technology in STEM instruction improves student engagement and leads to a greater understanding of complex scenarios (Lu et al., 2022). Experiments, simulated labs, and educational games are examples of interactive resources that have been found to improve student engagement and performance (Vlachopoulos & Makri, 2017). Researchers have highlighted that technology-enriched instruction helps connect the gap between theoretical comprehension and real-life application (Gençten & Aydemir, 2023). Furthermore, digital education with the help of artificial intelligence offers flexible content and is adapted to the interests of students (Alrawashdeh, 2023). These accomplishments help, address a long-standing challenge in STEM education, such as a lack of outstanding sources and falling student engagement and motivation (O'Leary et al., 2020a). AI in the learning sector offers personalized and individual learning methods by setting content to every single student's level of interest using methods such as Intelligent Tutoring Systems (ITS) (Lin et al., 2023). The combination of artificial reality (AR) and Extended Reality (XR) offers a learning experience to students by creating an immersive platform that increases motivation and engagement (Rosli et al., 2022). Moreover, artificial intelligence and extended reality have demonstrated the potential to reduce educational issues, particularly during the global outbreak of COVID-19 (Al-Qashouti, 2024). However, despite the promising evolution in AI and XR, few studies have investigated their combined use in promoting sustainability based Eco-friendly educational experiences. This study

addresses the essential gap in the existing literature. Furthermore, while individual technologies are well documented, integrated frameworks that leverage AI and XR for environmentally conscious education remain underdeveloped. Also, addresses these gaps by proposing a novel AI and XR-based learning model that enhances STEM learning and supports environmental sustainability and eco-friendliness via the use of recycled materials and a low-carbon digital environment. By aligning emerging technologies with sustainable practices, this research contributes a unique perspective to the evolving discourse on green digital pedagogy. Meanwhile, Artificial Intelligence and Extended Reality (XR) technologies have shown consistent effectiveness in increasing student motivation and engagement, which, in turn, has implications for environmental sustainability by encouraging low-power consumption solutions and reducing electronic waste. Additionally, highlights the vital intersection between technological innovation and ecological responsibility in education and identifies potential principles and models that integrate sustainable design into immersive learning systems. Finally, addresses the limitations of designing an AI-XR educational framework that actively incorporates recycling, energy efficiency, and minimalism into its instructional design (Khajeh Naeeni & Nouhi, 2024). Ethical concerns, including data privacy, big data governance, and algorithmic bias, are becoming increasingly central as XR and AI technologies are integrated into digital learning environments (Rezaei et al., 2024). The integration of sustainability dimensions is not only environmental but also ethical and social. However, some studies have offered strategies to ensure transparency and equity within AI-XR ecosystems (Alotaibi, 2024). This study responds to this challenge by integrating ethical design principles, such as explainable AI and secure data practices, into immersive educational experiences aimed at long-term responsible use. The Task-Centered Learning (TCL) approach enhances immersive learning by focusing on solving real-life problems through experiential and student-driven tasks (Demartini et al., 2024). This instructional approach is closely linked with the aim of our research, which is to make learning more relevant and transformative. However, the literature on TCL explores how eco-conscious XR environments, which have emerging pedagogical depth with environmental awareness, align with the research. Integrating AI and XR within educational design holds promise for aligning instruction with the United Nations Sustainable Development Goals (SDGs), helping to foster deep learning and long-term behavioral change (Barbu et al., 2025). This reinforces the idea that emerging technologies can play an essential role in learning outcomes and in shaping future citizens who are environmentally and socially responsible. Moreover, many studies have investigated models that translate these ambitions into classroom-ready systems, something this research directly uses via its practical AI-XR education toolkit. Morrison's Mastery Learning Theory, grounded in Bloom's taxonomy, provides a strong pedagogical foundation by breaking complex learning scenarios into smaller, manageable steps and reinforcing learning through repetition and feedback (Chang & Chen, 2022). This theory supports personalized interactive learning, a concept that is fully compatible with AI and XR platforms. However, its implementation in sustainable digital pedagogy remains lacking in the literature. By integrating mastery-based structures into the XR interface, this study links foundational theory with advanced eco-friendly learning design. The Task-Centered Learning (TCL) concept complements by engaging students in authentic, real-life workplace and teamwork, transforming the ideal for XR-

enhanced and project-based sustainability, such as robotics education using recycling materials (Kamdjou et al., 2024). This alignment between physical and hands-on learning and eco-conscious design demonstrates the relevance of TCL to environmental education in higher education. This present TLC theory is still unknown to most researchers in the education sector, and the literature on the combination of TCL, XR, and sustainability is limited. Our research addresses this gap by applying TCL within an AI- and XR-based robotics environment using recycled materials. When pedagogical models like TCL are combined with immersive technology, they have been shown to foster deep learning, critical thinking, and long-term skill acquisition, especially in technology-integrated educational settings (Rahmawati et al., 2020). This synthesis supports the notion that emerging technologies are the most powerful in active learning theory. This study contributes to the area of education in leveraging technologies for skill development and environmental literacy. Educational robotics platforms such as LEGO and Arduino improve experiential STEM learning by increasing student engagement and sensorimotor capacities, despite the fact that research in this field remains constrained (Fidai, 2021). However, research remains divided, often focusing on hardware or student outcomes without considering environmental footprints or sustainability. This study builds on such platforms by adapting them for exploiting recycled materials and embedding them in AI-guided XR environments to reinforce both ecological and cognitive aims. For example, PictoBlox offers robotics and artificial intelligence instruction that is more understandable by offering a low-energy, straightforward platform that corresponds with sustainability-focused instructional objectives (Auerbach et al., 2018). This reflects an increasing trend toward low-energy modular educational technologies. Our research serves as a pedagogical and environmental aim to incorporate PictoBlox-like logic into an AI-XR learning environment that simulates sustainable engineering challenges. Incorporating recycled materials into robotics projects gives students direct involvement with environmentally friendly designs, which promotes ecological understanding (Bulathwela et al., 2019). This practice strengthens students' ecological awareness and connects theoretical STEM concepts to practical environmental action. This research responds by placing sustainability at the core of the robotics-based learning experience, ensuring ecological and educational relevance. The performance and the weakness of previous studies, presented in **Table1**, show that each category of subfield of AI presented in **Figure1**, use the specific method /tool to achieve the goal

Summary

Overall, the literature review affirms the value of implementing AI, XR, and interactive technologies into STEM education to enhance engagement, personalization, and experiential learning. While task-centered approaches and educational robotics drives essential thinking and skill development, these innovations are treated in isolation, with little focus on their environmental or ethical implications. However, few researches have explored how AI and XR can be combined to support effective pedagogy and sustainability. Additionally, the use of robotics tools, like Arduino and LEGO, rarely incorporates recycled materials or energy-efficient practices. The research proposes an integrated pedagogical framework that merges Task-Centered Learning (TCL), AI, XR and

sustainable robotics to promote mastery-based, immersive, and eco-conscious learning. This Model Not only supports educational innovation but also advances climate-conscious practices in accordance with global sustainability aims

Table 1: Performance and Weakness of Reviewed Papers

Category	Auth ors	Performan ce	Weakness	Method s / Tools Used
STEM Education and Robotics	(Sen et al., 2018), (Lu et al., 2022), (Evríp idou et al., 2020), (Fidai , 2021), (Auer bach et al., 2018)	Enhanced engagement , improved psychomotor and cognitive STEM skills, use of open- source robotics	Limited access, low integration of programmin g in early stages, teacher training gaps	Educatio nal Robotics (LEGO, Arduino, Raspberr y Pi, RoboGe n)
Adaptive and Inclusive Learning	(Dem artini et al., 2024) (O'Le ary et al., 2020b),(Al- Qasho uti, 2024)	Personalize d instruction improves outcomes; culturally responsive pedagogy boosts inclusion	Scalability and ethical implementat ion of AI remain issues	Adaptiv e Learning Systems, Cultural Training , AI tools
Extended Reality (XR) Tools	(Barb u et al., 2025), (Kam djou et al., 2024), (Hein onen, 2023)	XR enhances immersion, comprehens ion, technical communicat ion	Hardware cost, complexity, tech limitations in real-time feedback	VR, AR, MR (Mixed Reality), Digital Twin Integrati on

Sustainability in Education	(Cellucci & Villani, 2024), (Abdellatif et al., 2022)	Promotes environmental literacy and eco-friendly habits	Application in STEM is underdeveloped in certain regions	Recycled Materials, Green Pedagogy, Circular Economy Models
Source(s): Authors compilation				

METHODOLOGY

This study used a quasi-experimental approach to investigate the incorporation of Artificial Intelligence (AI) and Extended Reality (XR) technology into sustainable educational methods. The technique has four fundamental components: (1) study design, (2) technical tools and sustainability content, (3) participant selection and ethical issues, and (4) implementation and assessment methods.

Research Methodology

The research was conducted during the fall and spring semesters of 2024 at a Candela Robotic School in Northern Cyprus. A quasi-experimental methodology was employed to assess the impact of AI- and XR-based learning modules on students' environmental awareness and motivation for sustainable actions. Two groups were established: an experimental group that received instruction through AI- and XR-enhanced modules, and a control group that followed the conventional curriculum. The intervention lasted for eight weeks and was implemented during regular science and technology classes. The instructional methodology was grounded in two pedagogical frameworks: Morrison's Mastery Learning Theory and the Task-Centered Learning (TCL) Approach. These frameworks ensured that the learning objectives were explicitly articulated and that students engaged in iterative experiential learning activities aligned with sustainability goals. Figure 2 illustrates the instructional design process using a methodological flowchart.

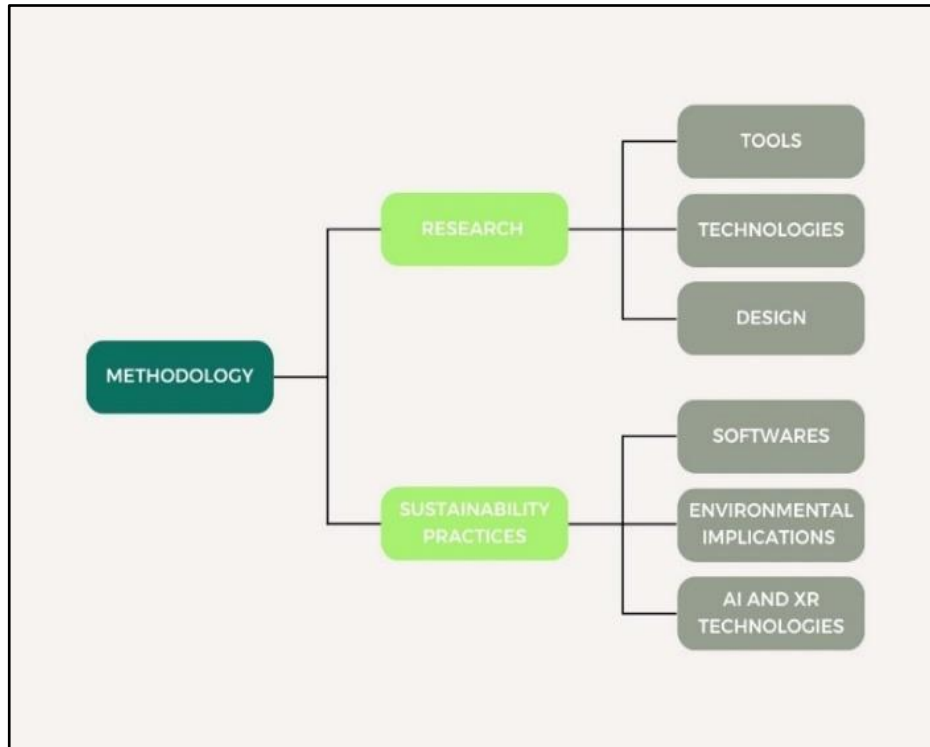


Fig 2: Flowchart of Methodology

Source(s): Adapted from Cellucci & Villani (2024); Authors' compilation

Participants and Sampling

The research included 100 children from diverse grade levels, consisting of 50 females and 50 males. The participants were divided into three unique age groups for representational variety throughout developmental stages: ages 7–10 ($n = 32$), ages 10–15 ($n = 38$), and ages 16 and above ($n = 30$). This categorization facilitated the analysis of the effects of AI- and XR-based sustainability courses on learners across various cognitive and educational levels. Participants were chosen using purposive sampling, considering their availability, interest in technology-enhanced learning, and desire to engage in a study concerning environmental awareness and sustainability. Each student held fundamental computer literacy and had access to essential digital devices supplied by the school during the deployment period.

Ethical Considerations

This study was conducted in compliance with both institutional and national ethical standards pertaining to research involving minors. The investigation took place in a non-clinical educational setting and did not involve the collection of sensitive personal data; therefore, formal approval from a university ethics committee was not required. Written informed consent was obtained from the parents or legal guardians of all student

participants. Additionally, all school officials were informed of the study's objectives and methodologies, and necessary permissions were secured from the school administration. Participation was entirely voluntary, and students were free to withdraw from the study at any time without any consequences.

Data Collection Tools and Procedure

The primary instrument for data collection in this study was a researcher-developed questionnaire, administered via Google Forms. This questionnaire aimed to evaluate students' attitudes, awareness, and motivation regarding sustainability both prior to and during the educational program. The questionnaire comprised 20 items, structured on a 5-point Likert scale ranging from "Strongly Disagree" (1) to "Strongly Agree" (5). The items were categorized into three dimensions:

1. Environmental Awareness (e.g., "I understand the impact of human activities on the environment."),
2. Incentive for Sustainable Practices (e.g., "I take pleasure in acquiring knowledge on environmental conservation."),
3. Utilization of Technology (e.g., "I appreciate incorporating innovative technologies such as virtual reality and artificial intelligence in my instruction.").

To ensure content validity, the initial version of the questionnaire was reviewed by two experts in science education and instructional technology, and necessary modifications were made based on their feedback. Data collection occurred in two phases: a pre-test conducted one week prior to the intervention and a post-test administered immediately after the eight-week instructional session. A pilot test was conducted with 10 students outside the main sample group to evaluate the clarity and reliability of the items. Data were exported directly from Google Forms to Microsoft Excel and analyzed using basic statistical methods to identify changes in students' perspectives.

Theoretical Framework

This study's instructional design is grounded in two pedagogical frameworks: Morrison's Mastery Learning Theory and the Task-Centered Learning (TCL) Model. These frameworks provide the foundation and rationale for the design, implementation, and evaluation of the AI- and XR-enhanced instructional modules.

Morrison's Mastery Learning Theory

Morrison's Mastery Learning approach focuses on deconstructing complex learning material into smaller, organized components, each with clearly defined learning objectives. The process follows a sequential framework that includes: Diagnostic Assessment: Evaluating students' existing knowledge prior to instruction. In this study, this was achieved

through pre-assessment exercises utilizing fundamental tasks with LEGO Education kits. Providing focused information and structured practice: Students engaged in practical training on constructing basic robots with recyclable materials alongside LEGO components. Evaluation: Assessing educational achievements through systematic assessments. Post-module quizzes and reflective inquiries were employed to evaluate both conceptual understanding and practical skills. Feedback and Re-instruction: Providing prompt, formative feedback to guide students towards proficiency. Students requiring additional support received individualized instruction until they demonstrated sufficient proficiency. This strategy ensures that every student attains a comprehensive understanding before progressing to subsequent topics. It aligns with Bloom's concepts of mastery learning, advocating for self-directed learning, personalized support, and individualized learning pathways(Evripidou et al., 2020).

Task-Centered Learning (TCL) Methodology

The Task-Centered Learning paradigm emphasizes student engagement in authentic, real-world activities that replicate significant problem-solving scenarios. The instructional process in TCL comprises five essential stages: Learning Task: Students are assigned a principal project, such as constructing a functional robot using recyclable materials. This practice reflects actual sustainability concerns and fosters environmentally responsible design thinking (Demartini et al., 2024). Activation: Students retrieve prior knowledge and acquire fundamental background information. Familiar LEGO Education kits were utilized to facilitate students' introduction to the field of robotics. Exhibition: Educators demonstrate the skills and concepts required to complete the activity. XR simulations were employed to illustrate how AI might assist in addressing real-world environmental challenges. Students apply newly acquired knowledge and skills to construct their robotic prototypes and provide sustainable solutions. Integration: Students reflect on their learning and explore other applications of their concepts, identifying opportunities for improvement and practical implementation. TCL enhances Morrison's approach by emphasizing the application of knowledge in practical contexts, thereby fostering critical thinking, creativity, and problem-solving skills(Chang & Chen, 2022). This hybrid instructional approach enables students to learn conceptual knowledge while simultaneously building confidence in its application to real-world sustainability concerns.

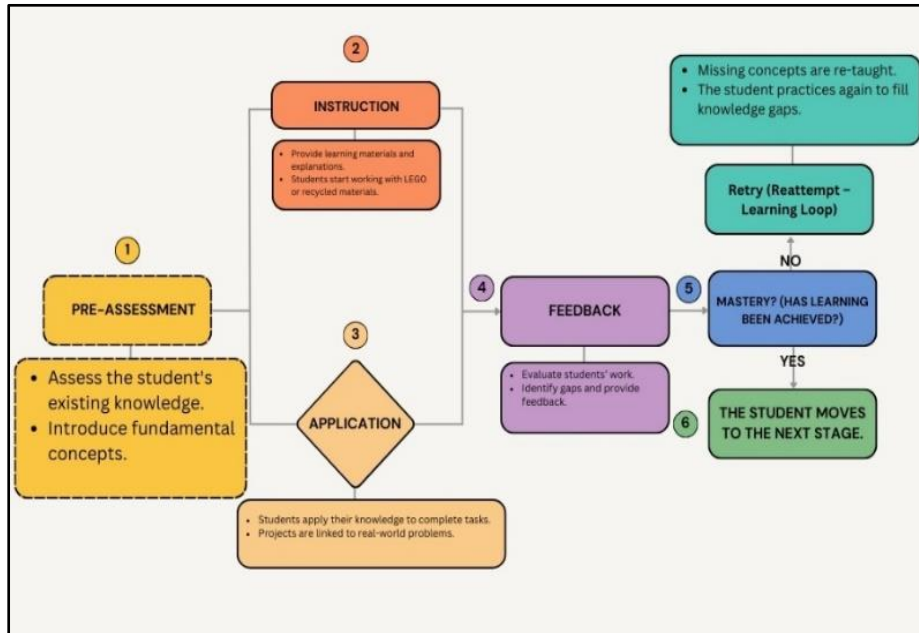


Fig 3: Flowchart of TCL method (Demartini et al., 2024)

Source(s): Adapted form Demartini et al., 2024 ; Authors compilation

Tools and Technologies

This study employed a combination of educational robotics kits, artificial intelligence (AI) platforms, and extended reality (XR) environments to facilitate technology-enhanced, sustainability-oriented learning. These tools were selected for their accessibility and alignment with constructivist and experiential learning methodologies.

Educational Robotics

The instructional modules utilized educational robotics equipment such as LEGO Education SPIKE Prime, Arduino UNO, and Raspberry Pi 4. These platforms enabled students to design and program autonomous robots using both commercial components and repurposed materials. Through these practical experiences, learners developed skills in mechanical design, sensor integration, and logic-based programming. The robotic components were intentionally integrated into sustainability scenarios; for example, students constructed waste-collecting robots using repurposed plastic, metal bottle tops, and cardboard. These activities not only enhanced STEM engagement but also promoted environmentally conscious problem-solving and innovative recycling of everyday materials.

Artificial Intelligence and Programming Tools

The study employed PictoBlox, a visual programming environment that supports both block-based and Python coding, to convey fundamental principles in artificial intelligence.

PictoBlox enabled students to implement AI functionalities such as gesture detection, image categorization, and speech recognition. The user-friendly interface made it suitable for younger learners, while the Python editor allowed older students to explore text-based machine learning applications. This tool was used to develop practical applications, including: A robot that navigates mazes through hand gesture control An AI-driven recycling classifier that differentiates among metal, plastic, and paper icons PictoBlox was chosen for its extensive interoperability with Arduino, micro:bit, and LEGO EV3 systems, as well as its accessibility on low-power devices.

Extended Reality (XR) Tools

XR features were implemented to enhance educational environments through simulated, immersive experiences. The offerings included 3D visualizations of intelligent recycling systems, clean energy simulations, and interactive sustainability missions, all accessible via standard VR headsets or smartphone viewers. The XR technologies enabled students to explore real-world environmental issues within a safe digital setting. Students navigated a virtual smart city, making environmentally conscious design choices that reinforced sustainability concepts through practical learning.

Sustainable Practices

In alignment with the primary objectives of this study, sustainable practices were integrated into the design and implementation of the instructional modules. These approaches emphasized ecological awareness, material repurposing, and sustainable technical solutions. The aim was not only to convey the concept of sustainability but also to exemplify it throughout each phase of the educational process.

Utilization of Recycled Materials

The principal sustainability strategy of this study involved the use of recycled and reused materials for robotic construction. Students were encouraged to collect and creatively repurpose domestic waste, including: rolls of newspaper, plastic bottle caps, cardboard, wood rods, and packaging materials. This approach enabled students to engage in cost-effective, eco-friendly prototyping, demonstrating that efficient engineering solutions can be achieved without reliance on expensive or novel materials. This technique not only reduced waste but also enhanced students' understanding of circular economy concepts and reinforced their environmental responsibilities(Cellucci & Villani, 2024).

Eco-Friendly Software and Hardware

The technical tools employed for the modules specifically PictoBlox and microcontroller-based platforms were selected due to their low energy consumption, cross-device flexibility, and minimal hardware requirements. The lightweight construction of PictoBlox facilitated the use of low-power laptops and tablets, thereby reducing the carbon footprint typically associated with computer-aided education. Activities were designed to operate offline or on battery-powered devices wherever feasible, thus further minimizing environmental impact. This intentional use of eco-efficient software and hardware

demonstrated the study's commitment to exemplifying sustainable practices in digital education.

Integration of Sustainability Themes into Instruction

Sustainability was incorporated into all learning activities rather than being treated as a separate subject. Students engaged in activities such as: programming robots to simulate automated recycling processes, developing smart city prototypes from recyclable materials, and creating XR-augmented experiences focused on climate action and renewable energy. These themes aligned with the United Nations Sustainable Development Goals (SDGs), including Goal 4 (Quality Education), Goal 9 (Industry, Innovation and Infrastructure), and Goal 12 (Responsible Consumption and Production). Through these assignments, students developed technical skills alongside critical thinking, ecological literacy, and systems thinking—competencies essential for sustainability education.

DISCUSSION

This study aimed to explore the incorporation of educational robots, extended reality (XR), and artificial intelligence (AI) into STEM education with an emphasis on sustainability. The results demonstrate that the use of practical, project-based learning modules significantly boosted students' enthusiasm, technical skills, and environmental awareness. These findings not only align with but also expand upon the existing body of research in multiple ways.

Integration of Robotics and Recycled Materials

The application of recycled materials in robotics construction has proven to be both educationally beneficial and environmentally sustainable. Students showcased their creativity and problem-solving skills by building robots from repurposed household items, aligning with the findings of Bulathwela et al.(2019), who underlines the ecological and cognitive benefits of sustainability-focused design. While Fidai (2021) and Auerbach et al.(2018) reported increased engagement and psychomotor development through the use of instructional robots, their studies did not emphasize sustainability to the same degree as this initiative. This suggests that combining robotics with recycling can potentially enhance STEM education and promote environmental consciousness.

AI and XR-Enhanced Learning Outcomes

The incorporation of AI and XR technologies in educational contexts has markedly advanced students' grasp of key computational and sustainability concepts. The deployment of image recognition and gesture-controlled robotics has made abstract machine learning concepts more accessible, aligning with the findings of Rezaei et al.(2024) and Alrawashdeh (2023), who underscored AI's capacity to tailor and enhance digital learning experiences. Additionally, the use of XR to model environmental challenges supports earlier studies by Rosli et al.(2022) and Barbu et al.(2025), which demonstrated that immersive technologies can significantly boost student engagement and conceptual understanding. This research underscores the potential for integrating AI and XR in

practical classroom settings, with a particular emphasis on sustainability, setting it apart from previous studies that explored these technologies independently. This is consistent with Kamdjou et al.(2024), who advocated for XR-enhanced project-based robotics education utilizing recyclable materials.

Pedagogical Alignment with Learning Theories

The configuration of the modules especially their focus on iterative learning, student introspection, and practical application corresponds directly with Morrison's Mastery Learning Theory and the Task-Centered Learning (TCL) model. Consistent with the results of Chang & Chen (2022) and Demartini et al.(2024), the study demonstrated that segmenting information into manageable tasks, along with prompt feedback and iterative practice, enhanced profound comprehension and knowledge retention. This framework enabled students to transition from supervised teaching to autonomous creativity, a fundamental aspect of effective STEM education (Rahmawati et al., 2020).

Feedback from Students and Parents

Survey data from students and parents corroborated the influence of the programs. A significant number of students indicated heightened interest in AI, robotics, and sustainability subjects, collaborating assertion that immersive, practical learning fosters engagement. Parental reaction was predominantly favorable, with more than 80% indicating pleasure with their children's creativity and development, and 99.7% recognizing the program's pertinence to their children's future employment in STEM.

Nonetheless, several problems were identified. The shift from block-based to Python programming presented challenges for students lacking prior coding knowledge, underscoring the scalability issues identified by O'Leary et al. (2020a). Moreover, procuring suitable recycled materials occasionally posed a logistical challenge; nevertheless, this also motivated students to seek alternate solutions and emphasized practical sustainability ideals.

Contribution to the Literature

This study consists and incorporates many research strands in educational technology, sustainability, and pedagogy. This study demonstrates how the integrated, practical

application of AI, XR, and recycled robotics can enhance both STEM education and ecological awareness, in contrast to prior research that examined these elements separately (Fidai, 2021; Lin et al., 2023; Barbu et al., 2025). By integrating these technologies inside a Mastery-TCL framework and using them in a resource-constrained, practical classroom environment, the project presents a scalable and sustainable strategy for future use.

Out of 100 students, 100 participated, and 120 parents. In survey results we focus more on parents to see they feedback on what their thinking and interest in STEM (Science, Technology, Engineering, Mathematics)? As shown in **Figure 4; question 4**, Parents express their satisfaction on their children creativity and ability in designing project, almost **82,1%** said the STEM method was very useful for their children.

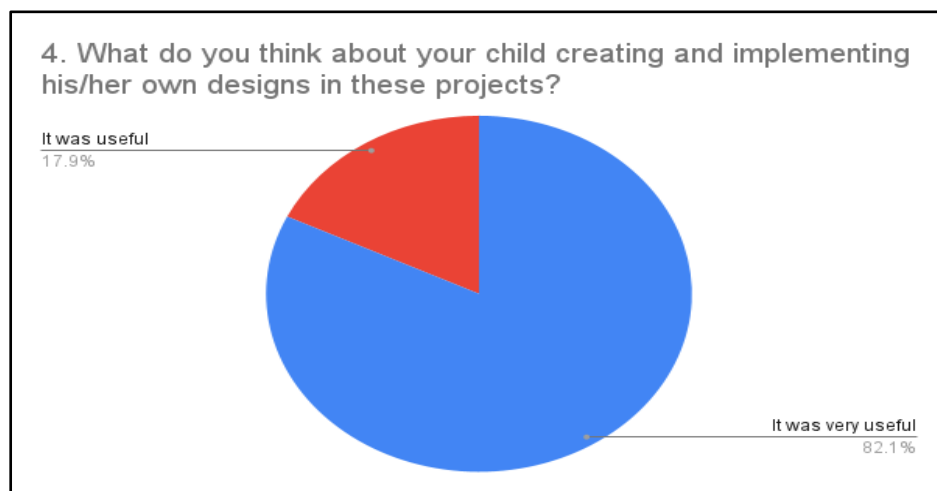


Fig 4: Parents Satisfaction

Source(s): Authors' compilation

Also, question 8, showing in **Figure5** help educators and parent in future career orientation of the children by choosing STEM method. From this particular question the parents 'agreement was super positive in adoptive the STEM method in the future career of their children such as 99,7% choose "Yes, it contributed a lot".

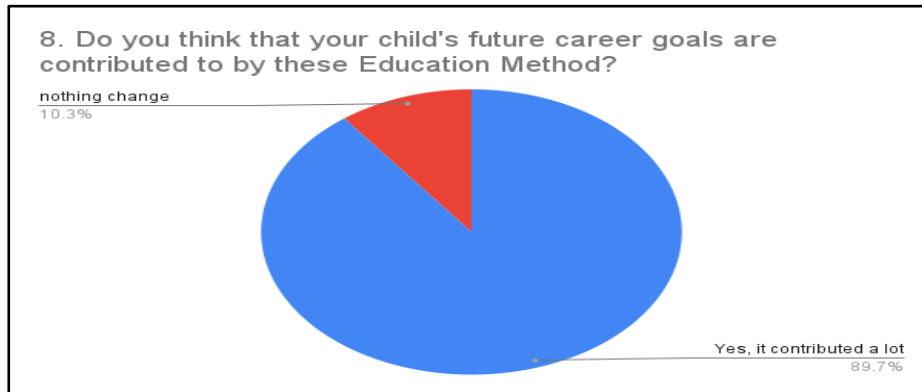


Fig 5: Future career orientation

Source(s): Authors' compilation

The results show that parent enjoy the children participation in recycling projects which teach their children sustainability and environmental awareness. **Figure 6**, shows in scale 25 participants said “**Yes, it increased a lot**” against less than scale of 5 participants said “**nothing changes**”

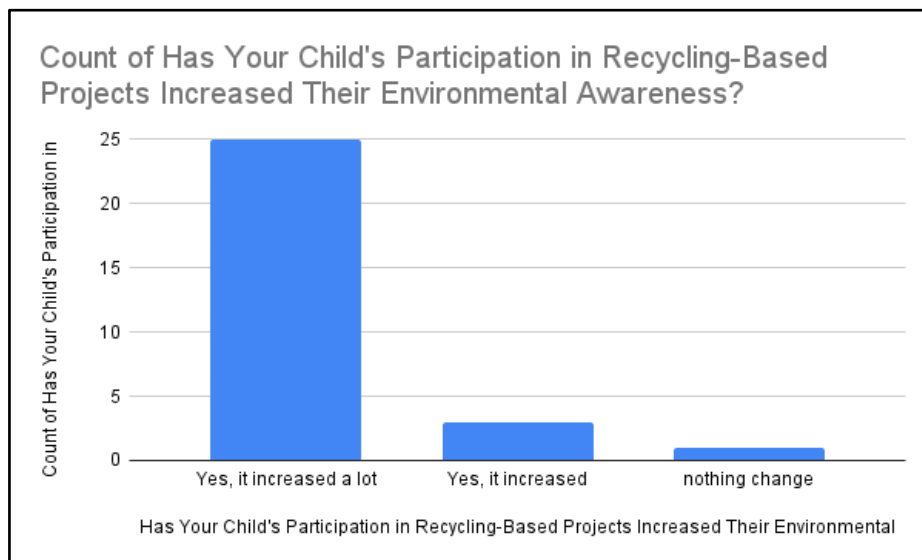


Fig 6: Future career orientation

Source(s): Authors' compilation

CONCLUSION

This research highlights that the incorporation of Artificial Intelligence (AI) and Extended Reality (XR) into educational frameworks not only boosts student engagement and learning outcomes but also enhances environmental consciousness by encouraging practices that are resource-efficient and sustainability-focused. The study's results show that students, when participating in hands-on robotics projects using recycled materials, can develop both technical competencies and a sense of ecological responsibility. The instructional approach, based on Mastery Learning Theory and the Task-Centered Learning (TCL) model, successfully promoted experiential learning and ensured the long-term retention of knowledge.

Despite these promising outcomes, the study encountered several limitations. Firstly, the transition from block-based coding to Python presented challenges for younger students with limited programming experience. Secondly, the availability and consistency of recycled materials varied, occasionally constraining the scope and standardization of the projects. Furthermore, the study was conducted within a single educational setting, which may not fully represent broader regional or international contexts. These factors may impact the generalizability of the findings.

Future research should examine the potential for this educational model to be effectively implemented across diverse age demographics, socio-economic backgrounds, and educational infrastructures. It is also essential to undertake longitudinal studies to determine the long-term impacts of AI- and XR-enhanced sustainability education. In addition, the formulation of standardized, energy-efficient digital tools and open-access curricula that are in harmony with sustainability objectives would be instrumental in reducing the ecological impact of educational technologies while simultaneously improving their accessibility.

In conclusion, this study contributes to the expanding body of literature that advocates for sustainable and technology-enhanced education by presenting a practical, interdisciplinary approach that integrates digital innovation with environmental awareness.

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