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Academic Article

Strategies for Utilizing AI Technology to Enhance Science Learning Management within the STEM Education Approach

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Abstract. The integration of Artificial Intelligence (AI) to enhance science learning within the STEM education approach is a significant advancement with the potential to revolutionize education. This paper explores four main strategies for utilizing AI: personalized learning, creating experiential learning environments, enhancing management and assessment efficiency, and fostering future skills. These strategies focus on adapting content to individual learners through intelligent tutoring systems, leveraging AI-powered virtual labs and simulations for realistic hands-on learning, using AI to reduce teachers' administrative burdens via automated assessment and deep learning analytics, and developing essential computational thinking and AI literacy for the 21st century. However, implementing AI in education presents significant challenges, including a lack of personnel knowledge and skills, infrastructure and budgetary constraints, and issues related to ethics, privacy, and data security. Furthermore, potential negative impacts include increased educational inequality if technology access is uneven, and the risk that over-reliance on AI might diminish students' critical thinking skills. To maximize the benefits of AI integration and mitigate these risks, this paper recommends crucial approaches. These include substantial investment in professional development, meticulous planning of infrastructure and policies concerning data usage and ethics, promoting continuous research and evaluation, and fostering collaboration among all stakeholders. Comprehensive implementation of these recommendations will enable educational institutions to fully harness AI's potential, creating high-quality and sustainable STEM learning for youth in the digital education era. While AI offers strategies to enhance STEM learning, its successful integration requires overcoming challenges like skill gaps and ethical concerns through professional development, careful planning, and stakeholder collaboration to create high-quality, sustainable education.

Keywords: AI Technology, Science Learning Management, STEM Education, Digital Education

INTRODUCTION

In the 21st century, technological advancements are rapidly and ceaselessly progressing, particularly with the advent of Artificial Intelligence (AI). AI has revolutionized our lives, work, and learning in unprecedented ways (Sposato, 2025). Within the educational context, AI holds immense potential to transform learning management, especially in Science, Technology, Engineering, and Mathematics (STEM) education, which forms the crucial foundation for driving national innovation and development (Vodenko & Lyausheva, 2020; Phakamach, 2023). Zhan et al. (2022) argued that STEM learning is not merely about memorizing scientific facts or mathematical formulas; it promotes critical thinking, problem-solving, creativity, and collaboration. Therefore, integrating AI into the management of science learning within a STEM framework is not just an option but an urgent necessity. This integration is vital to equip learners with the essential skills and competencies needed to navigate the challenges of a future world increasingly driven by rapidly changing and unpredictable technology (Kang, 2023; Jafari & Keykha, 2024). Modern STEM education must adapt to these shifts, and AI is key to making learning more effective and accessible for everyone, as well as inspiring students to explore the world of science with greater enthusiasm and deeper understanding. This article will provide an overview of strategies for using AI to enhance science learning within a STEM approach, which will help students develop their full potential and be ready to pursue in-demand STEM careers in the future (Cook & Cook, 2024; Payadnya et al., 2025).

AI offers unprecedented opportunities to enhance the efficiency and effectiveness of science learning management within the STEM approach. STEM learning often faces several limitations, such as restricted access to resources, a scarcity of expensive laboratory equipment, and the challenge of presenting complex concepts simply to diverse learners. AI can bridge these gaps by creating immersive, flexible, and adaptable learning environments tailored to the needs of each individual student (Abdekhoda & Dehnad, 2024; Mariyono & Nur Alif Hd, 2025). This includes utilizing AI to create Virtual Labs, where students can conduct experiments without geographical or equipment constraints, or simulating unseen scientific phenomena, such as the movement of electrons in an atom, the functioning of nerve cells, or the interaction of molecules in chemical reactions, to help students visualize and grasp abstract concepts more easily and deeply. These simulations not only enhance understanding but also significantly reduce the risks associated with real experiments and save enormous resources. Furthermore, Intelligent Tutoring Systems (ITS) powered by AI can provide immediate feedback and guidance customized to each student's comprehension level, accurately identifying their strengths, weaknesses, and knowledge gaps. This makes learning more efficient and targeted. ITS can automatically adjust the difficulty of questions, explain additional concepts, or even suggest supplementary learning resources appropriate for each student, helping them progress at their own pace and receive necessary support at every step. AI also enables educators to conduct detailed analyses of student learning data, from classroom engagement patterns and time spent on exercises to frequently made errors and their potential causes (Kang, 2023; Payadnya et al., 2025). These insights empower teachers to identify students who may be struggling, design appropriate learning activities, and provide targeted support, such as grouping students for remedial activities, offering supplementary instruction, or recommending specific additional learning resources (Weinhandl et al., 2020). This leads to more significant and sustainable improvements in students' science and STEM learning outcomes. Moreover, AI-driven data analysis can help curriculum developers and educational administrators evaluate the effectiveness of curricula and learning materials to improve and adapt them to meet the changing needs of students and the educational context (Cook & Cook, 2024; Bilal et al., 2025).

Therefore, the strategy for leveraging AI to enhance science learning management within the STEM education framework must focus on integrating AI technology into every dimension of the learning process, from curriculum design and instructional management to assessment and continuous improvement (Mudkanna Gavhane & Pagare, 2024). The core idea is to view AI not merely as a supplementary tool, but as an integral part of a learning ecosystem that fosters higher-order thinking skills, creative problem-solving, and collaboration (Payadnya et al., 2025). Abdekhoda and Dehnad (2024) has conducted research and found that applying AI in STEM education will not only deepen students' understanding of scientific content but also cultivate essential skills for becoming innovative thinkers, creators, and qualified citizens in the digital education era, such as computational thinking, which is the foundation for understanding and solving problems with computers and algorithms; data analysis skills, essential for interpreting quantitative and qualitative information in a data-rich world; and technological literacy, which includes understanding AI's potential and limitations, as well as its ethical and responsible use. Alsobeh and Woodward (2024) and Retno et al. (2025) have presented an AI integration also promotes project-based learning and inquiry-based learning, which are at the heart of STEM education, allowing students to engage in hands-on activities, create, and solve complex problems independently, working with AI as an intelligent assistant for data collection, analysis, or simulation. Furthermore, learning alongside AI helps foster adaptability and resilience, which are crucial in a rapidly changing world. Students will learn to work with new technologies and adapt to diverse tools and learning methods. Investing in the strategic development and systematic, thoughtful implementation of AI in STEM education is therefore a critical step in building a strong foundation for the nation's future, enabling youth to be leaders in science and technology and to apply their knowledge and skills to innovate and solve societal problems effectively and sustainably, thereby creating a truly knowledge-driven and innovative society in the AI era (Narayanan, 2023; Cook & Cook, 2024; Payadnya et al., 2025).

In summary, AI is transforming education, particularly in STEM fields, by providing essential tools for national development. Integrating AI into science learning is crucial to equip students with critical thinking, problem-solving, and collaboration skills. AI addresses traditional learning limitations, such as restricted access to resources, by creating immersive and flexible environments. It offers benefits like virtual labs for hands-on experience, intelligent tutoring systems for personalized feedback, and data analysis to help teachers provide targeted support. Ultimately, leveraging AI in STEM education helps prepare students for in-demand careers by fostering adaptability and technological literacy, paving the way for a knowledge-driven society.

LITERATURE REVIEW

In today's world, where digital technology plays a crucial role in every aspect of life, AI technology has emerged as one of the most influential innovations (Hannan & Liu, 2023; Abdekhoda & Dehnad, 2024). It has not only reshaped industries and economies but has also brought about a significant paradigm shift in education. This is particularly true in the fields of STEM education, which forms the vital foundation for driving national innovation and development. STEM education is an interdisciplinary approach to learning that integrates the four fields of Science, Technology, Engineering, and Mathematics. The core pedagogical goal is to move beyond traditional, siloed subject teaching to a more holistic, hands-on, and inquiry-based model. Instead of just memorizing facts, students learn to apply knowledge from multiple disciplines to solve real-world problems. This approach cultivates essential 21st century skills, including critical thinking, creativity, collaboration, and communication. It also fosters technological literacy and innovation. The ultimate aim is to empower students to become flexible thinkers and problem-solvers, prepared for a future workforce increasingly driven by technological advancements. Furthermore, STEM learning is not merely about transmitting knowledge; it's about nurturing essential 21st century skills such as critical thinking, complex problem-solving, creativity, and collaboration (Zhan et al., 2022). AI presents significant opportunities to revolutionize education by offering personalized learning experiences and automating administrative tasks for educators. It can create adaptive learning paths, provide instant feedback through intelligent tutoring systems, and automate grading, freeing up teachers to focus on student engagement. However, these benefits come with challenges. There are concerns about data privacy and security, as AI systems often collect vast amounts of sensitive student information. Additionally, the potential for algorithmic bias can lead to unfair assessments, and an over-reliance on AI might hinder the development of students' critical thinking and problem-solving skills. These qualities are crucial for driving future innovation and economic growth (Alsobeh & Woodward, 2024; Retno et al., 2025). Therefore, integrating AI into the management of science learning within a STEM framework is not just a passing trend but a strategic imperative. It must be systematically considered and implemented to equip learners with robust skills and competencies, preparing them to face the challenges and rapid, increasingly unpredictable changes of a technology-driven world. This literature review aims to explore and synthesize knowledge regarding strategies for using AI technology to enhance science learning management within a STEM education approach. It will highlight the benefits gained, the challenges faced, and feasible practical guidelines, ultimately leading to the creation of effective, accessible, and responsive learning experiences for diverse learners in the AI era (Abdekhoda & Dehnad, 2024; Jafari & Keykha, 2024).

The literature related to AI integration in STEM education points to its immense potential to transform learning processes and student outcomes. Li and Wong (2023), Alsobeh and Woodward (2024), Marengo et al. (2024), and Ellikkal and Rajamohan (2025) has conducted research and found that one of the most significant benefits is AI's ability to facilitate Personalized Learning. AI can analyze individual student learning data, such as their learning speed, strengths, weaknesses, distinct learning styles, and knowledge gaps, to tailor content, instructional materials, and exercises to their specific needs. Bilal et al. (2025) has conducted research and found that the use of Intelligent Tutoring Systems (ITS) powered by AI has been extensively studied and found effective in providing instant feedback and specific guidance that helps students better understand complex concepts in science and mathematics (Hardaker & Glenn, 2025). Alsobeh and Woodward (2024) mentioned these ITS can detect student errors, pinpoint the causes of misconceptions, and offer targeted remediation or supplementary content. Additionally, AI plays a crucial role in creating realistic and safe learning environments through the development of Virtual Labs and Simulations (Payadnya et al., 2025). These allow students to conduct scientific experiments that might otherwise be dangerous, costly, or time-consuming in a controlled and risk-free environment. Such simulations not only increase access to practical learning experiences but also enable students to explore scientific concepts in deeper dimensions, such as simulating quantum physics phenomena or analyzing chemical reactions at a molecular level, which are otherwise imperceptible. Bilal et al. (2025) mentioned the application of AI in Learning Analytics is another valuable strategy. It helps educators analyze large amounts of student learning data to identify learning trends, predict academic success, or even detect students at risk of academic difficulties, allowing for timely and effective intervention and support. The insights gained from AI analysis are also beneficial for improving curricula, instructional materials, and teaching methodologies to be more effective and responsive to the needs of modern learners, including fostering Computational Thinking, a key skill for understanding and utilizing AI (Aad & Hardey, 2025; Mariyono & Nur Alif Hd, 2025; Payadnya et al., 2025).

While the potential of AI in enhancing science learning management within STEM is immense, its practical implementation still faces significant challenges and considerations (Abdekhoda & Dehnad, 2024; Payadnya et al., 2025). Alsobeh and Woodward (2024) have reported research results from finding, Firstly, data quality used to train AI is critical, as the effectiveness of AI systems depends on the quality and diversity of the data. If the data used is biased or incomplete, the AI system may produce inaccurate results or create learning inequities. Secondly, there's a shortage of specialized personnel—both in developing AI for education and among educators who understand how to effectively integrate AI into teaching and learning. Educators need continuous training and development to fully leverage AI tools and adapt them to their specific learning contexts. Additionally, the high investment costs in developing and widely implementing AI technology represent another significant barrier, especially for educational institutions with limited budgets. Ethical considerations and data security are also paramount (Gafni & Levy, 2024; Chen et al., 2025; Mariyono & Nur Alif Hd, 2025; Payadnya et al., 2025). Since AI systems in education collect vast amounts of personal student data, maintaining data privacy, ensuring transparent and responsible data usage, and preventing data breaches are of utmost importance. The literature also emphasizes the necessity of fostering AI literacy among both students and teachers (Hur, 2025). This goes beyond merely using AI tools; it includes understanding AI's working principles, limitations, and societal impacts (Asad & Ajaz, 2024; Sposato, 2025). AI education should not solely focus on being a user but should encourage students to be ethical and impactful creators and innovators with AI, considering its broader implications. Therefore, developing strategies for using AI in STEM education must balance the technology's potential with these critical considerations to ensure that AI adoption genuinely elevates educational quality and sustainably benefits all learners (Routray & Khandelwal, 2024; Aad & Hardey, 2025; Ronaghi & Ronaghi, 2025).

Based on the analysis of the provided abstract and literature review, here is a conceptual framework for implementing AI in STEM education as shown in Figure 1. This model is designed to be holistic, addressing not only the strategic use of AI but also the foundational prerequisites and continuous evaluation necessary for sustainable and ethical integration.

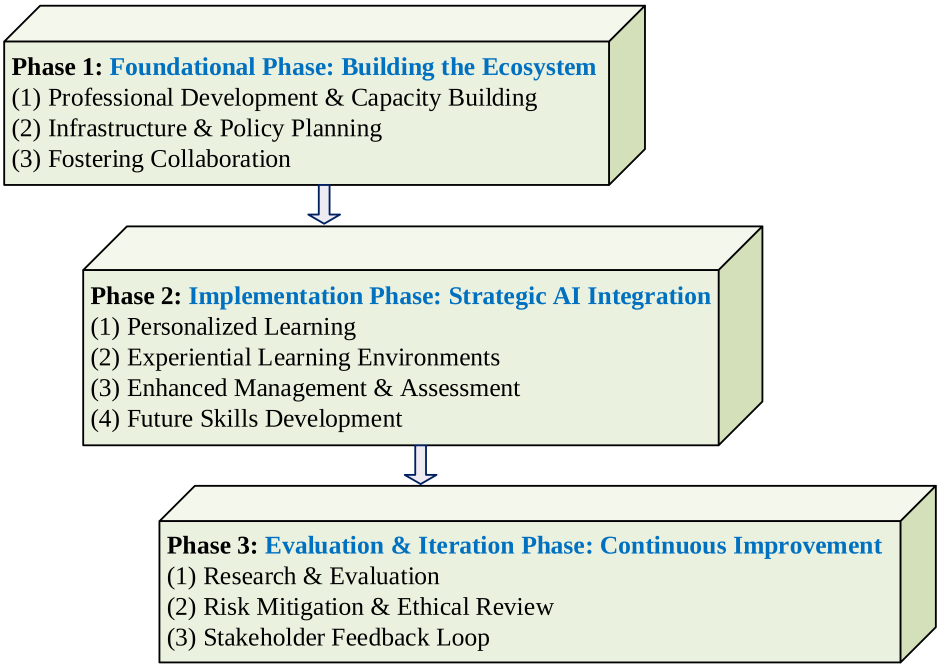

Figure 1: Conceptual framework for implementing AI in STEM education approach

This framework provides a holistic approach for implementing AI in STEM education, addressing the strategic use of AI alongside the foundational requirements and ongoing evaluation necessary for sustainable and ethical integration. The model is divided into three interconnected phases: Foundation, Implementation, and Evaluation & Iteration. The details were as follows:

1. Foundational Phase: Building the Ecosystem. This initial phase establishes the essential groundwork before any technology is deployed. It is designed to create a robust and ethical environment for AI integration by addressing key challenges.

(1) Professional Development & Capacity Building: Continuous training is crucial for educators to develop AI literacy, master AI-powered teaching tools, and understand the ethical implications of AI use.

(2) Infrastructure & Policy Planning: Careful planning is required for technological infrastructure and budgetary allocation. Clear policies on data privacy, security, and ethical AI usage must be developed to mitigate risks.

(3) Fostering Collaboration: Success depends on promoting collaboration among all stakeholders—teachers, administrators, parents, and industry experts—to ensure a shared vision and collective support.

2. Implementation Phase: Strategic AI Integration. This phase puts the strategies into practice, leveraging AI directly to enhance the learning process. It forms the core of the framework, built on the solid foundation established in the previous phase.

(1) Personalized Learning: Utilize AI-powered intelligent tutoring systems and adaptive platforms to tailor content to individual student needs, providing customized learning paths and targeted feedback.

(2) Experiential Learning Environments: Implement AI-powered virtual labs and simulations to offer realistic, hands-on learning experiences that transcend the limitations of cost and physical space.

(3) Enhanced Management & Assessment: Employ AI to automate repetitive administrative tasks, such as grading and data analytics, which reduces the teacher's burden and offers deeper insights into student performance.

(4) Future Skills Development: Integrate AI tools and curricula to actively develop students' computational thinking, data literacy, and AI literacy, preparing them for 21st century demands.

3. Evaluation & Iteration Phase: Continuous Improvement

(1) This final phase is a continuous loop of monitoring, refining, and adapting to new insights and technologies, ensuring the long-term sustainability and effectiveness of the framework.

(2) Research & Evaluation: Ongoing research and data-driven evaluation are essential to assess the effectiveness of AI implementation, measure its impact on learning outcomes, and identify areas for improvement.

(3) Risk Mitigation & Ethical Review: Policies must be regularly reviewed and updated to address emerging ethical issues, such as algorithmic bias and educational inequality, while ensuring human judgment remains the ultimate authority.

(4) Stakeholder Feedback Loop: A mechanism for gathering feedback from all stakeholders is vital to inform future iterations of the framework, ensuring it remains relevant and effective.

In summary, this framework represents a comprehensive and holistic approach that aims to fully harness AI's potential while proactively addressing its challenges, moving beyond simple tool use to a strategic, well-governed integration.

THE ROLE OF AI TECHNOLOGY IN MANAGING SCIENCE LEARNING WITHIN THE STEM EDUCATION APPROACH

In the current context of managing science learning within the STEM framework, AI has taken on an increasingly crucial role in transforming how we learn and develop essential 21st century skills (Ebekozien et al., 2023). AI is not merely a supplementary technology; it's a powerful tool capable of creating entirely new learning environments, making science education more engaging, accessible, and responsive to the diverse needs of learners. Kang (2023), Alsobeh and Woodward (2024), Mariyono and Nur Alif Hd (2025), and Payadnya et al. (2025) have given the primary roles of AI in managing science learning within STEM can be categorized into several dimensions:

1. Personalized Learning. AI excels at analyzing and adapting learning to each individual student, which is at the core of digital-era STEM education. Using Machine Learning Algorithms, AI can collect and process vast amounts of data about a student's learning behavior, including their comprehension speed, strengths, weaknesses, preferred learning styles, or even their emotional state during learning (Li & Wong, 2023). Based on this data, AI can precisely tailor content, instructional materials, exercises, and various activities to each student's unique needs. A clear example is Intelligent Tutoring Systems (ITS), which are powered by AI. These systems can provide immediate feedback when students make mistakes, identify the root causes of misunderstandings, and offer targeted remediation or supplementary content (Ellikkal & Rajamohan, 2025). This enables students to learn at their own pace and receive the necessary support to effectively develop their understanding of complex scientific and mathematical concepts.

2. Creating Realistic and Safe Learning Environments. Science and STEM learning often involves hands-on experiments and practical application, which can sometimes be limited by safety concerns, high costs, or equipment accessibility. AI addresses these challenges by developing highly realistic Virtual Labs and Simulations. Students can conduct potentially hazardous experiments, such as those involving dangerous chemicals or simulating nuclear reactions, in a controlled and risk-free virtual environment. Furthermore, simulations allow students to explore complex scientific phenomena invisible to the naked eye, like electron movement, molecular changes, or astronomical events. Students can repeat experiments, change variables, and observe results an unlimited number of times, thereby increasing access to practical experience and fostering deep inquiry-based learning (Cook & Cook, 2024).

3. Learning Analytics and Automated Assessment. AI plays a crucial role in collecting, analyzing, and interpreting vast amounts of student learning data, known as Learning Analytics. This data enables educators to quickly and accurately identify student learning trends, predict success, or even identify students at risk of academic difficulties. This allows for timely and effective intervention and support. Additionally, AI assists with Automated Assessment (Mudkanna Gavhane & Pagare, 2024), from grading multiple-choice questions and essay responses to analyzing programming code or scientific project designs. AI-powered assessment reduces the workload for teachers, giving them more time to focus on instruction, mentoring, and designing creative learning activities. Moreover, AI can provide detailed and systematic feedback to students, helping them understand their mistakes and continuously improve their work. It also helps reduce grading bias, leading to more fair and consistent evaluations.

4. Developing Computational Thinking and Future Skills. Directly integrating AI into STEM science learning also promotes the development of Computational Thinking, a fundamental skill for the digital education era (Kang, 2023). Students learn the principles of AI operation, basic programming, data analysis, and model creation, all of which are components of computational thinking. Furthermore, working with AI helps students develop other critical skills such as critical thinking (by evaluating AI-generated information), problem-solving (by using AI as a tool to find solutions), creativity (by designing new innovations collaboratively with AI), and technological literacy (which includes understanding AI's limitations and ethical considerations) (Bilal et al., 2025; Chen et al., 2025). These skills are essential for preparing students for future careers where AI will play an increasingly prominent role.

In conclusion, the role of AI in managing science learning within STEM education encompasses improving personalized and engaging learning experiences, increasing access to resources and practical experiences, assisting teachers with administration and assessment, and fostering essential future skills. Strategically and thoughtfully implementing AI in STEM is therefore a crucial step in creating high-quality education and preparing young people to be key contributors to society and the economy in the digital education era.

STRATEGIES FOR UTILIZING AI TECHNOLOGY TO ENHANCE SCIENCE LEARNING MANAGEMENT WITHIN THE STEM EDUCATION APPROACH

In the 21st century, with its relentless technological advancements, AI has become a crucial driving force transforming every aspect of life, including the education sector. This is particularly true in the fields of STEM education is paramount for nurturing essential future skills such as critical thinking, problem-solving, creativity, and collaboration, which form the bedrock of national development. The integration of AI into science learning management within the STEM framework is, therefore, more than just an option; it is a strategic imperative that demands serious consideration (Narayanan, 2023). This integration aims to cultivate a knowledgeable and capable citizenry prepared to tackle the challenges of a rapidly evolving, technology-driven world. This article will present key strategies for utilizing AI technology to enhance science learning management within the STEM education approach, focusing on creating effective, accessible, and responsive learning experiences for diverse learners (Alsobeh & Woodward, 2024; Aad & Hardey, 2025; Payadnya et al., 2025; Ronaghi & Ronaghi, 2025).

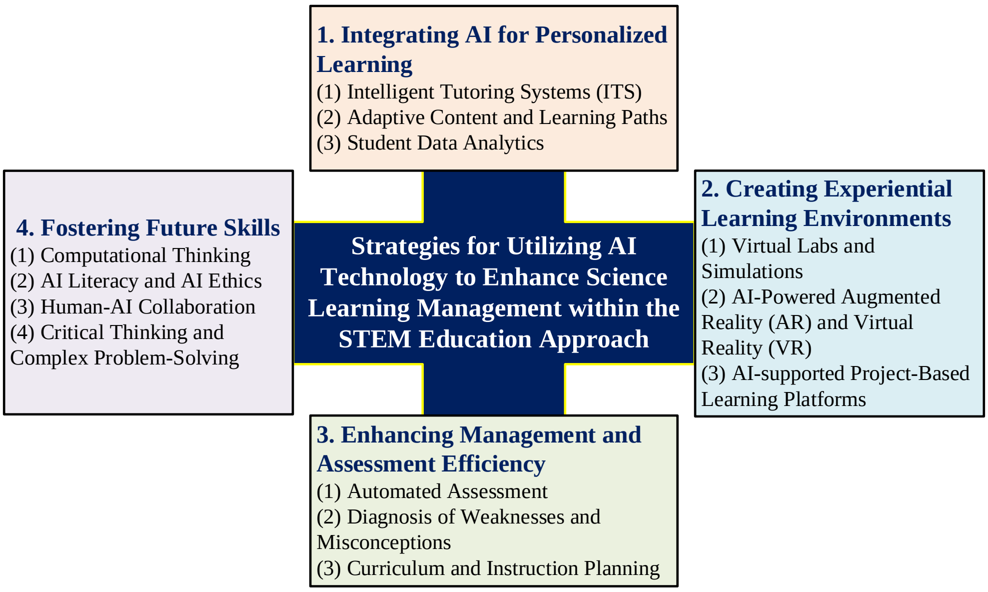

Figure 2: Strategies for utilizing AI technology to enhance science learning management within the stem education approach

Strategies for utilizing AI technology to enhance science learning management within the STEM education approach as shown in Figure 2, The details were as follows:

1. Integrating AI for Personalized Learning. One of the most powerful strategies for using AI in STEM education is its unprecedented ability to facilitate Personalized Learning (Li & Wong, 2023). Ellikkal and Rajamohan (2025) have given the core idea is that AI acts as an “intelligent teaching assistant” that deeply understands the unique differences among individual learners and tailors the learning experience to their specific needs. This strategy can be implemented in several ways:

(1) Intelligent Tutoring Systems (ITS), AI-powered ITS can analyze student learning data, such as their comprehension speed, common errors, and response patterns, to provide immediate feedback and guidance adapted to the student’s level of understanding (Hardaker & Glenn, 2025). For example, if a student struggles with the concept of gravity, the ITS might present an additional explanatory video, simpler exercises, or even a relevant simulation game, allowing the student to learn at their own pace and receive targeted support.

(2) Adaptive Content and Learning Paths: AI can recommend real-time content, instructional materials, or supplementary resources appropriate for each student's knowledge level and learning style (Bilal et al., 2025). For instance, if AI detects that a student learns best through visuals, it might suggest infographic videos or virtual simulations, whereas a hands-on learner might be advised to engage in virtual laboratory projects. This makes learning more effective and engaging for everyone.

(3) Student Data Analytics: AI can analyze vast amounts of Big Data generated from student interactions with learning platforms to provide educators with insights into overall and individual student learning performance (Alsobeh & Woodward, 2024). This data helps teachers identify students who may be struggling, plan appropriate interventions, or adjust teaching strategies to better align with the class’s needs.

2. Creating Experiential Learning Environments. True science and STEM learning necessitate hands-on practice and exploration, but often faces limitations due to equipment, cost, or safety. AI plays a crucial role in overcoming these obstacles through the following strategies:

(1) Virtual Labs and Simulations: AI can create highly realistic virtual laboratories where students can conduct complex or even dangerous scientific experiments safely and without limitations (Alsobeh & Woodward, 2024). For example, students can mix hazardous chemicals, simulate nuclear reactions, or experiment under conditions difficult to replicate in reality (e.g., in space or deep underwater) without any risk. Moreover, simulations allow students to explore abstract scientific concepts invisible to the naked eye, such as electron movement within atoms, molecular interactions in chemical reactions, or the functioning of the nervous system. These simulations help students visualize and understand concepts more profoundly.

(2) AI-Powered Augmented Reality (AR) and Virtual Reality (VR), Integrating AI with AR/VR technologies enables students to “step into” realistic scientific scenarios (Phakamach et al., 2022). This could involve exploring the human body at a cellular level, virtually navigating the solar system, or assembling virtual mechanical components. These experiences not only make learning enjoyable and engaging but also help develop spatial reasoning and empirical understanding.

(3) AI-supported Project-Based Learning Platforms: AI can act as an assistant in science and STEM projects, helping students collect data, analyze experimental results, propose ideas, or even assist in report writing (Retno et al., 2025). For instance, AI can help search for relevant information from large databases, assist in processing complex experimental data, or suggest problem-solving approaches that students might overlook. This fosters inquiry-based learning and real-world problem-solving skills.

3. Enhancing Management and Assessment Efficiency. AI benefits not only learners but also significantly reduces the workload for teachers and educators, allowing them to focus more on strategic roles:

(1) Automated Assessment: AI can assist teachers in quickly and accurately checking and grading various assignments, including multiple-choice questions, essay responses, programming code, or data analysis from experiments (Narayanan, 2023). This substantially reduces the time teachers spend on grading, freeing them up to provide in-depth feedback to individual students or design more complex and creative learning activities.

(2) Diagnosis of Weaknesses and Misconceptions: AI can analyze student answers or learning behaviors to identify systematic weaknesses or misconceptions (Narayanan, 2023). For example, if AI detects that many students misunderstand the same concept, it can alert the teacher to revisit that concept or organize supplementary activities for specific groups of struggling learners.

(3) Curriculum and Instruction Planning: AI can help teachers analyze learning data to improve curriculum and teaching methods more effectively (Narayanan, 2023). This includes identifying content areas where most students struggle, optimizing the sequence of instruction, or recommending diverse teaching materials to meet the needs of students in the classroom.

4. Fostering Future Skills. Using AI in STEM learning is not just about utilizing tools; it's about cultivating crucial 21st century skills that will empower students to be capable citizens in an AI-driven world:

(1) Computational Thinking: Interacting with AI systems or learning directly about how AI works helps students develop computational thinking skills, including decomposing large problems into smaller parts, creating models, thinking systematically, and applying logical reasoning (Kang, 2023). These are fundamental for solving complex problems in the future.

(2) AI Literacy and AI Ethics: Learning about AI within the STEM context will help students understand AI's potential, limitations, and societal impacts (Hur, 2025; Sposato, 2025). This includes ethical considerations such as data privacy, AI bias, and responsible use. This is crucial for fostering responsible citizens in the AI era (Chen et al., 2025).

(3) Human-AI Collaboration: Students will learn to work collaboratively with AI as a tool to aid in problem-solving, creation, and analysis. This is an increasingly vital skill in the future job market. Students will understand how AI can augment human capabilities and how to leverage AI for maximum efficiency.

(4) Critical Thinking and Complex Problem-Solving: Even though AI assists with analysis and processing, students will still need to apply critical thinking to evaluate AI-generated results and use problem-solving skills to formulate appropriate questions and interpret data logically.

Challenges and Considerations

While AI plays a vital role in enhancing science learning management within STEM, there are also challenges and important considerations that must be taken into account:

(1) Professional Development: Teachers need continuous training and professional development to acquire the knowledge and understanding to effectively use AI and integrate it into their teaching and learning practices.

(2) Infrastructure and Budget: Widespread AI implementation requires robust technological infrastructure and sufficient financial resources, which can be a barrier for some educational institutions (Aad & Hardey, 2025).

(3) Ethics and Data Privacy: The use of AI in education must prioritize ethical considerations and the security of students' personal data (Kang, 2023; Gafni & Levy, 2024).

(4) Flexible Curriculum Design: Curricula must be adapted to be flexible and effectively accommodate AI integration, including emphasizing future skills that AI cannot replace.

The utilization of AI technology to enhance science learning management within the STEM education approach is a crucial and necessary strategy in the current era. AI has the potential to transform learning to be personalized, create realistic experiences, enhance administrative efficiency, and foster essential 21st century skills (Kang, 2023; Gafni & Levy, 2024; Chen et al., 2025). However, the implementation of AI requires careful planning, investment in personnel and infrastructure, and strict adherence to ethical considerations. If implemented appropriately, AI will be a powerful force in creating a bright future for STEM education and preparing youth to be leaders in science and technology in the new world.

GUIDELINES FOR IMPLEMENTING AI TECHNOLOGY TO ENHANCE SCIENCE LEARNING WITHIN THE STEM EDUCATION APPROACH

Alsobeh and Woodward (2024), Payadnya et al. (2025), and Sposato (2025) argued that implementing AI technology in science learning management under the STEM approach is more than just adopting new tools; it's a paradigm shift in learning to meet the challenges and demands of the digital world. To effectively utilize the AI strategies mentioned earlier, a clear and systematic approach is essential. This approach must cover planning, professional development, technology selection, content creation, and continuous evaluation. These guidelines aim to create a learning ecosystem that fosters AI as an integral part of high-quality and sustainable STEM learning management. The details are as follows:

1. Clear Vision and Strategic Planning. Before introducing AI in any context, the most crucial step is to establish a clear vision and specific goals for how AI will enhance STEM learning and what the expected outcomes are. Sound strategic planning ensures that investments and operations are directed effectively. Clear vision and strategic planning can be achieved through the following methods:

(1) Assess Institutional Readiness: Conduct a SWOT Analysis (Strengths, Weaknesses, Opportunities, Threats) of the educational institution's current state. This includes technological infrastructure (e.g., high-speed internet, AI-compatible devices), budget, skilled personnel, and an organizational culture open to innovation (Narayanan, 2023).

(2) Define AI Integration Goals: Clearly state what problems AI will solve or what strengths it will augment. For example, the goals might be to enhance personalized learning, reduce teacher workload, develop computational thinking skills, or increase access to experimental experiences. Clear objectives will guide the selection of appropriate strategies and technologies (Li & Wong, 2023; Ellikkal & Rajamohan, 2025).

(3) Establish a Driving Team: Form a working committee or a driving team to lead the adoption of AI in STEM learning. This team should comprise administrators, teachers, educational technology specialists, and AI experts to ensure collaboration and leverage diverse expertise (Routray & Khandelwal, 2024).

(4) Develop an Action Plan: Create a concrete action plan, defining timelines, budget, necessary resources, responsible parties, and clear Key Performance Indicators (KPIs). It may be beneficial to start with a pilot program in specific subjects or with a select group of learners to learn and refine the approach (Narayanan, 2023).

2. Continuous Professional Development for Educators. Teachers are at the heart of successful AI implementation in education. Investing in professional development is therefore indispensable. Teachers must not only know how to use AI but also understand their role as facilitators of learning in the AI era. Continuous professional development can be achieved through the following methods:

(1) Build Awareness and Understanding of AI's Potential: Organize initial training workshops to help teachers grasp the fundamental concepts of AI, the benefits AI can bring to STEM learning management, and see examples of successful applications (Narayanan, 2023).

(2) Provide Training on AI Tools: Conduct practical workshops focusing on hands-on experience with the AI tools and platforms to be used in the institution. Examples include using intelligent tutoring systems, creating virtual labs, utilizing learning analytics tools, or employing AI to assist in creating instructional content.

(3) Promote the Development of AI-Driven Teaching Skills: Train teachers to effectively design learning activities that integrate AI. This could involve designing projects where students use AI as a problem-solving tool, fostering critical thinking about how AI works, or creating environments that promote human-AI collaboration (Mariyono & Nur Alif Hd, 2025).

(4) Foster Learning Communities and Experience Sharing: Establish Professional Learning Communities (PLCs) or teacher networks to allow educators to exchange experiences, share best practices, discuss challenges, and collectively develop innovative uses of AI in STEM learning (Phakamach et al., 2025).

3. Selection and Adaptation of Appropriate AI Technologies. Choosing AI technologies that align with the educational institution's context and needs is crucial; not every platform is suitable for every setting. The selection and adaptation of appropriate AI technologies can be achieved through the following methods:

(1) Consider Curriculum and Goal Compatibility: Select AI platforms or tools that align with the institution's established STEM curriculum and meet the defined goals for AI integration.

(2) Account for Customization and Scalability: Choose technology that allows for content customization to suit student knowledge levels and can be scaled for use with a large number of learners in the future.

(3) Evaluate User-Friendliness: Prioritize tools that are easy for both teachers and students to use, which helps them adopt new technologies quickly.

(4) Consider Budget and Infrastructure Issues: Assess initial investment costs, maintenance expenses, and technological infrastructure requirements (e.g., servers, internet bandwidth) (Narayanan, 2023).

(5) Prioritize Data Security and Ethics: Choose AI platform providers with high data security standards and data usage policies that adhere to ethical principles and relevant laws (Gafni & Levy, 2024; Bilal et al., 2025).

4. AI-Powered Content Development and Management. Having an excellent platform without quality content is futile. Creating and managing content that aligns with AI's functionality is essential. AI-powered content development and management can be achieved through the following methods:

(1) Create Adaptive Content: Develop STEM science learning content that can be dynamically adjusted by AI in terms of difficulty, depth, and presentation format, based on individual student learning data.

(2) Leverage AI for Content Creation: Consider using AI tools to assist in generating initial content, such as creating quizzes, summarizing material, generating questions, setting up simulated scenarios, or even creating interactive lessons (Kang, 2023). However, teachers must still review, refine, and infuse human creativity into the content.

(3) Systematize Content Databases: Establish a well-organized database system for content management to enable AI to access and utilize it efficiently, and for teachers to manage content easily.

Integrate External Resources: Connect AI platforms with reliable external science and STEM resources to broaden the scope of student knowledge and experience.

5. Continuous Evaluation and Improvement. Implementing AI in STEM learning management is an ongoing process that requires continuous learning and refinement, not just a one-time system installation. Continuous evaluation and improvement can be achieved through the following methods:

(1) Define Key Performance Indicators (KPIs), Regularly measure performance against established initial KPIs, such as average student scores, engagement rates, teacher and student satisfaction, time spent learning, or the development of specific STEM skills.

(2) Collect Data and Feedback: Utilize AI's Learning Analytics to gather quantitative data on student learning behaviors (Alsobeh & Woodward, 2024), and simultaneously collect qualitative feedback from teachers, students, and other stakeholders through surveys, interviews, or focus groups.

(3) Analyze and Interpret Results: Analyze the collected data to understand the effectiveness of the implemented AI strategies, identify areas for improvement, or pinpoint any emerging problems.

(4) Refine and Develop Plans: Use evaluation results to refine AI strategies, action plans, instructional content, or staff training methods to ensure that AI usage is maximally effective and responsive to evolving student needs and contexts.

(5) Promote Research and Development: Encourage teachers and educators to conduct research on AI's use in STEM learning to generate new knowledge and drive continuous innovation in education.

6. Fostering a Culture of Learning and Technology Acceptance. Last but not least, creating an environment where people embrace and recognize the benefits of AI is crucial for long-term success. Fostering a culture of learning and technology acceptance can be achieved through the following methods:

(1) Consistently Communicate AI's Value and Benefits: Highlight the value and benefits that AI brings to STEM learning for students, teachers, and the institution as a whole to build motivation and confidence.

(2) Promote Experimentation and Learning from Mistakes: Create an atmosphere that encourages teachers and students to experiment with AI without fear of failure, viewing mistakes as opportunities for learning and improvement.

(3) Emphasize the Human Role: Clarify that AI is a tool that augments human capabilities, not replaces them. Teachers retain their vital role in guiding, inspiring, and developing students' social and emotional skills.

(4) Encourage Multi-Stakeholder Engagement: Provide opportunities for parents, the community, and industry sectors to participate in and support the use of AI in STEM learning to foster sustainable collaboration.

In summary, effectively implementing AI technology strategies to enhance science learning management within the STEM education approach requires a comprehensive and holistic approach. This encompasses strategic planning, professional development, selecting appropriate technologies, content development, and continuous evaluation and improvement. Most importantly, it involves fostering an open and technology-accepting culture. If all stakeholders collaborate systematically and with dedication, AI integration will not only elevate the quality of STEM education but also truly prepare youth to be innovators and users of innovation in the future AI-driven world.

CHALLENGES AND OPPORTUNITIES

Cook and Cook (2024), Jafari and Keykha (2024), Routray and Khandelwal (2024), Ronaghi and Ronaghi (2025), and Payadnya et al. (2025) gave a perspective on the integration of AI into science learning management under the STEM approach represents a significant advancement with the potential to revolutionize education. However, like any major innovation, the adoption of AI in education comes with both challenges that must be overcome and vast opportunities waiting to be seized. A deep understanding of both these aspects is crucial for successful planning and implementation

Challenges

Implementing AI technology to enhance science learning management within the STEM education approach faces several obstacles that require careful handling. These challenges include:

1. Lack of Knowledge and Skills among Personnel

(1) Teachers: One of the biggest challenges is that many teachers still lack fundamental knowledge about AI, how it works, and how to apply it in teaching. Shifting from the role of knowledge transmitter to a learning facilitator who uses AI as a tool is not easy and requires time for adaptation (Alsobeh & Woodward, 2024).

(2) School Administrators: Administrators may lack a deep understanding of AI's potential and the necessary infrastructure requirements to support its implementation, which affects budget allocation and appropriate policy setting (Kang, 2023).

(3) Students: While Gen Z is familiar with technology, AI literacy and a deep understanding of its underlying principles are still necessary and must be systematically taught (Hur, 2025).

2. Infrastructure and Budgetary Constraints

(1) High Costs: Investing in AI platforms, compatible hardware, high-speed network systems, and maintenance involves significant costs (Jafari & Keykha, 2024). This can be a barrier for educational institutions with limited budgets, especially in developing countries.

(2) Unequal Access to Technology: The digital divide remains a significant issue. Students in remote areas or from low-income families may lack adequate devices or internet access, preventing them from fully utilizing AI (Assefa et al., 2025).

(3) Connectivity and Maintenance: AI systems require stable internet connections with high bandwidth, as well as regular maintenance and updates, which can be a technical and managerial burden for educational institutions.

3. Ethics, Privacy, and Data Security Issues

(1) Data Privacy: AI systems in education must collect large amounts of personal and learning data from students. Protecting this data from leaks or misuse is a significant challenge (Gafni & Levy, 2024).

(2) AI Bias: If the data used to train AI is biased or not diverse, it may lead to AI providing inappropriate recommendations or creating learning disparities for certain groups of students.

(3) Transparency and Auditability: Understanding how AI makes decisions or provides recommendations is crucial for users and administrators to be able to explain and correct errors (explainable AI).

(4) Over-reliance on AI: There are concerns that excessive reliance on AI systems might diminish essential human skills such as critical thinking, self-problem-solving abilities, or social interaction.

4. Curriculum Adaptation and Integration

(1) Curriculum Flexibility: Current curricula may not be designed to fully support AI integration, making it difficult to naturally incorporate AI into teaching and learning (Jafari & Keykha, 2024).

(2) Developing Appropriate Content: Developing STEM science learning content that can adapt to AI's capabilities and respond to personalized learning styles remains a challenge that requires resources and expertise (Li & Wong, 2023).

Opportunities

Despite the challenges, the potential of AI to enhance science learning management within the STEM education approach is immense, presenting opportunities we should seize. These opportunities include:

1. Personalized and Adaptive Learning

(1) Addressing Learner Diversity: AI can analyze each student's strengths, weaknesses, learning styles, and learning pace to adapt content, exercises, and activities accordingly. This maximizes learning effectiveness for everyone, regardless of their ability level (Li & Wong, 2023; Alsobeh & Woodward, 2024 Ellikkal & Rajamohan, 2025).

(2) Intelligent Tutoring Systems (ITS), AI can provide immediate and targeted guidance and feedback, helping students better understand complex scientific and mathematical concepts. This level of learning support is difficult to achieve in large classrooms (Ellikkal & Rajamohan, 2025)

2. Access to Realistic Learning Experiences

(1) Virtual Labs and Simulations: AI enables the creation of complex and expensive virtual laboratories and simulated scenarios where students can conduct potentially dangerous or difficult-to-access experiments safely and without limitations in a real classroom setting. This helps bridge the gap in access to practical STEM education.

(2) Exploring Beyond-Reality Scientific Worlds: AI can simulate phenomena invisible to the naked eye, such as the movement of atoms or molecules, or universal simulations, allowing learners to explore abstract concepts deeply and excitingly (Jafari & Keykha, 2024).

3. Enhanced Management and Assessment Efficiency

(1) Automated and Accurate Assessment: AI can help teachers quickly and impartially evaluate assignments and provide grades, whether by checking exams, analyzing programming code, or giving feedback on science projects. This significantly reduces teachers' workload (Mudkanna Gavhane & Pagare, 2024).

(2) Insights for Development: AI-driven Learning Analytics can provide insights into student learning behavior, helping teachers and administrators identify trends, emerging problems, and improve curriculum or teaching methods for greater effectiveness (Alsobeh & Woodward, 2024).

(3) Identifying At-Risk Learners: AI can help identify students who are likely to struggle early on, allowing for timely support and intervention.

4. Development of Future Skills

(1) Computational Thinking Skills: Directly using AI in STEM learning fosters computational thinking skills, which are crucial for problem-solving in a data- and technology-driven world (Bilal et al., 2025).

(2) AI Literacy and Collaboration with AI: Students will learn to work with AI as a tool and understand its potential, limitations, and ethical implications, which is essential for becoming responsible citizens in the digital education era (Cook & Cook, 2024; Hur, 2025).

(3) Critical Thinking and Complex Problem-Solving: Although AI assists in data processing, learners must still use critical thinking to ask questions, evaluate results, and apply creativity to utilize AI for solving complex problems.

In summary, implementing AI strategies to enhance science learning management within the STEM education approach is a journey filled with both challenges that must be overcome through good planning, investment in personnel and infrastructure, ethical considerations, and curriculum refinement, and immense opportunities to revolutionize learning to be personalized, accessible, efficient, and future-ready for students. Recognizing both these challenges and opportunities will enable stakeholders to plan and execute wisely, allowing AI to become a true force in driving the quality of STEM education and creating a bright future for our youth.

EXAMPLES OF SUITABLE AI TOOLS FOR ENHANCING SCIENCE LEARNING MANAGEMENT WITHIN THE STEM EDUCATION APPROACH

Integrating AI technology to enhance science learning management within the STEM education approach requires considering a diverse range of tools. These tools should address the four core strategies: personalized learning, creating experiential learning environments, enhancing management and assessment efficiency, and fostering future skills. Omran Zailuddin et al. (2024), Oyelude (2024), Ellikkal and Rajamohan (2025), Hardaker and Glenn (2025), and Williamson and Fernandez (2025) have presented an examples of suitable AI tools that could be applied:

1. AI Tools for Personalized Learning

1.1 Intelligent Tutoring Systems (ITS), These systems use AI to analyze each student's progress, strengths, weaknesses, and learning style. They then adapt content, explanations, exercises, and feedback in real-time. Examples include:

(1) Khanmigo (by Khan Academy), An AI-driven tool that helps teachers in the US create lessons and exercises tailored to students. It also acts as a personal tutor, answering questions and providing guidance to students.

(2) Century Tech: This platform uses AI to create personalized learning paths, incorporating gamification, scoring, and real-time data analysis to adapt the path to the learner.

(3) DreamBox Learning: Focuses on adapting math lessons based on student performance in real-time, providing appropriate support and challenges.

1.2 Adaptive Learning Platforms: These platforms adjust the difficulty of content and questions based on student comprehension, making learning efficient and challenging at the right level. An example is ALEKS (Assessment and Learning in Knowledge Spaces), An adaptive learning system that uses AI to assess student knowledge in math and science, then provides content directly addressing individual knowledge gaps.

2. AI Tools for Creating Experiential Learning Environments

2.1 Virtual Labs and Simulations (VR/AR with AI), Integrating AI with virtual reality (VR) and augmented reality (AR) technologies allows students to conduct complex, dangerous, or expensive experiments in a safe and realistic environment. Examples include:

(1) Labster: Offers virtual science labs where students can conduct biology, chemistry, and physics experiments in interactive simulated environments.

(2) VRLab Academy: Provides over 240 simulated science experiments aligned with international curricula, usable on desktops, tablets, and VR headsets.

(3) BodyViz / zSpace: Utilizes VR/AR to allow students to explore anatomy or scientific models in interactive 3D.

2.2 AI-powered Gamification Platforms: Using AI to add gaming elements to learning makes the experience more engaging and enjoyable. An example is Minecraft Education Edition (with AI integrations), While not directly AI, Minecraft can be integrated with AI to create complex STEM missions or scenarios where students solve problems and create in a virtual world.

3. AI Tools for Enhanced Management and Assessment Efficiency

3.1 Automated Assessment Tools: AI can help teachers grade assignments and provide feedback quickly and impartially, reducing workload and offering timely responses. Examples include:

(1) Turnitin: Uses AI to detect plagiarism and provide feedback on grammar and writing style, which is especially useful for science reports and projects.

(2) Gradescope: Leverages AI to streamline the grading process, making it faster and providing deeper insights, capable of reading both text and mathematical equations.

(3) SchoolAI: An AI platform that can rapidly process large volumes of student work, providing consistent and timely feedback to help students correct errors immediately.

3.2 Learning Analytics Platforms (AI-driven), These platforms use AI to analyze student learning data to identify trends, pinpoint areas where students struggle, and provide insights to teachers and administrators for instructional decision-making. Examples include LMS (Learning Management Systems) with AI features: Many LMS platforms, such as Disco, Docebo, Canvas, Moodle (with AI plugins), are integrating AI to provide deeper learner analytics and assist in course management.

4. AI Tools for Fostering Future Skills

4.1 Generative AI Tools (LLMs), Generative AI tools, especially Large Language Models (LLMs), can assist students with research, brainstorming ideas, writing scientific reports, and problem-solving. Examples include:

(1) ChatGPT / Google Gemini / Claude: Students can use these AIs to ask complex scientific questions, brainstorm project ideas, get explanations for difficult concepts, or even help with coding for STEM projects (Baber et al., 2024; Elbanna & Armstrong, 2024).

(2) Perplexity AI: Focuses on being a research-oriented AI chatbot, providing quick access to information with references, making it suitable for inquiry-based learning and fact-checking.

(3) Wolfram Alpha: More than just an advanced calculator, it's an AI-powered tool for computing, answering scientific and mathematical questions, and providing various data insights.

4.2 AI for Programming and Data Analysis:

(1) GitHub Copilot: An AI-powered code completion tool that helps students write code faster, learn language structures, and debug programming issues, which are essential STEM skills.

(2) AI-powered data visualization tools: Enable students to analyze and present complex scientific data in an easy-to-understand format.

The selection of appropriate AI tools should consider the educational institution's context, budget, staff readiness, and clear learning objectives. Implementing AI in STEM is not just about adopting technology; it's about using technology to transform the learning experience and prepare students for a future driven by science and technology.

POTENTIAL IMPACTS OF IMPLEMENTING AI STRATEGIES IN STEM SCIENCE LEARNING MANAGEMENT

Asad and Ajaz (2024), Alsobeh and Woodward (2024), Ronaghi and Ronaghi (2025), Aad and Hardey (2025), Bilal et al. (2025), Hur (2025), and Sposato (2025) gave a perspective on the implementing AI technology to enhance science learning management within the STEM education approach is not merely about adapting teaching methods; it's a profound transformation with wide-ranging impacts. These impacts include both positive outcomes that bring new opportunities and negative ones that require careful management. Understanding these impacts is crucial for judicious planning and execution, ensuring that AI integration maximizes benefits and mitigates potential risks.

Potential Positive Impacts

Integrating AI into STEM learning has the potential to generate numerous beneficial outcomes:

1. More Effective and Accessible Learning

(1) Personalized Learning: AI genuinely helps create learning experiences tailored to each student's individual needs (Li & Wong, 2023). This includes learning speed, learning styles, and strengths/weaknesses, allowing learners to achieve maximum efficiency and reduce educational disparities.

(2) Access to Learning Resources: AI can make complex scientific learning resources, such as Virtual Labs or simulations of dangerous/hard-to-access phenomena, more easily accessible to all students, regardless of their location (Cook & Cook, 2024).

(3) Increased Learning Motivation: AI's ability to present content in engaging and interactive formats, along with timely and specific feedback, will boost students' motivation and enthusiasm for learning science and STEM (Kang, 2023; Cook & Cook, 2024).

2. More Strategic Role for Teachers

(1) Reduced Administrative Burden: AI can assist with Automated Assessment and Learning Analytics, which will significantly reduce teachers' administrative workload.

(2) Emphasis on Coaching and Mentoring: With more time available, teachers can dedicate themselves to more crucial roles, such as coaching and mentoring students, designing complex learning activities, instilling ethics and morals, and developing social and emotional skills—tasks that AI cannot yet perform as well as humans (Kang, 2023; Cook & Cook, 2024).

(3) Data-Driven Decisions: Insights from AI enable teachers and administrators to make data-driven instructional and management decisions, making learning management more efficient and targeted.

3. Development of Essential Future Skills

(1) Computational Thinking and AI Literacy: Direct learning with AI will help develop Computational Thinking skills and AI Literacy in students, which are fundamental skills crucial in the digital world (Kang, 2023; Cook & Cook, 2024).

(2) Problem-Solving and Critical Thinking: Using AI as a tool to solve scientific and STEM problems will encourage students to develop complex problem-solving skills and critical thinking in evaluating AI-generated results (Kang, 2023; Cook & Cook, 2024).

(3) Workforce Preparedness: Students who are familiar with using AI in learning will be better prepared for a future job market where AI will play a significant role across all industries.

Potential Negative Impacts

Despite its immense benefits, implementing AI without careful consideration can lead to negative consequences:

1. Increased Educational Inequality

(1) Digital Divide: If access to AI technology and the internet remains unequal, educational institutions with limited resources or unable to invest in AI will further widen the gap and inequality in education between students with access to technology and those without (Assefa et al., 2025).

(2) Bias and Fairness: If the AI used is trained with biased data, it may lead to AI providing unfair recommendations or assessments to certain student groups, such as those from different socioeconomic backgrounds or diverse ethnic/gender identities.

2. Impact on Teacher Roles and Expertise

(1) Role Diminishment: If teachers do not receive adequate skill development, they may feel that AI diminishes their role and importance, leading to resistance or unwillingness to adopt AI.

(2) Lack of Interpersonal Interaction: Over-reliance on AI systems may reduce opportunities for students to receive direct interaction from teachers and peers, potentially impacting the development of social and emotional skills.

3. Ethical, Privacy, and Security Risks

(1) Privacy Violations: The collection of large amounts of personal and learning data from students by AI, without robust security measures, could lead to privacy violations or misuse of data.

(2) Over-reliance on AI and Lack of Critical Thinking: If learners rely on AI for answers without engaging in their own critical analysis, it may diminish their critical thinking and problem-solving skills.

(3) AI Errors: AI systems are not flawless; errors or glitches may occur. If used for learning assessment, this could impact students' educational futures.

4. Adaptation and Maintenance Challenges

(1) Technical Complexity: Implementing and maintaining AI systems in educational institutions can be highly technically complex and requires specialized personnel, which may be a burden for institutions.

(2) Rapid Change: AI technology evolves rapidly, requiring educational institutions to continuously adapt and update their systems, which can be a strain on both budget and human resources.

In summary, the impacts of implementing AI strategies in STEM science learning management include significant positive aspects, such as enhancing learning efficiency, making teachers' roles more valuable, and developing future-ready skills (Alsobeh & Woodward, 2024; Lytras & Ordonez De Pablos, 2024; Ronaghi & Ronaghi, 2025; Aad & Hardey, 2025; Chen et al., 2025; Bilal et al., 2025; Hur, 2025; Sposato, 2025). However, potential negative impacts must also be acknowledged and prepared for, particularly concerning the digital divide, ethical and data privacy issues, and challenges in professional development and infrastructure. Careful planning, supportive policy creation, and continuous investment will be key to mitigating negative impacts and leveraging AI's full potential for STEM education in the digital era (Assefa et al., 2025).

CONCLUSION AND DISCUSSION

Integrating AI technology into science learning management under the STEM education approach is a significant strategic advancement in the 21st century with the potential to revolutionize learning paradigms. This article presented four key strategies for leveraging AI to enhance STEM learning: 1) Personalized Learning, 2) Creating Experiential Learning Environments, 3) Enhanced Management and Assessment Efficiency, and 4) Fostering Future Skills. Furthermore, it discussed the systematic guidelines for implementation and the potential impacts, both positive outcomes bringing new opportunities and negative ones requiring careful management. A deep understanding of these dimensions is crucial for successful and sustainable planning and implementation. Based on all the information presented, a conclusion and discussion can be provided, divided into the following three key points.

Summary of Key Strategies and Implementation Guidelines

AI has the potential to revolutionize STEM learning, particularly in delivering personalized learning experiences. AI can analyze student learning data, such as learning speed, styles, and strengths/weaknesses, to adapt content, exercises, and activities to each student's specific needs (Li & Wong, 2023; Alsobeh & Woodward, 2024; Aad & Hardey, 2025; Ellikkal & Rajamohan, 2025). Through ITS and adaptive content, this allows learners to study at their own pace and according to their aptitude, significantly increasing learning efficiency and reducing educational gaps caused by individual differences.

Moreover, AI plays a crucial role in creating realistic experiential learning environments. AI enables the development of virtual labs and complex or dangerous simulations, offering learners hands-on experience with intricate scientific concepts like simulating hazardous chemical reactions or exploring hard-to-access cosmic phenomena, all without spatial or equipment limitations (Cahyono et al., 2024; Mariyono & Nur Alif Hd, 2025; Hardaker & Glenn, 2025). This expands the boundaries of traditional learning and enhances practical understanding.

In terms of management and assessment, AI significantly helps reduce teachers' administrative burden through automated assessment for tasks such as grading exams, analyzing code, or providing initial feedback on projects. Crucially, AI-driven Learning Analytics tools ((Mudkanna Gavhane & Pagare, 2024; Bilal et al., 2025) provide detailed insights into student learning behaviors, pinpointing areas where students struggle and overall trends. This allows teachers and administrators to make data-driven instructional and management decisions and plan curriculum improvements effectively.

Finally, adopting AI also fosters essential future skills for the digital education era and an AI-driven world. Students will develop computational thinking skills through interacting with AI systems and learning about AI's working principles (Bilal et al., 2025). This also includes developing AI literacy and understanding AI's ethical implications, which is crucial for becoming responsible citizens (Hur, 2025). Additionally, using AI as a tool to solve scientific and STEM problems cultivates complex problem-solving skills and critical thinking in evaluating AI-generated results, vital for preparing youth for the future workforce.

Discussion on Challenges and Impacts

While AI strategies offer immense opportunities, their implementation faces several significant challenges that need careful management. Firstly, there's a lack of knowledge and skills among personnel; both teachers and school administrators require continuous professional development to effectively and creatively use and integrate AI into teaching and learning. Secondly, infrastructure and budgetary constraints pose a hurdle. Investing in AI platforms, compatible hardware, high-speed networks, and maintenance is costly, which can be an obstacle for resource-limited institutions, especially in developing countries. This could lead to a digital divide if access to AI technology and the internet remains unequal. Thirdly, ethical, privacy, and data security issues are critical. Collecting large amounts of student personal and learning data via AI, without robust and transparent security measures, risks privacy violations or AI bias stemming from non-diverse training data.

Significant positive impacts include students gaining more effective and accessible learning experiences tailored to individual needs, increased motivation, and teachers shifting to more strategic and creative coaching and mentoring roles. However, potential negative impacts must be acknowledged and prepared for. There's a risk of AI diminishing teachers' roles or causing resistance if teachers aren't adequately upskilled. Over-reliance on AI systems, without engaging in critical analysis, could reduce students' critical thinking and problem-solving skills. Most importantly, the digital divide could widen if technology access isn't comprehensive and equitable.

Conclusion and Suggestions

Implementing AI strategies in STEM science learning management offers a golden opportunity to revolutionize education. However, this must be pursued with a deep understanding of its potential and inherent challenges. Prudent planning, investing in skilled personnel, and strengthening technological infrastructure are all crucial steps. We also need to develop robust policies that address ethical considerations, data privacy, and equity to ensure AI benefits all students. To truly unlock AI's potential and create a sustainable, beneficial future for STEM education, collaboration is key. The government, educational institutions, the private sector, and AI experts must work together. This collective effort will ensure successful AI integration, fostering innovations that not only prepare our youth for the digital era but also benefit society as a whole. By carefully navigating both the promises and pitfalls, we can create an educational system that empowers the next generation to be leaders in science and technology.

RECOMMENDATIONS

To leverage AI for enhancing science learning management within the STEM education approach, both now and in the near future, a comprehensive, systematic, and highly flexible approach is essential. This ensures the maximum potential of AI to transform education while mitigating potential challenges and negative impacts.

The first key recommendation focuses on visionary personnel development and infrastructure, starting with a serious investment in training and upskilling teachers. This training should equip them with a deep understanding of AI principles and the ability to apply AI tools to design complex, analytical learning activities, rather than just using off-the-shelf software. The training should also emphasize transitioning teachers' roles from knowledge transmitters to facilitators, coaches, and mentors. They should be able to use AI for administrative tasks, automated assessments, and extracting deep insights into student learning behaviors to effectively refine their teaching.

Alongside personnel development, educational institutions must prioritize planning and allocating budgets for appropriate and sustainable technological infrastructure. This includes AI-compatible devices, stable high-speed internet networks, and reliable AI platforms with high security standards. Furthermore, clear policies regarding the collection, use, and protection of student data, as well as measures to prevent potential AI algorithm biases, are absolutely crucial. This builds trust and ensures safety for users and parents.

The second recommendation emphasizes creating a supportive and dynamic learning ecosystem. This begins with promoting systematic and continuous research and evaluation. Educational institutions should regularly assess the use of AI in STEM learning, utilizing data from AI-generated Learning Analytics alongside qualitative feedback from teachers, students, and other stakeholders. This data should then be analyzed to continuously refine strategies, tools, and teaching methods. Supporting teachers and educators in conducting research on AI use in STEM contexts to generate new knowledge and disseminate best practices will drive innovation and overall educational development.

Moreover, fostering strong partnerships with all stakeholders is paramount. This includes collaborating with AI experts from universities and research institutions, industry sectors, and other educational bodies to exchange knowledge, experiences, and resources, as well as jointly funding and developing innovations. Last but not least, establishing an open organizational culture that encourages creative AI experimentation in the classroom, viewing mistakes as part of the learning process (Culture of Experimentation), will reduce technophobia and stimulate the full potential application of AI. By diligently and systematically implementing these recommendations, educational institutions can effectively leverage AI to enhance science learning management within the STEM approach, preparing students to be future-ready citizens and fostering innovations that genuinely benefit society in the digital education era.

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Research Article

Ethnoscience Study of Madura in the Process of Making Sarkoyo Herbal Medicine as a Learning Resource for Science Material

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Abstract. Sarkoyo herbal medicine is one of Madura's cultural heritages in Sumenep Regency that has become less known to the younger generation, resulting in its limited utilization in science education. This study aims to reconstruct local knowledge about the process of making Sarkoyo herbal medicine so that it can be used as a source of ethnoscience-based science learning. The study employed a mixed-methods approach with a sequential descriptive design. Quantitative data were obtained from 150 junior high school students through questionnaires, while qualitative data were collected through interviews with science teachers and herbal medicine makers, as well as through observations and documentation. Quantitative data were analyzed descriptively, while qualitative data were analyzed using the Miles and Huberman interactive model. The results showed that most students were familiar with Sarkoyo herbal medicine, but the integration of ethnoscience into science learning was remained low. The process of making Sarkoyo herbal medicine consisted of 12 stages containing science concepts such as homogeneous mixtures, heat transfer, and nutritional content, all of which are relevant to basic junior high school science competencies. Sarkoyo herbal medicine can be reconstructed as an ethnoscience-based science learning resource that integrated biology, chemistry, and physics, and thereby contributing to the improvement of students' knowledge, the preservation of Madurese local wisdom, and the implementation of the Merdeka Curriculum in schools, ultimately strengthening students' character and scientific literacy.

Keywords: ethnoscience; Sarkoyo herbal medicine; local wisdom; science education

INTRODUCTION

Education as stipulated in Law Number 20 of 2003, is a conscious and planned effort to create a learning environment that encourages the development of students' potential, including spiritual strength, self-control, personality, intelligence, noble character, and the necessary skills for individuals, society, the nation, and the state (Azzahra *et al*., 2024). According to a study by Rizova *et al*. (2020), the lack of quality education can significantly impact an individual's quality of life over an extended period (Firdaus, 2025). Therefore, educators and students must collaborate to create an effective learning environment. Three key components in the learning process include the curriculum as a guideline, teachers as facilitators, and the interaction between students, educators, and learning resources (Rikizaputra *et al*., 2022). Science education can be enhanced by linking scientific concepts to everyday phenomena (Firdaus *et al*., 2025). At the junior high school level, understanding science concepts is crucial for developing analytical reasoning skills to explain events and solve problems (Pratiwi, 2022; Firdaus *et al*., 2024). Therefore, it is important to emphasize that science education should not only focus on conceptual understanding, but should also be directed towards developing various dimensions that support the formation of students' comprehensive competencies.

Science education in schools aims to develop students through four dimensions: products, processes, attitudes, and technology (Elisa *et al*., 2023; Firdaus *et al*., 2025). Science as a product encompasses conceptual, procedural, and metacognitive knowledge, consisting of facts, laws, principles, and theories that have been empirically validated (Arslan & Genc, 2024; Noushad, 2024). Teachers' ability to identify the categories of science content can facilitate the delivery of material through appropriate strategies (Muria & Budianti, 2021). Meanwhile, the process of science learning emphasizes the importance of direct experiences through investigations or experiments, which not only enhance students' understanding but also foster scientific attitudes (Mufidzah, 2024). Development in science education can be strengthened through a contextual approach that links scientific concepts to local culture, one of which is through the application of ethnoscience in learning.

Ethnoscience is a pedagogical strategy that creates a learning environment and experiences by integrating cultural elements into the learning process (Lidi *et al*., 2022). One cultural element that can be integrated is the community's system of knowledge, or indigenous science (ethnoscience), which differs from modern science. Science refers to systematically acquired knowledge obtained through the application of scientific methods. In contrast, ethnoscience refers to the knowledge of a community formed through socio-cultural constructions, which can be acquired through both scientific and non-scientific means (Mukti *et al*., 2022). The integration of ethnoscience in learning offers various benefits, including helping students understand meaningful local knowledge, engaging in cultural socialization based on local standards, and exhibiting attitudes and behaviors that align with local environmental principles (Syahputri *et al*., 2025). The application of ethnoscience in science education is very important for developing culture-focused education.

Culturally focused education is essential for students, as the application of this method fosters a sense of love for culture and nation. The process of learning that integrates culture into learning experiences is known as ethnoscience (Rikizaputra *et al*., 2022). Moreover, the study of ethnoscience in science education utilizes local knowledge as a learning resource or object, which can be incorporated into contextually presented lessons. Therefore, science education based on ethnoscience will integrate scientific concepts with local wisdom or culture (Kholidah *et al*., 2023). Ethnoscience refers to the indigenous knowledge held by a particular community. The goal of ethnoscience is to describe the environment from the perspective of the community under study. Meanwhile, the application of ethnoscience in the learning process aims to integrate local culture with teaching materials, thereby helping students understand content that is highly relevant to their daily lives. By using an ethnoscience approach, science learning can be conducted more scientifically and effectively (Siyati & Kamariyah, 2022). However, the implementation of ethnoscience in learning still faces a number of obstacles that require serious attention.

Based on previous studies conducted by Saputri & Desstya (2023), it was found that many educators have not yet integrated local wisdom into the learning process, particularly in the subject of Science, making the achievement of learning objectives quite difficult. This result is further supported by research from Wilujeng *et al*. (2024), which indicates that educators' lack of utilization of the surrounding environment, which integrates local potential as a learning resource for students, is a key issue. Additionally, according to research by Alfiana & Fathoni (2022), many teachers still face difficulties in linking learning with ethnoscience due to insufficient training in creating teaching materials focused on ethnoscience, which limits teachers' understanding of integrating material with the environment. Therefore, innovative efforts are needed in science education that can integrate local culture so that the learning process becomes more relevant to students.

Incorporation of local culture into science education is an innovative approach that yields more meaningful learning experiences, facilitating students' comprehension of the subject matter (Zidny *et al*., 2021; Marosi *et al*., 2021). Education that integrates ethnoscience perspectives tends to attract students' interest and enhance their curiosity (Kantina *et al*., 2022). However, the lack of ethnoscience research in Sumenep Regency is a primary factor contributing to the low application of ethnoscience in the learning process. This situation is further exacerbated by science education that still heavily relies on government-issued textbooks, which do not fully reflect the cultural characteristics of students in the region. One example of the application of local culture in science education can be found in the local wisdom of the Madurese people, particularly in Sumenep Regency.

Madura Island has a variety of traditional herbs, especially in Sumenep Regency. One of them is Sarkoyo herbal medicine, a Madurese cultural heritage. Sarkoyo herbal medicine is a traditional herb that has been used by the Madurese people for many years. Made from coconut milk, eggs, ginger, sugar, and cloves, this medicine is believed to help maintain health, treat internal heat, and even relieve headaches. Although a number of ethnoscience studies have been conducted highlighting various local intelligences, such as the production of Gunung Krayan salt (Kantina *et al*., 2022), Banten-style milkfish satay (Kholidah *et al*., 2023), and smoked fish (Syahputri *et al*., 2025), studies on Sarkoyo herbal medicine from Madura have never been systematically addressed in the context of science education. In fact, Sarkoyo is a cultural heritage that is beginning to be abandoned by the younger generation and has great potential as a source of contextual learning. This research gap has led to a knowledge gap, namely the lack of efforts to reconstruct local knowledge about Sarkoyo into scientific concepts that are in line with the basic science competencies in junior high school. Therefore, this research is novel in that it reconstructs traditional knowledge of Sarkoyo into an ethnoscience-based science learning resource, which not only contributes to strengthening students' science literacy but also to the preservation of Madurese local wisdom and the implementation of the Merdeka Curriculum. The production of Sarkoyo herbal medicine can be used as a learning resource in science education, with a focus on specific competencies through natural production that supports the sustainability of human life. In addition, it aims to reintroduce cultural heritage that is increasingly forgotten by the community and reconstruct the traditional knowledge of the Madurese people in making Sarkoyo herbal medicine, transforming it into scientific knowledge that can be a source of science learning.

METHODOLOGY

Research Design

This study used a mixed-methods approach by combining quantitative and qualitative methods (Creswell & Creswell, 2018) to analyze the application of ethnoscience in the process of making Sarkoyo herbal medicine as a source of science learning. The quantitative approach was used to examine the relationship between variables that influence learning, while the qualitative approach, through interviews with teachers and herbal medicine makers, helped to explore meanings and contexts that cannot be measured statistically. This design was chosen so that the research results would be more comprehensive and able to show how local knowledge about Sarkoyo herbal medicine can be integrated into science learning.

Population and Sample

Population of this study consisted of three main groups, namely junior high school students in Sumenep Regency, science teachers, and Sarkoyo herbal medicine practitioners in the Sumenep area, Madura. The involvement of students aimed to determine their knowledge and perceptions of the integration of ethnoscience in science education, while interviews with teachers were conducted to gather information about the learning media and curriculum used, as well as to identify the extent to which schools have integrated ethnoscience into learning. Meanwhile, the participation of Sarkoyo herbal medicine makers was intended to obtain authentic local knowledge that has been passed down from generation to generation.

Student samples were taken from several junior high schools in Sumenep Regency using questionnaires. There were 150 respondents aged around 13-15 years, which is the appropriate age for early adolescence, an important stage in the development of scientific reasoning and the cultivation of appreciation for local culture (Maison *et al*., 2020). The sample of science teachers was selected through interviews to identify learning practices, media utilization, and their relevance to the applicable curriculum, particularly regarding the integration of ethnoscience in science learning.

Sample of Sarkoyo herbal medicine makers was selected using purposive sampling, namely native herbal medicine makers from the Sumenep community who have inherited knowledge about making Sarkoyo herbal medicine from generation to generation. These herbal medicine makers were selected based on their local knowledge. Sarkoyo herbal medicine was chosen as the focus of this study because this traditional drink is beginning to be forgotten by the community, making it important to document it and examine its potential as a source of science-based ethnoscience learning.

Combining quantitative data from students, qualitative data from teachers, and qualitative data from herbal medicine practitioners, this study uses triangulation of sources to gain a more comprehensive understanding of how Sarkoyo herbal medicine can be reconstructed into a source of science learning.

Instrument and Data Collection

Instrument used in quantitative data collection was a questionnaire consisting of two scales designed to measure the variables studied in students. This questionnaire used a 10-point Guttman scale for each item, facilitating data collection and statistical analysis. Meanwhile, the instruments used to collect qualitative data are interview guides, observation protocols, and documentation. These interview guides include open-ended questions to explore the challenges and obstacles faced by teachers in using learning media and curriculum, as well as to identify the extent to which schools have integrated ethnoscience into the science learning process.

Data collection technique used in this study for quantitative data is simple random sampling, which is a sampling technique in which every member of the population has an equal chance of being selected, so it is done randomly (Subhaktiyasa, 2024). Meanwhile, purposive sampling is used for qualitative data. Purposive sampling is a technique for selecting samples (Ahmad & Wilkins, 2024). In addition, according to research Sugiyono (2015), sample selection is based on certain criteria, such as sources who are considered to be most knowledgeable about the topic being studied. Furthermore, the research data includes the results of an analysis of local wisdom in a particular region with additional data sources taken from relevant articles. This data served as a basis for describing the findings, while additional data from related articles provides a more in-depth context, so this approach is designed to ensure the completeness of the data to validate the research findings. In addition, the literature review in this article is written based on aspects of ethnoscience and local wisdom.

Data Analysis

Data analysis in this study used a mixed methods design of sequential explanatory models, thereby systematically combining quantitative and qualitative analysis. Quantitative data obtained through student questionnaires were analyzed descriptively using frequency distributions with the help of Excel (Hafizah *et al*., 2022) to determine students' knowledge, perceptions, and attitudes toward ethnoscience in the production of Sarkoyo herbal medicine. The results of this quantitative analysis then became the basis for determining the focus of the qualitative stage. Meanwhile, qualitative data was obtained through interviews with teachers and herbal medicine makers, field observations, and documentation analyzed using an interactive model proposed by Miles and Huberman. The Miles and Huberman model consists of three interrelated components: data reduction, data presentation, and conclusion drawing or verification (Miles & Huberman, 1994; Zulfirman, 2022). These stages were carried out sequentially during the qualitative research process to manage and interpret the collected data, particularly data on the process of making Sarkoyo herbal medicine and the ethnoscience study contained therein. The stages of data collection and analysis are presented in Figure 1.

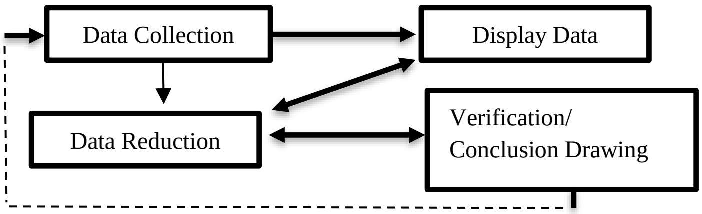

Figure 1. Stages of Miles and Huberman's data analysis model for qualitative data

Steps of interactive data analysis using the modified Miles and Huberman model from Wandi (2013), are as follows. In the data collection stage, researchers collect research data related to selected local wisdom through interviews, recording interview results, observation, and documentation. In the data reduction stage, researchers summarize, select key points, and focus on matters related to the selected local wisdom ethnoscience study. In the data presentation stage, researchers collected structured information and provided the possibility of drawing conclusions and making inferences. In the conclusion drawing or verification stage, researchers sought, tested, rechecked, or understood the meaning, regularity, patterns, explanations, flow, cause and effect, or propositions and described the findings.

RESULTS AND DISCUSSION

Results of the Study

These findings indicated that although students' prior knowledge of Sarkoyo herbal medicine was quite good, the implementation of ethnoscience in science education is still limited. Therefore, the development of ethnoscience-based teaching materials that highlight the process of making Sarkoyo herbal medicine can be an alternative to improve scientific concept understanding while strengthening the internalization of local cultural values. The questionnaire results are shown in Figure 2.

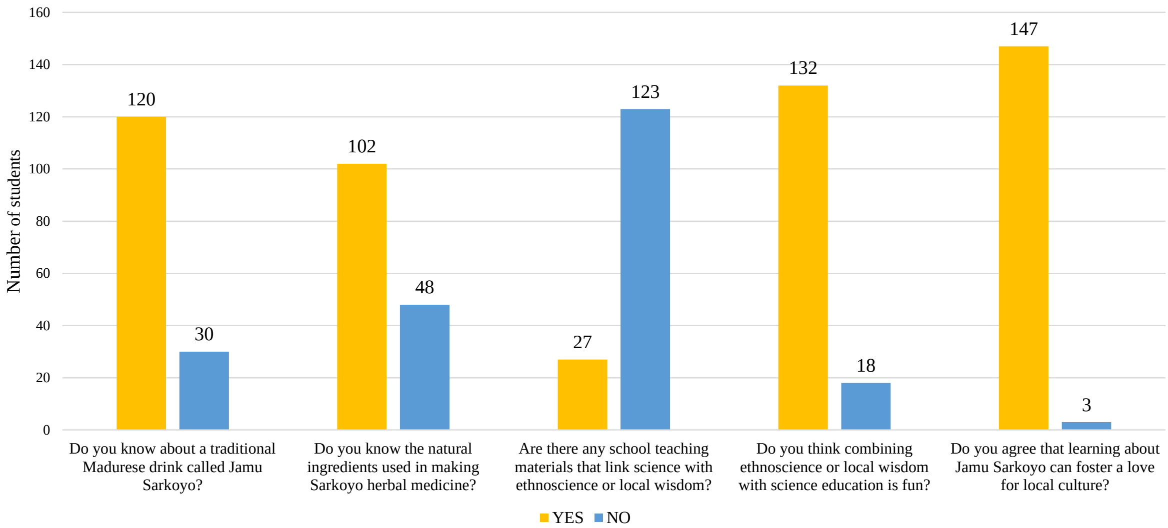

Figure 2. Results of the questionnaire on students' knowledge and perceptions of Sarkoyo herbal medicine ethnoscience

Results of the questionnaire analysis regarding students' knowledge and perceptions of JSarkoyo herbal medicine ethnoscience show that the majority of students are aware of this traditional Madurese drink. A total of 120 respondents stated that they knew about Sarkoyo herbal medicine, while 30 other respondents were not aware of it. Knowledge about the natural ingredients used in making Sarkoyo herbal medicine was also relatively high, with 102 students answering yes and 48 students answering no. However, the implementation of ethnoscience in science education in schools is still low. This is evident from the finding that only 27 students stated that they had found a connection between science teaching materials and ethnoscience or local wisdom, while 123 students stated that they had never found it. This condition shows that the potential for utilizing ethnoscience, especially related to Sarkoyo herbal medicine, has not been optimized in learning. Ethnoscience in education is very important because it contains natural sciences that study natural conditions and phenomena (Silla *et al*., 2023). In addition, students' local knowledge can bridge indigenous science with scientific science, thereby providing a more complete understanding (Mukti *et al*., 2022). With this background, it is important to look at how students perceive the implementation of ethnoscience in learning.

Students' perceptions of the implementation of ethnoscience are very positive. A total of 132 students believe that combining ethnoscience with science learning is an enjoyable approach, while only 18 students disagree. Furthermore, 147 students agree that learning about Sarkoyo herbal medicine can foster a love for local culture, while only 3 students disagree. Through the application of ethnoscience, teachers can make learning more interesting, relevant, and meaningful (Lestari & Nabila, 2024). Ethnoscience also increases the relevance of learning, helps students connect scientific concepts with local life, and can increase interest and motivation in learning science (Sari *et al*., 2023). These positive findings are further reinforced by various studies showing the effectiveness of ethnoscience in improving the quality of learning.

These findings are in line with various studies that confirm the effectiveness of ethnoscience in learning. According to Anggraini & Asante (2024), students who use ethnoscience-based worksheets show greater learning outcomes than the control group. Furthermore, according to Pitri *et al*. (2025), ethnoscience has been proven to increase students' motivation, curiosity, and independence in learning, while also preserving local wisdom. Thus, the application of ethnoscience, especially in the context of Sarkoyo herbal medicine, has great potential to be integrated more widely into science education.

Integration with Science Concepts

Based on the research process conducted through observations and interviews with the Prenduan community in Sumenep, who possess the skill and knowledge of preparing Sarkoyo herbal medicine, it was revealed that the preparation of Sarkoyo herbal medicine is a tradition for the local community. It is typically consumed by families or served during special events, such as weddings and the month of Ramadan. The preparation of Sarkoyo herbal medicine is still carried out traditionally, on a small-scale production basis by the local people, passed down through generations from their ancestors. The stages of the Sarkoyo herbal medicine preparation process are depicted in Figure 3.

Figure 3. Stages of the Sarkoyo herbal medicine manufacturing process (Personal Document)

Figure 3 shows the traditional steps in making Sarkoyo herbal medicine, starting from grating coconut and preparing the main ingredients such as ginger, eggs, and brown sugar. After the ingredients are filtered and mixed, the mixture is then boiled to produce a herbal drink that is ready for consumption. The entire process is carried out traditionally using simple household appliances by the people of Madura. Figure 1 above illustrates that the process of preparing Sarkoyo herbal medicine, as practiced by the local community, involves 12 steps. This information was revealed through observations and interviews conducted with the community. The first step is grating the coconut. The second step is to add a small amount of water to the grated coconut and then strain it to extract the coconut milk. The third step involves grating ginger. The fourth step is to add a little water to the grated ginger, squeeze it, and then place the ginger extract into the container used for the coconut milk. The fifth step is adding one free-range egg to the mixture of coconut milk and ginger extract. The sixth step involves adding palm sugar to the mixture in moderation. The seventh step is thoroughly mixing all the ingredients until they are well combined. The eighth step is pouring the herbal mixture into an aluminum bowl. The ninth step is placing the bowl containing the mixture into a pot of water for the steaming process. The tenth step is to steam the herbal mix for approximately 10 minutes, until it thickens, and water forms beneath the coagulated coconut milk and egg mixture. The eleventh step is inspecting the herbal medicine; if it has thickened and clumps have formed, it indicates that the Sarkoyo herbal medicine is ready. Finally, in the twelfth step, the Sarkoyo herbal medicine is prepared for serving and consumption.

Preparation of Sarkoyo herbal medicine by the Prenduan community in Sumenep, particularly those skilled in its traditional formulation, generally follows 12 stages (Figure 1). Each stage is an essential prerequisite for the next, ensuring that the final product of the herbal medicine is of high quality, both in terms of flavor, consistency, efficacy, and shelf life.

The first step is grating the coconut. The second step involves squeezing the grated coconut to obtain pure coconut milk, which serves as the primary component in the preparation of Sarkoyo herbal medicine. Coconut milk serves as the base ingredient, binding all other components together while providing a smooth texture and distinctive flavor. The quality of the coconut milk is greatly influenced by factors such as water content, pH level, and free fatty acids. A study by Diana *et al*. (2023) demonstrated that coconut milk with a water content of approximately 60.4%, a pH of 6.2, and free fatty acids below 0.1% exhibits good quality and stability. Therefore, optimal quality coconut milk is crucial in determining the success of the Sarkoyo herbal medicine, both in terms of flavor and nutritional value.

Third step is grating the ginger. The fourth step involves adding water to the grated ginger, squeezing it, and mixing the ginger extract with the coconut milk. Ginger is chosen as an additional ingredient due to its active compounds, such as gingerol, shogaol, and zingiberene, which possess antioxidant and anti-inflammatory properties. Research by Mao *et al*. (2019) revealed that ginger contains bioactive components like gingerol, beta-carotene, capsaicin, caffeic acid, curcumin, and salicylates, which enhance the immune system and help alleviate mild health issues such as nausea, digestive problems, and minor infections. The addition of ginger extract to Sarkoyo not only enriches the flavor and aroma but also enhances the medicinal properties of the herbal drink, making it a traditional immunity booster.

Fifth step involves adding one free-range egg to the mixture of coconut milk and ginger extract. Free-range eggs are selected because they are rich in vital nutrients, including iron, vitamin B12, high-quality proteins, and amino acids that are beneficial for the body. According to Tirtawati *et al*. (2023), regular consumption of free-range eggs can increase hemoglobin levels due to their easily absorbed iron content and the role of vitamin B12 in red blood cell formation. The inclusion of eggs in Sarkoyo not only enhances the nutritional value but also contributes to the texture and thickness of the herbal medicine, improving overall stamina.

Sixth step is adding an appropriate amount of palm sugar to the mixture. Palm sugar is chosen as a natural sweetener, which not only enhances the taste of Sarkoyo with its distinctive flavor but also provides essential nutrients for the body. Palm sugar contains various minerals such as calcium, phosphorus, and iron, as well as sucrose, fructose, and glucose that support the body's energy metabolism. Research by Arziyah *et al*. (2022) indicates that the addition of palm sugar improves the organoleptic properties of beverages, particularly in terms of color and flavor, which are highly favored by consumers.

Seventh step is stirring all the ingredients to ensure uniformity. Stirring is crucial to ensure that the coconut milk, ginger, egg, and palm sugar blend homogenously. According to Dasopang *et al*.

(2025), the speed and duration of the homogenization process impact the chemical and visual quality of coconut milk, including its pH, TSS (total soluble solids), and color. While the particle size does not significantly change, homogenization improves the consistency and stability of the coconut milk used as the base ingredient for the beverage. The stirring process in making Sarkoyo is essential to guarantee the stability and quality of the herbal medicine.

Eighth step is pouring the herbal mixture into an aluminum bowl. The choice of an aluminum bowl is to support even heating or steaming in the subsequent step. Aluminum is an excellent thermal conductor, which helps distribute heat evenly throughout the herbal mixture. A study by Sari *et al*. (2023) found that among various metal materials tested, such as aluminum, iron, and brass, aluminum exhibited the highest rate of heat transfer, reaching an average of 325.5 watts at 80°C, twice the heat transfer rate of iron (±147.1 watts) and brass (±218.5 watts). This result demonstrates the effectiveness of aluminum in heat transfer. By using aluminum containers, the entire Sarkoyo herbal mixture receives consistent heat during steaming, ensuring optimal cooking without uneven heating.

Ninth step involves placing the aluminum bowl containing the herbal mixture into a pot of water for the steaming process. Steaming is chosen because it provides moist heat that envelops the ingredients evenly without direct contact with water, thus reducing the risk of burning and preserving nutrients that are sensitive to high heat. Research by Moyo (2024) indicates that steaming preserves more vitamins and minerals than direct boiling, as water contact is minimal and the temperature is lower. Therefore, the use of steaming in preparing Sarkoyo helps preserve the bioactive compounds and nutrients in the coconut milk, ginger, egg, and palm sugar more effectively than direct heating.

Tenth step is to steam the herbal medicine for approximately 10 minutes, until it thickens, forms clumps, and water appears beneath the coagulated coconut milk and egg. This process involves the coagulation of egg proteins and the stabilization of the coconut milk emulsion, resulting in the characteristic texture of Sarkoyo. Research by Riyada (2022) shows that steaming at 85 °C causes the egg emulsion to transition from a liquid (sol) to a semi-solid (gel) due to protein coagulation. This process creates clumps as proteins denature and bind together to form a solid structure that can trap water and fat. Coconut milk also responds similarly to heating. Additionally, research by Putranto *et al*. (2022) indicates that appropriate heating duration reduces water content and enhances emulsion stability. This process yields a desirable texture and improves shelf life.

Eleventh step involves observing the herbal mixture in the bowl. If the texture has thickened, clumps have formed, and liquid has separated around the mixture, this signals that the coagulation and emulsification processes are complete, indicating that the Sarkoyo herbal medicine is ready. This consistency is the result of the stable bonding between egg proteins and coconut milk fats after heating.

Finally, the twelfth step marks the readiness of the Sarkoyo herbal medicine to be served and consumed. At this stage, the herbal medicine exhibits its characteristic consistency, aroma, and flavor, with the nutrients having blended optimally, making it ready to deliver functional health benefits, particularly in terms of energy recovery and immune support.

Reconstruction of Indigenous Knowledge into Scientific Knowledge

Based on the interviews conducted, it was found that the entire process of preparing Sarkoyo herbal medicine, ranging from selecting natural ingredients to mixing, processing through steaming, and finally serving, embodies a wealth of local knowledge (indigenous science) that can be correlated with scientific knowledge. This local knowledge has been passed down through generations in Madurese culture. Therefore, the process of preparing Sarkoyo herbal medicine can be utilized as a learning resource in Science education, including subjects such as Biology, Physics, and Chemistry. The reconstruction of indigenous knowledge into scientific knowledge is illustrated in Table 1.

Based on the reconstruction of local knowledge into scientific knowledge as shown in Table 1, it can be seen that the process of making Sarkoyo herbal medicine contains various scientific concepts that are relevant to science learning. However, to make it clearer and more systematic, the stages of developing local knowledge into ethnoscience-based teaching materials need to be visualized in the form of a flowchart. This diagram provides a comprehensive overview of the flow from the identification of community knowledge to the process of developing it into a learning resource that is integrated with the curriculum, as shown in Figure 4.

Table 1. Reconstruction of indigenous knowledge into scientific knowledge

No	Topic	Indigenous Knowledge	Scientific Knowledge
1	Coconut Selection	Old coconut because it has a lot of coconut milk.	Old coconut is chosen as the best raw material because the maturity level of the coconut endosperm significantly affects its physicochemical characteristics (such as brix, fat, and total solids), thus producing more coconut milk with high fat and nutritional content (Konadu *et al*., 2023).
2	Soaking and Washing	The materials will be clean and easy to boil.	The soaking and washing stages are crucial in the processing of traditional herbal ingredients, particularly for removing dirt, reducing antinutritional compounds, and facilitating the extraction of active ingredients for cooking or use. However, this process is also recognized as one of the primary sources of water usage in the natural ingredient processing industry, generating liquid waste containing organic and inorganic compounds that can pollute the environment (Safitriyawi *et al*., 2024). Therefore, implementing clean production strategies with a focus on water use efficiency and wastewater management is crucial for improving the sustainability of processes, enhancing product quality, and minimizing environmental impact (Akbari & Moslem, 2025).
3	Use of Coconut Milk	Coconut milk can strengthen the immune system.	Coconut milk is widely used in food and beverage processing because it enhances aroma, flavor, and nutritional value, while also improving the texture of food (Lina, 2022). Besides its distinct taste, coconut milk also contains essential nutrients, including fat, protein, carbohydrates, vitamins, and minerals, that are beneficial for health (Meilizar *et al*., 2024). Saturated fatty acids, such as lauric acid, also offer additional benefits to the body (Dasopang *et al*., 2025).
4	Boiling Coconut Milk	To make it more savory and last longer.	Boiling coconut milk triggers the release of lauric acid, a substance with antimicrobial properties (Dasopang *et al*., 2025). Additionally, boiling with coconut milk can reduce the fishy odor and enrich the aroma of food (Syefani & Nuraeni, 2024). However, it is essential to pay attention to the temperature and duration of boiling because excessive cooking time may reduce the content of specific vitamins, although it can enrich flavor and texture (Permata & Abdiel, 2025).
5	Egg Selection	Free-range chicken eggs are better.	Free-range chicken eggs are preferred because they have a better taste and chewier texture compared to regular eggs (Elu *et al*., 2024). Free-range chicken eggs have equivalent or even better nutritional value in certain aspects (protein, vitamins, minerals) compared to commercial chicken eggs, although their cholesterol levels tend to be higher (English, 2022). Furthermore, free-range eggs contain 12.80% protein, 11.5% fat, 0.75% carbohydrates, and 74.0% water, making them a high-nutrient food source for animals (Amalyadi & Yanti, 2025).
6	Use of Eggs	It can relieve pain or discomfort.	Eggs are rich in various vitamins and minerals needed by the body, such as vitamin A, riboflavin, folic acid, vitamins B6 and B12, choline, iron, calcium, and phosphorus. Although the iron content in eggs is not as high as in red meat, eggs are still effective in reducing inflammation. This is due to the vitamin A content in eggs, which plays a key role in relieving pain and inflammation (Sherly & Kamidah, 2024).
7	Use of Ginger	To warm up the body.	Ginger is believed to be an effective remedy for warming the body, relieving nausea, and enhancing blood circulation. Additionally, ginger serves as a tonic to improve overall health and alleviate various ailments (Ahnafani *et al*., 2024).
8	Adding Palm Sugar	To make it sweeter.	Palm sugar is a natural sweetener that is safe for the body and offers various benefits, including boosting the immune system, acting as an antioxidant source, preventing anemia, stabilizing cholesterol levels, warming the body, improving blood circulation, and treating internal heat (Aprianto *et al*., 2024).
9	Stirring	To mix everything.	Stirring is the process of mixing two or more substances to create a homogeneous mixture (Eggl & Schmid, 2022). Additionally, stirring can help create a suspension of solid particles, accelerate heat transfer between liquids and heat sources, and mix miscible liquids (Miller *et al*., 2025).

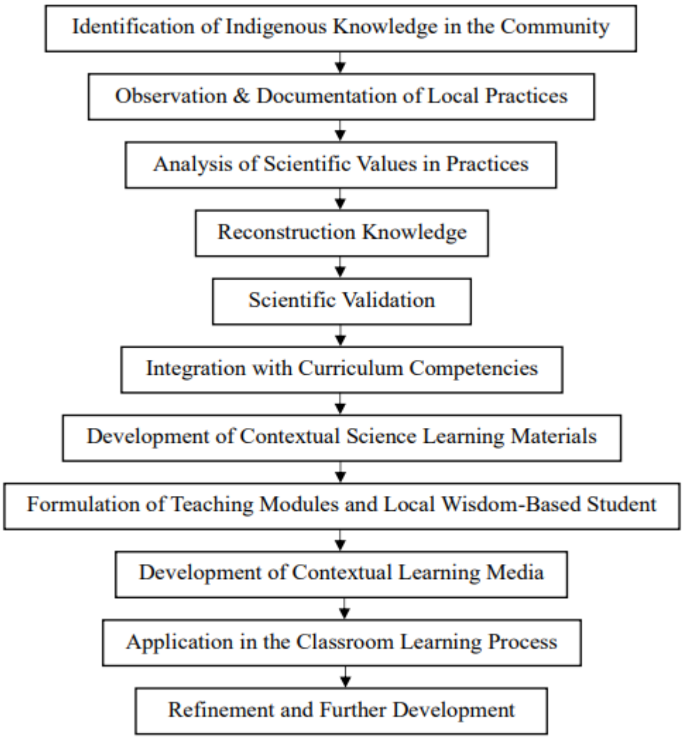

Figure 4. The development of ethnoscience-based science teaching materials for science education

Through the stages shown in Figure 4, the process of developing ethnoscience in science education becomes more focused and measurable. Each step, starting from the identification of local knowledge to its application in the classroom, demonstrates the continuity between local culture and scientific concepts. Thus, this flowchart not only emphasizes the importance of strengthening scientific knowledge of traditional knowledge, but also provides a clear framework for teachers to integrate local wisdom values into teaching materials. This framework can increase the relevance of science learning while preserving the culture of the local community.

Application in learning

Sarkoyo herbal medicine, a traditional concoction of the Madurese community and a form of local wisdom in Sumenep Regency, can be utilized as a learning resource for Junior High School Science through the transfer of indigenous knowledge into scientific knowledge. Thus, this ethnoscience study can serve as a valuable contextual resource for science learning. The integration of Science concepts with Sarkoyo herbal medicine, linked to the basic competencies of the Junior High School Science curriculum, is presented in Table 2.

Based on the source analysis conducted in Table 2, it was found that the explanation of the process of preparing Sarkoyo herbal medicine is closely related to several basic competencies within the Science curriculum. This will help teachers connect science concepts with the herbal preparation process. The connection between the basic competencies and the components involved in the preparation process can serve as a contextual learning resource for students. With this understanding, students will develop a greater appreciation for local wisdom and cultural values, which are also fundamental to the objectives of national education.

Providing learning materials related to the values, traditions, norms, or local culture within the students' environment is one approach that teachers can use to support curriculum policies. According to a study by Annisha (2024), the integration of local wisdom values within the context of the Merdeka Curriculum not only preserves local culture and traditions but also strengthens the educational foundation for students across various life aspects. Furthermore, according to

Rikizaputra *et al*. (2022), many teachers still struggle to connect Science material with the local wisdom present in their environment, a concept known as ethnoscience.

Table 2. The relationship between sarkoyo herbal medicine and basic science competencies

No	Basic Competency (KD)	The Concept of Science in Sarkoyo	Example of Class Assignment	Assessment Idea
1	KD 3.3: Explain the concepts of pure substances (elements, compounds) and mixtures, as well as their physical and chemical properties in everyday life.	The preparation of Sarkoyo involves a homogeneous mixture (coconut milk + ginger + palm sugar + eggs).	Students were asked to make a chart distinguishing pure substances and mixtures from Sarkoyo materials.	Worksheet analyzing pure substances vs. mixtures (concept accuracy rubric).
2	KD 3.5: Analyzing temperature, heat, expansion, heat transfer.	The heating/steaming process of Sarkoyo demonstrates conduction, protein coagulation, and emulsion stability.	Simple experiment: observe physical changes (egg coagulation, changes in coconut milk when heated).	Practical report with criteria: process description, heat concept, conclusion.
3	KD 3.7: Describe the diversity of genes, species, and ecosystems.	Sarkoyo ingredients (coconut, ginger, free-range chicken eggs) represent biodiversity.	Group discussion: identifying the conservation potential of natural materials used in Sarkoyo.	Group presentation with assessment of scientific aspects + environmental awareness.
4	KD 3.11: Explaining additives and addictive substances and their effects.	Sarkoyo uses natural ingredients without synthetic additives.	Case study: compare traditional beverages (Sarkoyo) with modern packaged beverages (synthetic additives).	The written test consists of analytical questions (essays) about the benefits and risks of additives.

CONCLUSION AND LIMITATIONS

Conclusion

This study shows that the process of making Sarkoyo herbal medicine by the Madurese people, especially in Sumenep Regency, contains a wealth of traditional knowledge (ethnoscience) that can be systematically reconstructed into scientific concepts and effectively utilized as a meaningful learning resource for science education. Empirical findings show that the preparation process, which involves 12 stages, facilitates a clear integration between biological, chemical, and physical concepts, such as homogeneous mixtures, heat transfer, and nutritional content, which are directly relevant to the junior high school science curriculum. In addition, the mixed-methods approach revealed that students had positive perceptions of ethnoscience integration, with the vast majority agreeing that this approach was enjoyable and fostered a love for local culture. This positive attitude among students strongly supports the application of local wisdom in the classroom. This integration of science and culture strengthens the connection between subject matter and students' daily lives, while instilling an important sense of appreciation for local culture and strengthening scientific literacy. Therefore, Sarkoyo herbal medicine can be effectively utilized as an additional ethnoscience-based learning resource that supports the implementation of the Merdeka Curriculum in schools, which ultimately strengthens students' character and scientific literacy.

Limitations

Although this study provides valuable insights into the potential of Sarkoyo herbal medicine as a source of science learning, several limitations must be acknowledged. The specific qualitative sample, namely herbal medicine practitioners in the Sumenep region, as well as the limited coverage of schools in Sumenep Regency, limit the generalization of findings on the reconstruction of local knowledge to cultural or educational contexts outside Madura. This study focuses on knowledge reconstruction and analysis of students' and teachers' initial perceptions of ethnoscience integration, thus neglecting the evaluation of the effectiveness of the final product. This study does not present longitudinal data and does not consider how the long-term impact of ethnoscience-based teaching materials can influence the strengthening of students' character and scientific literacy. Further research is needed to address these limitations, including the development of ethnoscience-based teaching modules and student worksheets using Sarkoyo herbal medicine ethnoscience-based learning media, as well as validation of feasibility by experts and measurement of the effectiveness of teaching materials integrated with Sarkoyo herbal medicine using test instruments such as science literacy test sheets in the form of pre-tests and post-tests on students in a controlled classroom environment (quasi-experimental) that can be presented with a participatory approach, where students are encouraged to be active and to ensure that the materials developed are in line with the needs and cultural context, such as Sarkoyo herbal medicine, of the students.

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Research Article

Beyond Formula: Exploring Students' Lived Experiences in Physics Problem-Solving

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Abstract. Understanding how students engage during physics problem-solving is crucial for improving learning outcomes. Despite efforts to enhance conceptual understanding and support meaningful learning, few studies have examined how strategic, emotional, and agentic engagement intersect in students' lived experiences of solving physics problems. This study explored how high school STEM students from Baybay City, Leyte, experience and express these dimensions, highlighting engagement as extending beyond formulas into meaning-making and self-directed learning. Using a descriptive phenomenological design guided by Giorgi's (2009) method, ten students were interviewed with semi-structured, open-ended questions that prompted them to narrate their problem-solving experiences. Interviews were audio-recorded, translated from Bisaya to English using AI-assisted tools, and analyzed through phenomenological reduction, segmentation into meaning units, and synthesis into essential psychological structures. Analysis revealed four interrelated constituents of engagement: (1) strategic engagement, reflected in deliberate, organized problem-solving methods such as GAFSA and visual representations; (2) emotional engagement, manifested in regulating anxiety, stress, and excitement into calmness and satisfaction; (3) agentic engagement, demonstrated through proactive self-direction and collaboration, including creating reviewers, clarifying concepts, and supporting peers; and (4) transformative impact, where students internalized clarity, reflection, and initiative as transferable skills. Physics problem-solving thus emerged as a lived experience integrating thought, emotion, and action. The study concludes that reflective, student-centered pedagogies that cultivate these three dimensions can humanize physics learning, fostering conceptual mastery, emotional resilience, and empowered, self-directed learners.

Keywords: Strategic engagement; Emotional engagement; Agentic engagement; Phenomenology; physics problem-solving

INTRODUCTION

Physics is more than formulas and equations. It is a puzzle, a challenge, and sometimes a battlefield of the mind. For many Filipino students, solving physics problems can feel overwhelming as they try to translate abstract concepts into step-by-step solutions and apply mathematical reasoning to unfamiliar situations (Laguindab & Cagas, 2025). Teachers often point out that weak mathematical foundations make problem-solving one of the hardest skills to master. Despite these challenges, some students persist, finding strategies and small victories that often go unnoticed. By examining how students navigate challenges, interpret abstract concepts, and employ mathematical reasoning, educators and researchers can develop instructional practices that are more responsive to learners' needs (Pasigon, 2024). This focus aligns with contemporary educational priorities that emphasize holistic learning, student well-being, and the cultivation of lifelong problem-solving skills (OECD, 2023). Moreover, insights into students' experiences can inform curriculum design, teaching strategies, and assessment methods that not only evaluate conceptual understanding but also nurture curiosity, persistence, and confidence in tackling complex scientific tasks.

Physics education research has predominantly emphasized cognitive outcomes, such as conceptual understanding, misconceptions, and problem-solving performance (Mestre et al., 2011; Favale & Bondani, 2014). While these studies have yielded important instructional insights, they often overlook the subjective experiences that shape students' engagement and learning strategies. For instance, students' frustration, anxiety, or excitement during problem-solving can significantly influence both their performance and motivation, yet these affective dimensions remain underexplored in the Philippine context. Recent international studies suggest that addressing these experiential factors is linked to higher persistence, improved self-efficacy, and better learning outcomes in STEM education (Mohamoud, 2024; Pasigon, 2022).

Despite the recognized challenges of physics problem-solving, few studies focus on the Filipino learners' personal experiences as they navigate abstract and mathematically intensive problems. Existing research tends to measure performance outcomes without exploring the cognitive-emotional interplay that occurs during the problem-solving process. This gap limits our understanding of how students develop strategies, sustain effort, and negotiate complex tasks, leaving educators with an incomplete picture of learners' needs.

Studies from other contexts highlight that students' engagement in problem-solving involves both cognitive strategies and affective responses. Espinoza (2020) and Nautiyal et al. (2025) observed that students frequently encounter moments of confusion, trial-and-error experimentation, and strategic reflection, which are crucial to conceptual development. These findings suggest that examining lived experiences provides complementary insights to traditional performance-based assessments, revealing processes that are otherwise hidden in test scores.

While localized and innovative teaching approaches have shown promise in improving performance, there remains a lack of research capturing how students personally experience these interventions in the Philippine context. Understanding students' emotional, strategic, and agentic responses can inform more targeted instructional designs that enhance engagement, persistence, and confidence in physics learning.

Paulmitan and Manceras (2025) and Gardose et al. (2025) demonstrate that contextualized modules and multimodal strategies improve conceptual understanding. However, the studies do not address how students internally process these experiences, make decisions during problem-solving, or reconcile abstract concepts with practical applications. Integrating these experiential insights could deepen the impact of instructional interventions and promote more learner-centered approaches.

In the Philippines, physics continues to be one of the most challenging subjects for high school students. National assessments and classroom observations indicate that learners often struggle with mathematical formulations, interpreting physical models, and applying theory to unfamiliar problems (Bogador et al., 2024; Donalie et al., 2024). Teachers report that students' engagement varies widely, with some demonstrating resilience and strategic initiative, while others experience persistent anxiety and avoidance behaviors. These patterns highlight the need for research that examines both the cognitive and affective dimensions of problem-solving within the local educational context.

This study aims to explore the lived experiences of Filipino high school students as they engage in physics problem-solving. Specifically, it investigates how students navigate challenges, integrate conceptual understanding with mathematical reasoning, and exercise personal initiative during problem-solving tasks. By capturing these experiences, the study seeks to identify patterns in students' strategies, emotional responses, and reflective practices, providing insights that can inform learner-centered instruction and support holistic science education.

The primary aim of this paper is to provide a rich, qualitative understanding of students' experiences in physics problem-solving, moving beyond traditional performance measures. By documenting the narratives of how students perceive, interpret, and respond to complex tasks, this study contributes to the development of instructional approaches that enhance conceptual mastery, confidence, and persistence. Ultimately, it seeks to advance inclusive and equitable science education by informing interventions that support not only academic success but also the well-being and engagement of learners in the Philippine context, in alignment with SDG 4.

RESEARCH QUESTION

How do students experience and express their engagement in physics problem-solving?

METHODOLOGY

Research Design

This study employed a descriptive phenomenological research design to explore the lived experiences of students' while solving physics-related problems. Descriptive phenomenology is appropriate for this study because it aims to uncover the essential structure and meaning of a phenomenon as it is experienced by individuals rather than to test hypotheses or measure variables (Creswell & Poth, 2018). The research followed Giorgi's (2009) method, which involves a systematic approach to analyzing first-person narratives and transforming them into psychologically sensitive meaning units. Specifically, the researcher first adopted a phenomenological attitude through bracketing, setting aside personal assumptions to maintain objectivity. Each transcript was then read repeatedly to gain a holistic understanding, followed by identification of meaning units and their transformation into expressions that capture the psychological essence of participants' experiences. This step-by-step process ensured that the analysis remained grounded in the participants' lived experiences, providing detailed insight into how students think, feel, and act during physics problem-solving. By clearly outlining the procedural steps of data analysis, this study enhances methodological transparency and allows for replication in similar educational contexts.

Participants

The participants in this study consisted of ten High School students enrolled in the Science, Technology, Engineering, and Mathematics (STEM) Program at Baybay city, Leyte. This sample size aligns with recommendations for descriptive phenomenological studies, which emphasize depth over breadth to generate rich, detailed data suitable for uncovering lived experiences (Creswell & Poth, 2018). Purposive sampling was employed to ensure that all participants had firsthand engagement with physics problem-solving and could articulate their engagement. This approach provided in-depth insights essential for addressing the study's focus on understanding how students navigate and experience physics problem-solving beyond formulas.

Table 1. Participants of the Study.

Participants	Sex	Age	Q1- Science Grade '25-26
P1	F	15	97
P2	M	16	94
P3	F	15	94
P4	M	15	94
P5	F	15	93
P6	M	17	98
P7	F	16	97
P8	F	15	97
P9	F	15	92
P10	F	16	97

Research Tools

This study employed semi-structured interviews with carefully designed open-ended questions to explore participants' lived experiences in depth. Aligned with Englander's (2012) phenomenological perspective, the interviews prioritized detailed descriptions of participants' experiences rather than rigid questioning.

Interviews began with broad invitations to describe relevant situations, followed by context-sensitive prompts that avoided leading assumptions, ensuring both depth and flexibility in data collection. Responses were captured through audio recordings and supplemented with observational notes. The interview protocol was reviewed for clarity and piloted with a small sample to confirm its effectiveness.

To enhance trustworthiness, member checking, peer debriefing, and detailed field notes were employed. Ethical considerations, including informed consent, confidentiality, and participant comfort, were strictly observed. These measures collectively strengthened the reliability, credibility, and rigor of the research tool.

The semi-structured interview protocol consisted of open-ended questions designed to capture the participants' lived experiences in solving physics problems. Questions began with broad prompts such as, "Can you describe a situation where you solved a physics problem?" and were followed by context-sensitive probes to explore strategic approaches, emotional responses, and initiatives taken during problem solving, for example: "What steps did you take to organize information or visualize the problem?", "How did you feel when you encountered confusion or difficulty?", and "Did you help yourself or others during the process? If so, how?" Each question was carefully formulated to avoid leading assumptions and encourage rich, descriptive responses. The protocol was piloted with a small sample to confirm clarity, relevance, and flexibility, and revised based on feedback. To ensure quality, measures such as member checking, peer debriefing, and detailed field notes were employed, strengthening the reliability, credibility, and rigor of the research tool.

Data Collection

Data were collected through individual semi-structured interviews with ten participants, guided by Englander's (2012) recommendations for descriptive phenomenological interviewing. Each interview began with an open-ended invitation for participants to recount specific situations in which they solved physics-related problems, followed by context-sensitive prompts to encourage elaboration while minimizing researcher bias.

Interviews were conducted in a quiet, mutually agreed-upon space within the school to ensure participants' comfort and privacy, with each session lasting approximately 20–25 minutes. With informed consent, all interviews were audio-recorded using a dedicated device, with a backup software application to prevent data loss. Additionally, key responses were highlighted in written bullet form during the session, and follow-up questions were collected via Google Forms for participants who preferred non-face-to-face interaction. Detailed field notes were taken during and immediately after each session to capture non-verbal cues, contextual factors, and reflexive observations (Merriam & Tisdell, 2016).

Together, these data collection ensured an accurate, comprehensive, and ethically sound record of each participant's account. Furthermore, the explicit description of data collection procedures enhances the study's transparency and replicability, allowing other researchers to follow the same systematic steps in future phenomenological investigations (Lincoln & Guba, 1985).

Data Analysis

The study employed Giorgi's descriptive phenomenological method (Giorgi, 2009) to analyze the interview data and uncover the phenomenological structure of students' lived experiences of in physics problem-solving. Following Giorgi's (2009) five-step Descriptive Phenomenological Method, the researcher: (1) adopted the phenomenological attitude through bracketing; (2) read each transcript repeatedly to gain a holistic sense; (3) segmented the data into meaning units at points of psychological significance; (4) transformed these units into psychologically sensitive expressions while preserving participants' intent; and (5) synthesized the transformed units to articulate the general structure of students' strategic, emotional, and agentic engagement in physics problem-solving. Grounded in Husserlian phenomenology (Husserl, 1913/1982), this method aims to describe phenomena as they are lived rather than explain them through external theories. By following Giorgi's approach, participants' first-person accounts were systematically organized and transformed into psychologically sensitive expressions that captured the essence of their experience.

Meaning units emerged directly from participants' narratives without pre-assigned categories. Units reflecting cognitive, emotional, or behavioral significance were transformed into psychologically sensitive expressions. For example, statements describing organizing information, drawing diagrams, or sequencing steps were interpreted as strategic engagement; managing anxiety or taking reflective pauses were categorized as emotional engagement; and preparing reviewers, sharing solutions with peers, or suggesting instructional improvements were identified as agentic engagement. Through repeated comparison and synthesis, these constituents naturally emerged from the data, grounded in students' lived experiences rather than researcher assumptions.

Artificial intelligence (AI) tools were utilized to assist in translating students' statements from Bisaya to English to ensure clarity and linguistic accuracy while preserving the authenticity of their meanings. AI-assisted applications were also employed for grammar and spelling refinement to enhance the readability of transcribed and translated data. However, all processes of interpretation, meaning transformation, and phenomenological reduction remained entirely researcher-driven in accordance with Giorgi's (2009) method.

Throughout the analysis, the researcher maintained methodological rigor by carefully following Giorgi's (2009) systematic steps. Trustworthiness was enhanced through reflexivity—*regularly reflecting on personal assumptions to minimize bias*—and by keeping a clear, transparent record of all analytic decisions (Lincoln & Guba, 1985). This careful approach ensured that the findings accurately reflected students' lived experiences and provided a credible basis for the constituents discussed in the Findings section.

Ethical Consideration

To ensure the ethical conduct of this research, informed consent was obtained from parents or guardians, and assent was secured from student participants to confirm their voluntary participation and right to withdraw at any time without academic or personal consequence. Confidentiality and anonymity were strictly maintained by assigning pseudonyms and securely storing all research data in compliance with the Philippine Data Privacy Act of 2012. The researchers upheld a respectful and empathetic stance throughout the interviews to minimize distress, while participants were encouraged to seek assistance from the school's support services if needed. These measures were implemented in alignment with the ethical principles of respect for persons, beneficence, and justice, as well as the standards set by the Department of Education's Basic Education Research Agenda (DepEd Order No. 39, s. 2016).

RESULTS AND DISCUSSION

This section presents the findings on students' lived experience in solving physics problems. Data from interviews were analyzed to show how students' approach/engagements and its impact during physics problem-solving. Each finding is discussed in relation to its implications for learning and understanding physics.

Table 2. Students' Strategic, Emotional, and Agentic Engagement in Physics Problem-Solving.

Constituents	Identification Number of Participants
The use of organized, step-by-step methods and visual tools to handle physics problems.	
- Students used structured methods like GAFSA or *"list, draw, substitute"* to organize information and reduce confusion.	P1, P5, P7, P9, P10
- Students commonly wrote down given/asked values, recalled formulas, and converted units to SI before computing to avoid errors.	P2, P6, P9
- Many drew diagrams or sketched setups to visualize the problem and guide groupmates.	P3, P4, P5, P9
- A number preferred to solve independently first and then share results with peers to ensure clarity and spot mistakes.	P6, P8, P10
Managing stress, confusion, and excitement while solving physics problems.	
- Students often started tasks feeling confused or anxious, especially under time pressure or new topics.	P1, P3, P5
- Several panicked at wrong answers but used notes or calming strategies to stay composed.	P2, P5, P6
- Many shifted from frustration to relief and pride after fixing mistakes or confirming answers.	P3, P5, P7, P9
- Students balanced excitement and worry during real or outdoor experiments, feeling more connected after succeeding.	P2, P9
Taking initiative to support one's own learning and improve group performance.	
- Students often asked for clarification and reviewed notes to grasp difficult parts.	P1, P3, P6
- Several made reviewers, flashcards, or simplified steps before tests to guide themselves under pressure.	P4, P5, P6, P10
- Many led in explaining formulas, drawing setups, or suggesting improvements to help their group.	P2, P6, P8, P9
- Even quieter students shared notes online and used AI only to confirm their solutions, showing proactive self-help.	P6, P9, P10
Transformative impact on students' future approaches to physics learning	
- Students realized that practice and breaking down problems eased anxiety and built confidence for future tasks.	P1, P3, P5
- Many learned to ask questions and double-check their work, seeing these as skills they can carry to harder topics.	P3, P5, P6
- Several adopted habits like unit checking, neat tables, and visualizing setups, making physics feel like teamwork and self-management.	P2, P6, P9, P7

Table 2 presents the lived experiences of high school students enrolled in the STEM Program as they engage in physics problem-solving. The phenomenological analysis of their narratives revealed four core constituents that frame the essential structure of this experience: *(1) strategic engagement, (2) emotional engagement, (3) agentic engagement, and (4) their transformative impact on learning.* These constituents emerged from transformed meaning units distilled from the students' own descriptions, capturing how they organize, feel, and take initiative during problem-solving and how these actions reshape their approach to future tasks.

Use of organized, step-by-step methods and visual tools to handle physics problems

The first constituent highlights students' intentional use of organized, step-by-step methods to approach physics problems systematically. Many participants described adopting structured approaches such as the GAFSA method (Given, Ask, Formula, Solution, Answer) or "list, draw, substitute" to arrange information and reduce confusion. This experience was consistently lived as turning something initially confusing into something understandable and orderly. Participants reported identifying known and unknown values, selecting appropriate formulas, converting quantities into SI units, and sketching diagrams to visualize scenarios. These actions were experienced not as routine habits but as deliberate moves to bring clarity, reduce mistakes, and sustain a sense of progress in the problem-solving process.

One participant expressed this experience by stating:

> *"I usually use the GAFSA method (Given, Asked, Formula, Solution, Answer) when solving physics problems because it makes everything clearer and easier to follow. Before, I would get confused about where to start, but with GAFSA, everything becomes organized and I immediately know what comes first and what to do next. This step-by-step approach helps me avoid confusion and trace my errors. It has become my go-to method because it gives me confidence and a sense of 'peace of mind gyud' whenever we answer in class." (P1)*

Another student echoed this mindset, saying,

> *"First, I organized everything clearly in my notebook. I made a clean table showing all the given values and available measurements, and I highlighted the unknown so I would know exactly what to look for. I also wrote down the units for each quantity and converted them to SI to avoid mistakes during computation. Doing this makes the flow of my solution clearer and helps me trace where I went wrong if ever I make a mistake—para dili ko malipat ba [so that I won't get confused/forget]." (P2)*

These statements show that students lived the act of writing, listing, and tabulating as a way of externalizing the problem, transforming it from a confusing situation into one that could be sequentially managed (Wienecke et al., 2023).

This tendency is also evident in students' use of visual tools. P4 and P9 illustrated how visual strategies supported their problem solving. Being a visual learner, the participant described starting by drawing the lens and marking the placement of the screen to understand the problem more clearly. This aligns with the findings of Bande (2025), which showed that students enhance their understanding when lessons are presented visually, as it allows them to see and organize abstract concepts more concretely. They noted that this practice extends beyond classroom activities, as they also sketch scenarios at home whenever possible before carefully inputting the data (Cabugwason, et al., 2024). This shows that visual representation was not a mere supplement but was lived as part of the thinking process itself (Endiape et al., 2023). Drawing allowed students to "see" and "grasp" relationships that were otherwise abstract, making the situation more concrete and manageable (Bacarro et al., 2024).

Taken together, these findings suggest that organized methods and visual tools serve as intentional structures that reshape how students live through the difficulty of solving physics problems. This idea aligns with a study showing that students who adopt structured strategies demonstrate stronger problem-solving performance and cognitive regulation in physics learning (Sauro, 2024). Cognitively, they transform complex and confusing tasks into clear, ordered sequences by making information easier to follow, showing where to begin, and allowing students to retrace their steps whenever needed; this is supported by studies reporting that learners use planning, monitoring, and evaluating strategies to organize their thought processes during problem solving (Presto & Menorca, 2023). Emotionally, they generate a lived sense of control, calmness, and confidence that counters the anxiety often felt in problem solving; this is consistent with evidence that effective instructional and learning strategies reduce anxiety and improve students' self-efficacy in physics contexts (Hermoso, 2025). In phenomenological terms, students are not merely applying techniques but are constituting the learning situation so that it is less overwhelming and more approachable. This description emerged through careful attention to participants' accounts while setting aside presuppositions, allowing the essence of their experience to show itself.

The essential meaning that emerges from this constituent is the experience of *"clarity through structure."* Through listing, drawing, tabulating, and sequencing, participants consistently described a shift from confusion to order, from uncertainty to predictability, and from anxiety to assurance. This essence captures how organized, step-by-step methods and visual tools are not just aids but integral to the lived experience of making physics problems solvable and livable.

Managing stress, confusion, and excitement while solving physics problems

The second constituent highlights how students manage stress, confusion, and excitement while solving physics problems. Their narratives reveal that emotional experiences are not separate from cognitive activity but are interwoven with the very act of solving. Students do not simply "feel" nervous or excited; they regulate these states through deliberate strategies that allow them to persist in the task.

One participant expressed this experience by stating,

> *"At the start, I felt nervous because the task was timed and individual. I even noticed my hands getting a bit cold. But once I began writing the given and the formula, I started to calm down because I knew the process—nakabalo ko unsay buhaton [I know what to do.]." (P5)*

Another student reflected,

> *"At first, I felt excited because it was a new topic, and total internal reflection was interesting for me. But I also knew I sometimes got confused with the ratio of indices, so I felt a bit anxious. When I got the wrong answer, I felt discouraged for a moment, but I reminded myself to 'tan-awa balik sa formula' [Check the formula again]. After correcting it and finally getting the right angle, I felt relieved and even a little proud." (P6)*

These statements reveal that emotions such as nervousness, discouragement, and excitement are not static; students employ self-reminders, procedural routines, and calm re-checking to manage them. This recurring pattern shows how emotional states shift in relation to problem-solving actions. Several students described starting from confusion or anxiety, experiencing momentary panic when an answer seemed wrong, and then moving toward relief and pride once they corrected the mistake or confirmed their answer (Esto et al., 2025). In line with this study, Filipino learners who demonstrated stronger self-regulation and emotional regulation skills were more likely to perform well in complex tasks, such as science and mathematical reasoning (Molina et al., 2025). P3, for example, noted that at first, they were *"confused and a little nervous"* but "*began to feel more relaxed as the steps became clearer"* and eventually felt *"very happy and relieved"* upon reaching the correct answer. In phenomenological terms, this reflects a lived experience in which emotional regulation emerges within the act of solving itself. Recent studies show that students apply self-monitoring or reflective pauses during challenging tasks (Siason et al., 2025). Students' strategic actions such as writing lists, checking formulas, or taking deep breaths serve as coping mechanisms through which stressful moments are transformed into calmer and more confident engagement (Haberlin, 2024).

The essence of this constituent lies in the way emotions are inseparably woven into the experience of problem solving. Stress and confusion initially disrupt the process but are gradually transformed through actions such as writing down givens, checking formulas, or taking deliberate pauses. Excitement likewise becomes interlaced with the effort, intensifying the sense of relief and pride once solutions are reached. Across participants, the invariant meaning is that emotional regulation is not an additional step but part of the essential structure of the lived experience of solving physics problems (Pasigon, 2022).

Taking initiative to support one's own learning and improve group performance

The third constituent highlights how students demonstrated initiative to strengthen their own learning and enhance the performance of their group. Rather than relying passively on instructions, they prepared resources, clarified uncertainties, and introduced improvements during activities.

One participant expressed this experience by stating,

> *"During the quiz, I couldn't ask the teacher for help, but I had already prepared by practicing problems at home. I also made my own short reviewer from the module, writing simplified steps like 'list, draw, substitute, check units' in bold at the top. This was my initiative to guide myself during timed tests—para ma-guide akong self jud [To guide myself properly.]" (P5)*

Another student described,

> *"Even though I'm usually quiet, I took the initiative to share my answers with the group. I explained that $\sin\theta_c = n_2/n_1$ and why it shouldn't be reversed. I also suggested to the teacher that having a printed formula sheet for the next activity would save time. I have a habit of making flashcards for formulas to use during review, and I also share them with my groupmates on Messenger—ako jud nag-take initiative [I really took the initiative]." (P6)*

These accounts show that initiative is not limited to leadership roles; even quieter students develop personal strategies and contribute actively to the collective learning process. The essential structure revealed that students' initiative emerged in two interrelated forms (Briones et al., 2023). On the individual level, they created their own reviewers, flashcards, and simplified steps ahead of tests to reduce stress and guide themselves under pressure (Yusefzadeh et al., 2019). On the group level, they explained formulas, suggested improvements such as printed formula sheets, and shared learning materials to support collective outcomes, leveraging professionally guided worksheets that include formulas and visual cues to help students systematically approach and solve problems, thereby reducing confusion and enhancing understanding.

These actions represent intentional acts of self-direction and collaboration that shaped the classroom into a space of shared problem solving rather than passive reception (Cagatan & Quirap, 2024). The essence of the experience is that initiative gives students a sense of confidence, resilience, and agency, while also fostering a culture of mutual support among peers (Blegur et al., 2019).

Transformative Impact on Students' Future Approaches to Physics Learning

The fourth constituent highlights how students rely on emotion-focused and socially mediated coping strategies to sustain their learning in physics. Rather than simply enduring stress or confusion, they regulate their emotions, pause intentionally, and seek support to remain engaged with the subject.

One participant expressed this experience by stating,

> *"When I feel nervous, I pause and review my notes instead of panicking. It's like a reminder to chill lang, ayaw dali-dali [just relax, don't rush.]. Sometimes I play music or take a short break to calm down. After that, my mind is clearer, and I feel more confident returning to the task—mas confident ko mu-balik sa task [I feel more confident to go back to the task]." (P2)*

This experience reflects how students use emotional regulation as part of their study routine, pausing and resetting themselves to regain focus before continuing a problem-solving task (Simpal, 2024). Another participant (P3) noted that asking for help and checking notes made learning "easier and less stressful," demonstrating that seeking support and leveraging personal resources are integral to coping with academic challenges. These acts reveal students' awareness that effective learning is sustained not by avoidance, but by intentional self-care and connection with others..

Students described positive self-talk, social support, and encouragement from peers or family as vital in maintaining motivation. In phenomenological terms, these are intentional coping acts that transform anxiety and confusion into manageable experiences. Students consciously shift from isolation to engagement, relying on small emotional resets and supportive interactions to remain active in learning (Felizardo et al., 2024).

The essential structure of this experience shows that coping is not a peripheral behavior but a core aspect of learning physics. Emotional regulation and social connection allow students to restore calm, think clearly, and re-engage with the subject (Panjaitan et al., 2025; Tomas et al., 2015). Through these strategies, students develop a sense of control and resilience, enabling them to approach future physics tasks with greater confidence and persistence (Serrano & Reyes, 2022).

Taken together, the four constituents reveal physics problem-solving as a holistic experience where thinking, feeling, acting, and becoming are intertwined. Students engaged strategically, organizing information to transform confusion into clarity and gain control over problems. Emotional regulation emerged alongside these strategies, with reflective pauses, self-reminders, and careful rechecking supporting persistence. This interplay fostered agentic engagement, as students guided their own learning, supported peers, and suggested improvements. Over time, these patterns reshaped their approach to future physics tasks, building confidence, resilience, and a positive relationship with the subject. Physics problem-solving, therefore, is not merely technical but a transformative process in which students construct meaning, regulate themselves, and develop agency as learners.

This holistic engagement was evident throughout the learning process. Students began by organizing information, identifying unknowns, and applying structured strategies such as GAFSA, listing, and drawing. During problem-solving, they regulated emotions, checked formulas, corrected errors, and persisted despite confusion or anxiety. Participation extended beyond individual tasks, as students prepared reviewers, shared explanations, suggested instructional improvements, and reflected on how strategies and emotional regulation would guide their future learning.

CONCLUSION AND IMPLICATIONS

The phenomenological analysis revealed that students' lived experiences of physics problem-solving are structured by four interrelated constituents: *(1) strategic engagement, (2) emotional engagement, (3) agentic engagement, and (4) their transformative impact on learning.* Overall, students actively created meaning, clarity, and composure while navigating physics problems. They experienced strategic engagement as a process of transforming confusion into order through deliberate organization, listing, drawing, and sequencing steps that made abstract concepts more approachable. Emotional engagement manifested as a shift from anxiety and uncertainty toward calmness, relief, and satisfaction, as students regulated their emotions through self-reminders, reflective pauses, and positive coping strategies.

Students also demonstrated agentic engagement by taking initiative to improve understanding, share insights, and support peers—even those who were usually quieter. The transformative impact emerged as students recognized that these ways of thinking, feeling, and acting reshaped their relationship with physics and their sense of self as learners. This shows that physics problem-solving is not merely a technical or intellectual task but a lived experience where strategy brings clarity, emotion provides balance, and agency fosters confidence. Learning physics thus became an experience of self-formation, where students lived through confusion, effort, and reflection to develop a more grounded and resilient awareness of themselves as learners.

These findings suggest that physics education should intentionally cultivate strategic, emotional, and agentic engagement. Teachers can integrate structured problem-solving methods, reflective practices for emotional regulation, and opportunities for learner autonomy and collaboration. For example, educators might use concept maps or checklists (strategic), reflective journaling or stress breaks (emotional), and peer teaching or choice-based problem tasks (agentic). By nurturing these interconnected dimensions, physics instruction can move beyond formulaic learning toward a more humanized and empowering practice that supports cognitive growth, emotional well-being, and authentic participation in scientific learning. Ultimately, this approach contributes to inclusive and transformative science education, aligning with SDG 4 by fostering reflective, capable, and self-directed learners.

LIMITATION OF THE STUDY

The findings of this study should be interpreted in light of several limitations. First, the results are based on a small and context-specific group of students, and therefore are not intended to be generalized to all physics learners or instructional settings. Second, the analysis relied on participants' self-reported narratives, which, while essential for capturing lived experience in phenomenological research, may be influenced by recall, articulation, or social desirability. Third, the study focused on students' experiences within particular physics problem-solving tasks and instructional conditions, and does not account for variations across different topics, grade levels, or longer learning periods. Finally, although methodological rigor and reflexivity were maintained, the interpretation of meanings remains shaped by the researcher's analytic lens, as complete elimination of subjectivity is not possible in phenomenological inquiry.

RECOMMENDATION

Based on the study's findings, it is recommended that teachers and curriculum designers adopt reflective, student-centered strategies that foreground learners' lived experiences in physics problem-solving. Instruction should integrate cognitive structuring techniques, such as the GAFSA method, with opportunities for emotional expression, self-regulation, and peer collaboration. Embedding reflective activities like journaling, group dialogue, or process-based feedback can help students become more aware of their thinking and emotional patterns while solving problems.

Future researchers are encouraged to extend this phenomenological approach to other physics domains or grade levels to examine how engagement evolves across contexts. Comparative studies may explore how strategic, emotional, and agentic engagements manifest among diverse learners or under different instructional modalities. Moreover, it is recommended that the participants or sample include an equal proportion of males and females to provide a more balanced perspective on experiences in physics learning.

Finally, professional development programs should equip teachers to recognize affective and agentic dimensions of learning and design lessons that support student agency and resilience. By following these directions, both educational practice and research can further humanize physics learning, empowering students to engage meaningfully with science beyond mere formulas.

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USE OF ARTIFICIAL INTELLIGENCE TOOLS

Artificial intelligence (AI) tools were utilized to assist in the translation of students' statements from Bisaya to English to ensure clarity and accuracy while preserving the original meaning of their responses. In addition, AI-assisted applications were used for grammar refinement and spelling correction to maintain the academic quality and readability of the manuscript. All AI tools were employed solely as linguistic and editorial aids, while the interpretation and analysis of data remained entirely researcher-driven.

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Research Article

Enhancing Conceptual Understanding of Climate Change in Non-Science Preservice Teachers Using DIY Model Kits

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Abstract. Climate change education is critical for improving climate literacy; however, non-science preservice teachers often hold persistent misconceptions that limit their instructional readiness. This study examined the effectiveness of low-cost DIY Model Kits in enhancing conceptual understanding of climate change among 45 non-science preservice teachers with limited exposure to climate science. Participants engaged in three inquiry-based activities via DIY model kits addressing greenhouse gases and the greenhouse effect, global warming and urban heat islands, and climate change–related natural disasters. The experimental models revealed clear cause–effect patterns, including progressively greater temperature increases with increasing CO_2 concentration, minimal temperature change in non-greenhouse gas conditions, and higher heat accumulation in built environments compared with vegetated models. The statistical methods used for data analysis were clearly specified, including the dependent samples *t*-test and normalized gain. Conceptual understanding was assessed using 10 items of the Conceptual Test of Climate Change (CTCC) through a one-group pretest–posttest design. Results showed a statistically significant increase in total CTCC scores from 28.64% (mean = 8.02, S.D. = 2.59) on the pretest to 84.93% (mean = 23.78, S.D. = 2.27) on the posttest ($p < 0.05$), with a high normalized gain ($\langle g \rangle = 0.79$). These findings demonstrate that inquiry-based DIY model kits can effectively support conceptual change and strengthen climate literacy among non-science preservice teachers.

Keywords: DIY climate change kits, Non-Science Preservice Teachers, Conceptual Understanding

INTRODUCTION

Climate change poses severe threats to ecosystems, human health, and global sustainability, demanding urgent societal responses, including within education, which plays a critical role in preparing future generations to understand and respond to this crisis (Abbass et al., 2022). Despite growing public awareness, research consistently shows that students' climate literacy remains insufficient, limiting their ability to make informed decisions and engage in sustainable behaviors (Ramos & Rodrigues, 2024). Climate change education (CCE) presents particular instructional challenges because it requires learners to integrate complex scientific concepts across multiple Earth systems, temporal and spatial scales, and feedback mechanisms. Consequently, effective CCE emphasizes the development of conceptual understanding, systems thinking, and evidence-based reasoning rather than rote memorization. Recent reviews highlight the importance of instructional approaches such as inquiry-based learning, project-based learning, and community-connected learning to support learners in constructing scientifically accurate understandings of climate systems and their societal implications (Monroe et al., 2017; Rousell & Cutter-Mackenzie-Knowles, 2020; Luthfia, 2025).

Empirical studies indicate that many learners struggle to understand fundamental climate change terminology, leading to persistent misconceptions and reduced effectiveness of scientific communication (Bruine de Bruin et al., 2021). Climate understanding is also influenced by cultural and social contexts, demonstrating that increased factual knowledge does not necessarily translate into meaningful climate-related action (Alexandra, 2021). Although children and adolescents often express concern about climate change, misconceptions about its causes, impacts, and mitigation strategies remain widespread, and willingness to engage in climate action may decline with age (Lee et al., 2020). School-based research further reveals that learners may possess fragmented factual knowledge while lacking deeper systems thinking, highlighting a persistent gap between climate awareness and climate-friendly behaviors (Feldbacher et al., 2024). These challenges are especially significant in teacher education, as teachers' conceptual understanding directly influences how climate change is framed, taught, and interpreted in classrooms.

Research on preservice teachers shows that misconceptions about climate-related phenomena, particularly the greenhouse effect and global warming, are common and resistant to change. Early studies documented misunderstandings among preservice teachers regarding atmospheric processes and human contributions to climate change (Khalid, 2001; Çelikler, 2011). More recent research indicates that although many preservice teachers express strong concern about climate change, their conceptual understanding and pedagogical readiness remain uneven (Boon, 2016; Tolppanen et al., 2021). This mismatch between concern and understanding suggests that traditional instruction may be insufficient for promoting meaningful conceptual change and highlights the need for instructional approaches that actively engage preservice teachers in reasoning about causal mechanisms and evidence.

During the COVID-19 pandemic, rapid shifts to remote and hybrid instruction accelerated the adoption of digital and hands-on learning tools to support science education. Abriata (2022) reported that teachers creatively employed DIY tools, smartphone sensors, and simulations to maintain meaningful practical science experiences during periods of restricted classroom access. Hands-on learning resources, including portable science kits, have been shown to enhance student engagement and learning outcomes and to support knowledge retention beyond initial instruction (Foley et al., 2013). In technology-enhanced STEM education, low-cost learning kits and DIY tools have also been found to support inquiry processes by enabling learners to manipulate variables, observe outcomes, and test explanations (Bajracharya et al., 2021; Li et al., 2022). These characteristics align closely with the goals of inquiry-based learning, which emphasizes question generation, evidence collection, explanation, and reflection.

However, while DIY kits and hands-on tools have been widely applied in general STEM education, relatively few studies have examined their use specifically for climate change learning. Climate change concepts are highly abstract and system-oriented, requiring learners to reason about invisible processes and long-term interactions. Inquiry-based learning has been identified as a promising approach for CCE because it allows learners to actively explore cause–effect relationships, confront misconceptions, and construct explanations grounded in evidence (Monroe et al., 2017). From a theoretical perspective, conceptual change theory explains how learners replace existing misconceptions with scientifically accepted conceptions through experiences that create cognitive conflict and promote restructuring of prior knowledge (Posner et al., 1982). Inquiry-based learning environments are particularly well suited to support this process by engaging learners in investigating phenomena, testing ideas, and revising explanations based on evidence.

Despite increasing attention to climate change education, several research gaps remain. First, a population gap persists, as much of the existing research focuses on school students or preservice science teachers, while non-science preservice teachers remain underrepresented in empirical studies (Boon, 2016; Tolppanen et al., 2021). Second, a knowledge gap exists concerning interventions that explicitly target conceptual understanding and causal reasoning in climate science, as many studies emphasize attitudes or general awareness rather than coherent mental models of climate mechanisms (Khalid, 2001; Bruine de Bruin et al., 2021). Third, an empirical gap remains regarding the effectiveness of low-cost DIY instructional interventions designed specifically for climate change learning within teacher education contexts (Foley et al., 2013; Abriata, 2022). Finally, a methodological gap is evident, as relatively few studies employ quantitative pre- and post-test designs to examine conceptual change resulting from inquiry-based climate instruction among preservice teachers.

Addressing these gaps is essential for strengthening teacher preparation programs, particularly for non-science majors who may have limited formal training in climate science but will play an important role in shaping public understanding of climate issues. Accordingly, this study investigates the effectiveness of DIY climate change kits implemented through inquiry-based learning in enhancing non-science preservice teachers' conceptual understanding of key climate change concepts, grounded in conceptual change theory (Posner et al., 1982). This study extends existing climate change education research by providing empirical evidence on the effectiveness of inquiry-based, low-cost DIY climate model kits for enhancing conceptual understanding among non-science preservice teachers in a Thai teacher education context.

RESEARCH QUESTIONS

The aim of this study was to examine the effectiveness of DIY Climate Change Kits implemented through inquiry-based learning in supporting non-science preservice teachers' understanding of climate change. Specifically, the two research questions were posed:

1. To what extent do inquiry-based DIY Climate Change Kit activities demonstrate observable cause–effect relationships in key climate processes?
2. To what extent does the DIY Climate Change Kit intervention improve non-science preservice teachers' conceptual understanding of climate change?

METHODOLOGY

This study employed a quantitative one-group pretest–posttest design to examine preliminary instructional effectiveness under authentic classroom conditions typical of non-science teacher education programs. The study consisted of two key phases: (1) the development of DIY Climate Change Kit activities, and (2) the implementation of these activities to enhance student teachers' conceptual understanding of climate change within the sample group. The effectiveness of the DIY Climate Change Kits was evaluated by comparing the average pre-test and post-test scores of the participants. The intervention was conducted over three lesson plan activities at Chanthaburi College of Dramatic Arts, Chanthaburi, Thailand, during June–July 2024, with the researcher serving as the instructor for the activities. To ensure systematic improvement, quantitative statistical findings were directly compared to assess the learning outcomes. The overall research process is illustrated in Figure 1.

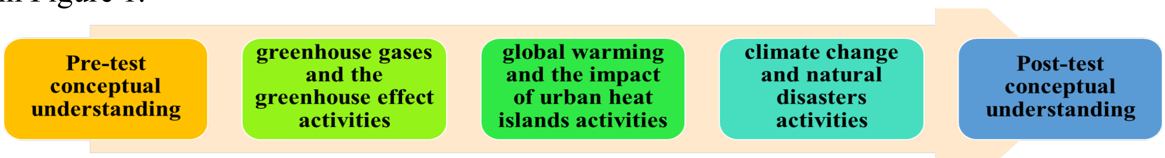

Figure 1. Process of the methodological approach: enhancing conceptual understanding through activities using DIY Climate Change Kits.

Participants

This study involved 45 student teachers enrolled in the Music Education and Thai Dance Education programs at Chanthaburi College of Dramatic Arts, Thailand. These participants represent non-science preservice teachers who typically receive limited formal instruction in climate science as part of their teacher education curriculum. All participants were registered in the Science and Technology in the Digital Age course during the second semester of the 2024 academic year, which provides interdisciplinary exposure to scientific and technological issues relevant to contemporary society. The participants were purposively selected to reflect a population that is often underrepresented in climate change education research but is likely to encounter climate-related topics in future teaching contexts. Participation was voluntary and anonymous, and purposive sampling was employed to ensure alignment between the study objectives and the participants' educational background.

Research Tools

To evaluate the impact of the DIY Climate Change Kits, two quantitative instruments were employed.

1) The DIY climate change activity kit provides a total of 12 hours of instruction, including 3 hours on greenhouse gases and the greenhouse effect, 6 hours on global warming and the urban heat island phenomenon, and 3 hours on climate change and related natural disasters. This initiative was developed by the Department of Climate Change and Environment (DCCE, 2020).

2) Conceptual Test of Climate Change (CTCC): The CTCC contained 10 multiple-choice items covering three domains: (a) greenhouse gases and the greenhouse effect 4 items, (b) global warming and urban heat islands 4 items, and (c) broader climate processes 2 items. Items were adapted from Leiserowitz et al. (2011), content validity was reviewed by three experts in climate education, and item clarity was confirmed through pilot testing with a comparable learner group. and refined for the Thai context. Each item included one correct response and three distractors based on common misconceptions. Pilot testing produced difficulty indices (0.30–0.75), discrimination indices (0.50–0.68), and reliability (KR-20 = 0.79).

Data Collection

Ethical approval for this study was obtained from the Human Research Ethics Committee of Ubon Ratchathani University (Approval No. UBU-REC-29/2567). To preserve natural classroom conditions, data collection was conducted during regular course sessions of the Science and Technology in the Digital Age course. The data collection process consisted of three sequential stages. First, participants completed the Conceptual Test of Climate Change (CTCC) as a pre-test prior to the intervention (approximately 30 minutes). Second, participants engaged in three inquiry-based learning activities using the DIY Climate Change Kits. The activities were structured according to the 5E inquiry learning cycle (Bybee, 2014): the Engagement phase introduced real-world climate-related scenarios to elicit prior knowledge; the Exploration phase involved constructing and experimenting with DIY climate models; the Explanation phase required group discussion and presentation of observed results; the Elaboration phase encouraged comparison of experimental outcomes with scientific explanations and real-world climate data; and the Evaluation phase focused on reflection and discussion of climate-related implications. Finally, after completion of all inquiry activities, participants completed the same CTCC as a post-test (approximately 30 minutes) to assess changes in conceptual understanding. A six-item semi-structured interview protocol was designed to capture pre-service teachers' perceptions of the climate change learning activities. The interview questions were reviewed by the research advisor to ensure content validity and linguistic clarity. Following the completion of the instructional activities, in-depth interviews were conducted with six pre-service teachers, comprising three students with high achievement scores and three students with low achievement scores. The interview data were subjected to interpretive qualitative analysis, and the findings are reported in a descriptive narrative format.

Data Analysis

Quantitative data were analyzed to evaluate the effectiveness of the DIY Climate Change Kits in enhancing non-science preservice teachers' conceptual understanding of climate change. Descriptive statistics, including mean and standard deviation, were calculated for pre-test and post-test CTCC scores. A dependent sample t-test was conducted to determine whether the observed differences between pre-test and post-test scores were statistically significant at the 0.05 level. In addition, normalized gain (<g>) was calculated to assess the magnitude of learning improvement (Christman et al., 2024) across three conceptual domains: greenhouse gases and the greenhouse effect, global warming and urban heat islands, and climate change processes. All statistical analyses were performed using Microsoft Excel, and the assumptions for dependent-sample t-tests were examined prior to analysis. Interpretation of learning gains followed established criteria, with <g> values greater than 0.7 indicating high conceptual improvement.

RESULTS AND DISCUSSION

The results are presented in relation to the two research questions, addressing (RQ1) the extent to which the inquiry-based activities demonstrate observable cause–effect relationships in key climate processes and (RQ2) the effectiveness of the DIY Climate Change Kit intervention in improving conceptual understanding.

Cause–Effect Relationships in Climate Processes Using DIY Climate Change Kits

The inquiry-based DIY Climate Change Kit activities were implemented with 45 non-science preservice teachers across three climate change learning sessions, each lasting three hours. The instructional design aimed to support participants in exploring core climate mechanisms through hands-on investigation and guided inquiry. In the first session, participants engaged in an activity designed to illustrate greenhouse gases and the greenhouse effect, adapted from the DIY Climate Change Kits developed by the Department of Climate Change and Environment (DCCE, 2020). Subsequent sessions focused on global warming and the urban heat island phenomenon, as well as climate change–related natural disasters. Throughout the intervention, participants constructed and used physical models as inquiry tools to observe phenomena, collect data, and reason about cause–effect relationships (Figure 2).

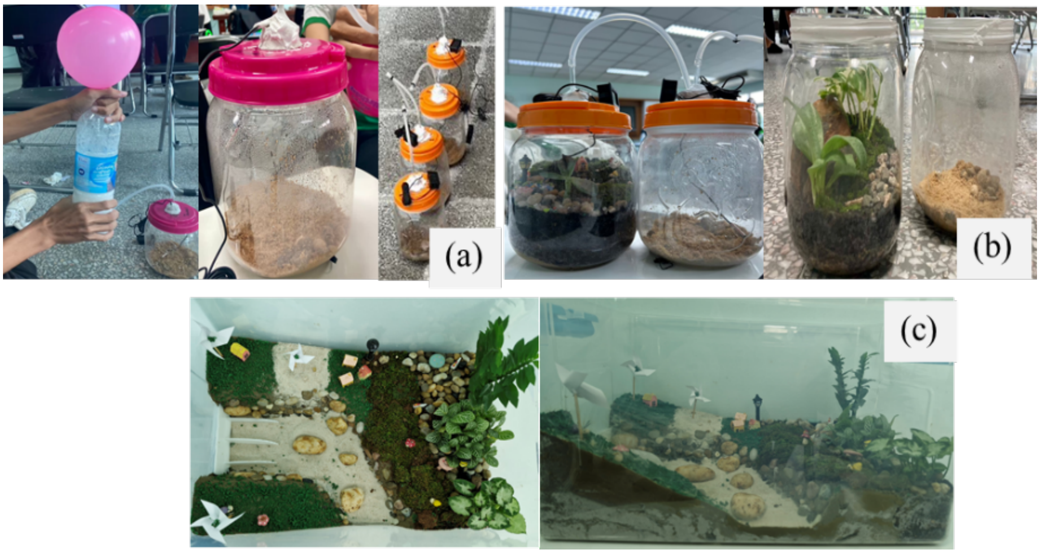

Figure 2. DIY Climate Change Kits for exploring greenhouse gases and the greenhouse effect (a), global warming and the impact of urban heat islands (b), and climate change and natural disasters(c).

Results from the greenhouse gas activity demonstrated a clear pattern of temperature change across different atmospheric conditions (Table 1). Models representing a normal atmosphere showed only modest temperature increases over time, whereas models with added CO_2 exhibited progressively larger temperature increases, with the greatest rise observed when CO_2 concentration was doubled. In contrast, models containing added O_2 showed relatively minimal temperature change. These findings align with established scientific explanations of the greenhouse effect and provide tangible evidence of the heat-trapping properties of greenhouse gases. Similar instructional approaches have been shown to help learners differentiate between greenhouse and non-greenhouse gases by linking abstract atmospheric processes to observable outcomes (Khalid, 2001; Bruine de Bruin et al., 2021).

In the urban heat island activity, models simulating vegetated environments experienced smaller temperature increases than those representing built environments composed of materials such as bricks and stones. This pattern reflects well-documented differences in heat absorption and retention between natural and urban surfaces and mirrors findings from environmental and geography education research on urban heat islands (Feldbacher et al., 2024). The use of simplified physical models enabled participants to visualize how land-use characteristics influence local temperature patterns, supporting inquiry-based reasoning about real-world climate phenomena.

The third activity, focusing on climate change and natural disasters, allowed participants to explore hydrological impacts through a dam-and-river model. Observations of water overflow and flooding after simulated rainfall helped illustrate the relationship between extreme weather events, infrastructure capacity, and downstream impacts on communities and agricultural areas. Such experiential representations are particularly valuable for non-science learners, as they support understanding of complex climate impacts that are often difficult to grasp through text-based instruction alone. Collectively, these findings are consistent with prior studies showing that hands-on, low-cost instructional tools can enhance engagement and support conceptual understanding in STEM and environmental education (Foley et al., 2013; Abriata, 2022).

Table 1. Experimental results from the DIY Climate Change Kits of greenhouse effect, urban heat islands, and natural disasters.

Model / Times (min)	Temperature inside the model (°C)				
	0	15	30	45	60
Model 1: Exploring greenhouse gases and the greenhouse effect					
Model 1.1 Normal atmosphere	35.0	35.3	35.6	36.5	37.2
Model 1.2 Filled with CO_2 gas	35.0	36.5	37.0	37.6	38.8
Model 1.3 Filled with 2 times the CO_2 gas of Model 1.2	35.0	36.9	38.0	41.0	42.2
Model 1.4 Filled with O_2 gas	35.0	35.1	35.5	36.0	36.5
Model 2: Investigating global warming and the impact of urban heat islands					
Model 2.1 Environment with plant and moss	24.0	24.8	25.7	26.3	26.7
Model 2.2 Environment with brick, stones	24.0	26.8	27.5	27.8	27.9
Model 3: Investigating climate change and natural disasters					
Model 3.1 Before the rain	The model represents a dam in the center for water storage, with a river flowing from the dam. Farming areas and houses are situated on both sides.				
Model 3.2 After the rain	The dam reached its capacity, water started overflowing. The water gradually turned brown and eventually spilled over, flooding the nearby houses and agricultural areas.				

* Models 1.1 - 2.2 have a temperature error of no more than ± 0.5.

Importantly, the inquiry-based nature of the activities encouraged participants to generate questions, test explanations, and reflect on observed outcomes, aligning with recommendations for participatory and action-oriented climate change education (Rousell & Cutter-Mackenzie-Knowles, 2020). By making climate mechanisms observable and open to investigation, the DIY Climate Change Kits helped participants confront initial misconceptions and construct more coherent explanations of climate processes. During model-based experimental activities, explicit emphasis must be placed on procedural accuracy for students. Nevertheless, minor discrepancies may still arise as a result of incomplete adherence to the prescribed model procedures established by the instructor.

Non-Science Preservice Teachers' Conceptual Understanding of Climate Change

Quantitative analysis of Conceptual Test of Climate Change (CTCC) scores revealed substantial improvements in participants' conceptual understanding following the inquiry-based intervention (Table 2). Prior to the activities, participants demonstrated low overall performance, with a mean pre-test score of 8.02 (28.64%), reflecting limited understanding of key climate concepts. After completing the DIY Climate Change Kit activities, the mean post-test score increased to 23.78 (84.93%), representing a statistically significant improvement ($p < 0.05$). The overall normalized gain (<g> = 0.79) indicates a high level of conceptual improvement. When examined by content domain, similar patterns of improvement were observed. Participants showed low pre-test performance across greenhouse gases and the greenhouse effect (GG and GE), global warming and urban heat islands (GW and UHI), and broader climate change processes (CC). Post-test results demonstrated marked gains in all three domains, with normalized gains ranging from <g> = 0.76 to <g> = 0.87. To ensure consistency in measurement, the same test instrument was employed for both the pre-test and post-test, with the order of questions and answer choices randomized in the post-test. The post-test was administered after the completion of Learning Activity 3, following a total instructional duration of four weeks. These findings suggest that the inquiry-based DIY activities were effective in supporting conceptual change across multiple aspects of climate science.

Table 2. Non-Science Preservice Teachers' pre- & post test scores of the conceptual understanding on climate change

Conceptual understanding	**mark**	**Pre-Test**			**Post-Test**			**<g>**	**t-test**	
		mean	**S.D.**	**%**	**mean**	**S.D.**	**%**		**t**	***p*-value**
GG and GE	10	2.62	1.19	26.20	8.33	1.41	83.30	0.77	22.53	0.000*
GW and UHI	7	3.07	1.32	43.86	6.49	0.63	92.71	0.87	19.83	0.000*
CC	11	2.33	1.68	21.18	8.96	1.68	81.45	0.76	22.05	0.000*
Total	**28**	**8.02**	**2.59**	**28.64**	**23.78**	**2.27**	**84.93**	**0.79**	**34.61**	**0.000***

* Statistically significant at p-value 0.05.

Note: GG and GE = greenhouse gases and greenhouse effect, GW and UHI = global warming and urban heat island, and CC = climate change.

Although the GW and UHI topics are allocated a lower overall score (7 points), they are intentionally structured to promote higher-order cognitive engagement, such as analytical thinking and evaluative reasoning. Meeting these cognitive requirements involves a longer instructional duration, particularly through group-based activities and classroom discussions, amounting to six hours of instruction. In contrast, the GG and GE topics are assigned a higher total score (10 points) but predominantly emphasize theoretical understanding and core conceptual knowledge. As foundational content, these topics can be delivered within a shorter instructional period of three hours; however, their fundamental importance justifies assessment across multiple aspects of understanding. These results are consistent with prior research indicating that preservice teachers often enter teacher education programs with fragmented or incorrect understandings of climate-related concepts (Khalid, 2001; Çelikler, 2011; Boon, 2016). The significant learning gains observed in this study support the argument that inquiry-based, hands-on instruction can help address these misconceptions by allowing learners to actively engage with evidence and revise their prior conceptions. Similar improvements in conceptual understanding have been reported in studies using hands-on kits and inquiry-oriented approaches in science education (Foley et al., 2013; Abriata, 2022). Moreover, the high normalized gain suggests that the intervention supported not only factual learning but also deeper reasoning about causal relationships within climate systems. This aligns with research emphasizing the role of inquiry-based learning in promoting systems thinking and meaningful engagement with climate issues (Rousell & Cutter-Mackenzie-Knowles, 2020; Feldbacher et al., 2024). Given that misconceptions among future teachers can negatively influence classroom instruction and public understanding of climate science (Bruine de Bruin et al., 2021), the observed improvements highlight the potential value of integrating inquiry-based climate activities into non-science teacher education programs.

Taken together, the results addressing RQ1 and RQ2 suggest a clear relationship between observable inquiry experiences and conceptual learning outcomes. The cause–effect patterns demonstrated through the DIY Climate Change Kit activities (RQ1) provided concrete experiential evidence that supported preservice teachers in revising prior misconceptions and constructing more coherent explanations of climate processes. These inquiry experiences appear to underpin the substantial gains in conceptual understanding measured by the CTCC (RQ2), indicating that engaging learners in hands-on investigation of climate mechanisms is an effective pathway for promoting conceptual change. This alignment between process-level evidence and learning outcomes reinforces the value of inquiry-based instructional designs for climate change education, particularly for learners with limited prior science backgrounds.

The significant learning gains observed in this study are consistent with national education goals articulated in Thailand's Basic Education Core Curriculum B.E. 2551 (A.D. 2017), which emphasizes the development of essential knowledge, thinking skills, and scientific understanding to prepare learners for a rapidly changing society, including environmental and sustainability challenges (Office of the Basic Education Commission, 2017). The Curriculum includes environmental education within science learning standards and supports inquiry and problem-solving approaches that foster meaningful engagement with real-world phenomena such as climate variation and Earth processes, thus aligning with the inquiry-based learning design used in this study. Moreover, Thailand's participation in international frameworks such as Sustainable Development Goal 4 (Quality Education) and its commitment to mainstreaming environmentally informed approaches in education further reinforce the importance of strengthening climate literacy and teacher preparation through hands-on, evidence-based instructional strategies

A comprehensive examination of the improvement and development associated with the DIY Climate Change Kit activities was conducted using semi-structured interviews. Interpretations were derived from student teachers' responses to the interview questions. The findings indicate that group work and simulation-based activities foster skill development and promote an engaging, iterative learning process. Moreover, well-structured activities support deeper conceptual understanding while strengthening essential competencies, thereby effectively preparing students to address real-world challenges. Through participation in the DIY Climate Change Kit activities, student teachers demonstrated a heightened awareness of climate change, including its global impacts and the role of human actions in contributing to environmental problems. They also became more reflective about their daily behaviors and recognized how small behavioral changes can contribute to climate change mitigation. In particular, activities focusing on global warming and urban heat islands emphasized the influence of human activities on the environment and encouraged the adoption of practical solutions, such as reducing unnecessary use of air conditioning. Overall, these activities effectively enhanced climate change awareness and motivated student teachers to take proactive actions in their everyday lives to address climate-related issues.

CONCLUSION AND IMPLICATIONS

This study investigated the effectiveness of inquiry-based DIY Climate Change Kits in enhancing non-science preservice teachers' conceptual understanding of climate change. The findings demonstrate that low-cost, hands-on inquiry activities can successfully support learners in observing and reasoning about key climate mechanisms, including the greenhouse effect, urban heat islands, and climate-related natural disasters. Experimental results from the DIY models revealed clear cause–effect relationships, while quantitative analyses showed statistically significant improvements in conceptual understanding with a high normalized gain. The results indicate that inquiry-based learning supported by DIY climate models can reduce common misconceptions and promote more coherent and scientifically accurate understandings of climate processes among non-science preservice teachers. Given that this population often receives limited formal instruction in climate science but plays an important role in future interdisciplinary teaching contexts, the use of accessible and scalable instructional tools is particularly valuable. Overall, this study contributes empirical evidence to climate change education research by addressing gaps related to learner population, instructional approach, and assessment of conceptual change. The findings indicate that inquiry-based learning using DIY climate model kits can effectively enhance non-science preservice teachers' understanding of complex climate mechanisms and reduce persistent misconceptions. Given the interdisciplinary teaching roles of non-science preservice teachers, integrating such inquiry-based climate activities into teacher education programs may strengthen climate literacy across subject areas. Beyond climate change education, this instructional approach may be adapted to other complex socio-scientific issues to support conceptual understanding and scientific reasoning in non-science teacher education contexts.

The findings of this study provide important implications for science education, particularly in preparing non-science preservice teachers to teach climate change effectively. The significant conceptual gains observed after using DIY Climate Change Kits suggest that the low-cost hands-on inquiry activities should be more widely integrated into teacher education programs to strengthen climate literacy and reduce misconceptions. These results highlight that experiential learning can help future teachers develop accurate mental models of greenhouse gases, urban heat islands, and climate-related natural disasters—concepts that are often difficult to grasp through traditional instruction. Implementing DIY kits can also promote scientific reasoning and systems thinking, supporting 21st-century teaching competencies. Therefore, curriculum designers, science educators, and policy makers should consider incorporating DIY climate models as core instructional tools to enhance the quality and accessibility of climate change education across disciplines. This study also highlights the potential for integrating DIY Climate Change Kits into national teacher preparation standards, particularly for non-science majors who often receive limited exposure to climate science. The DIY model kit together with the inquiry approach supports the development of systems thinking and scientific reasoning—competencies emphasized in sustainability education frameworks.

LIMITATIONS

This study is limited by its small, purposive sample; the absence of a comparison group; and the short intervention duration. Future studies should incorporate mixed-methods designs and longitudinal measurements of conceptual change.

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