SciEd

SEAQIS Journal of Science Education

vol. 5 / no. 2 / December 2025
E-ISSN 2964-7533
P-ISSN 2987-8101

Indexed by:
Google Scholar GARUDA
Dimensions DOAJ

DOI prefix: 10.58249 by Crossref

www.journal.qitepinscience.org

ISSN 2964-7533
ISSN 2987-8101

SEAMEO Regional Centre for QITEP IN SCIENCE

SciEd

SEAQIS Journal of Science Education

Director's Message

We are honoured to present Volume 5, Issue 2 of the SEAQIS Journal of Science Education (SciEd). This issue reaffirms our commitment to advancing rigorous, relevant, and classroom-ready scholarship that strengthens science education across Southeast Asia and beyond.

In this edition, we spotlight a systematic review of experiential learning for climate-change awareness; an empirical study on laboratory anxiety among Indian secondary students with practical strategies to address it; a RStudio-driven analysis of how augmented reality supports microbiology learning; a pedagogical integration of STEAM4Innovator, gamification, and design thinking to enhance students' innovative skills; and a teacher-preparation model intertwining STEM and design thinking to strengthen sustainability learning for pre-service biology teachers.

Collectively, these contributions illuminate how thoughtful pedagogy, purposeful technology use, and attention to learner well-being can raise the quality and equity of science learning. They offer concrete insights for curriculum developers and school leaders, while providing educators with evidence-based strategies to cultivate scientific literacy, creativity, and problem-solving in authentic contexts.

As the educational landscape continues to evolve, science educators remain pivotal to shaping resilient, future-ready learners. We extend our heartfelt appreciation to the authors for choosing SciEd as a venue for their work, to the reviewers for generous and rigorous feedback, and to the editorial and production team for their professionalism and dedication to quality.

We invite you to engage deeply with the research presented here and consider its implications for your practice, programs, and policies. Together, let us continue to collaborate, innovate, and elevate the standards of science education in our region.

Sincerely,
Reza Setiawan, S.Si., M.T.
Director, SEAMEO QITEP in Science

From the Editor-in-Chief

It is with great pleasure that I welcome you to Volume 5, Issue 2 of the SEAQIS Journal of Science Education (SciEd). This issue furthers our commitment to rigorous research that addresses regional needs while engaging global dialogues in science education.

The articles in this issue span a systematic review of experiential learning for climate-change awareness; an empirical study of laboratory anxiety among Indian secondary students with practical remedies; an RStudio-based analysis of how augmented reality supports microbiology learning; an integrated STEAM4Innovator–gamification–design-thinking approach to build students' innovation; and a teacher-education model weaving STEM and design thinking for sustainability. Together, they showcase methodological breadth, classroom relevance, and a shared focus on learner outcomes and educator professionalism.

I extend my sincere appreciation to all who made this issue possible, our authors, reviewers, editorial board members, designers, and the publishing office staff. Your expertise and dedication uphold the quality, integrity, and timeliness of SciEd. As part of our ongoing editorial practice, we continue to prioritize transparent reporting, ethical conduct in research with learners and educators, and constructive peer review that strengthens every manuscript.

At SciEd, I believe in fostering a space for critical inquiry, collaboration, and dialogue that bridges research and classroom practice. This journal serves not only as a venue for disseminating findings but also as a forum for exchanging ideas that can shape policy, curriculum, and professional learning. I encourage you to engage deeply with the content, reflect on the insights offered, and consider their implications for your local contexts.

Thank you for your continued support of SciEd. I hope the contributions in this issue will inform your work and inspire further inquiry into the evolving landscape of science education.

Warm Regards,
Dr. Elly Herliani, M.Phil., M.Si.

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SEAQIS Journal of Science Education (SciEd)

Volume 5 | No 2 | December 2025
E-ISSN 2964-7533 | P-ISSN 2987-8101

SEAQIS Journal of Science Education (SciEd), The Southeast Asian Journal of Science Education, is a scientific publication of SEAMEO QITEP in Science published once a year. It contains scientific research articles in Science Education and a review article. A guide for the author can be found on the website.

SciEd Editorial Office
SEAMEO QITEP in Science, Kompleks Balai Besar Guru dan Tenaga Kependidikan Provinsi Jawa Barat, Gedung B, Jl. Dr. Cipto No.9, Bandung, West Java 40171, Indonesia
E-mail: seaqis.journal@seameo.id | Home page: journal.qitepinscience.org

Cover:
Ai-Technology-energy-future-innovation-Coding

2025

SciEd
SEAQIS Journal of Science Education

SEAQIS Journal of Science Education (SciEd)
ISSN: 2987-8101 | E-ISSN: 2964-7533
Vol: 5, No: 2, PP: 01-10
www.journal.qitepinscience.org

Research Paper Open Accsess

Investigating Critical Thinking Skills in Rural Middle School Students through STEM Education: A Qualitative Case Study from Sumedang

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Article history:
Received: May 7, 2025
Revised: May 23, 2025
Accepted: June 24, 2025

Abstract

Learning plays a crucial role in fostering students' critical thinking skills, enabling them to address the challenges they face in their daily lives. This study was conducted in Sumedang, West Java, where students experience limited water availability. The main water sources are located far from residential areas, requiring students to make long trips each morning to fetch water from a distant river. This qualitative descriptive study aimed to explore how students employ critical thinking skills while engaging in contextual STEM learning through the development of a non-electric water pump project. The project involved seventh-grade students participating in science classes using a contextual STEM approach over one semester. Data were collected and analysed through observation, document analysis, and audio and video recordings using Transcript-Based Lesson Analysis. Indicators of critical thinking such as questioning, articulating assumptions, and demonstrating open-mindedness were observed during the STEM learning process of designing the non-electric water pump. The emergence of these skills varied across learning phases, individual characteristics, and group dynamics. Contextual STEM learning not only promotes critical thinking but also equips students with essential life skills for global competition in the 21st century by preparing them to solve real-world problems. The findings of this study provide insights for educators in designing more meaningful science learning experiences in the future.

Keywords: *Student Critical Thinking Skills, Contextual STEM Learning, Non-Electricity Water Pump Projects*

Introduction

Critical thinking skills serve as a fundamental building blocks for students' future success, providing them with the tools to tackle challenges, make intelligent decisions, and thrive in an ever-changing world (Ellerton & Kelly, 2021; Lipman, 1988). These skills enable students analyse information, consider multiple perspectives, and solve real-world problems creatively (Ellerton & Kelly, 2021). As students' progress through school and enter the workforce, their ability to think critically becomes increasingly essential, shaping their success in education, career growth, and lifelong learning (Tanti et al., 2020). Therefore, developing and refining critical thinking skills are crucial for preparing students to adapt, innovate, and succeed in the future (Yuan & Liao, 2023).

Enhancing critical thinking skills is a central goal in the STEM (Science, Technology, Engineering, and Mathematics) approach, which serves as an essential foundation for achieving this objective (Lacrin, 2021). By integrating these four disciplines, STEM provides a holistic understanding of the natural world and enables students to develop interdisciplinary skills that are essential for problem-solving (Gonzalez & Kuenzi, 2012; Morris et al., 2021). In response to the demand for a skilled and technically proficient workforce, the STEM approach emphasises the integration of knowledge, skills, and problem-solving within contexts relevant to students' daily lives (Corrigan et al., 2021). Consequently, STEM not only prepares students for future workplace success but also empowers them to become competent change-makers in an increasingly complex and globally interconnected society (Morris et al., 2021).

Contextual STEM learning has emerged as a dynamic approach to fostering these essential cognitive abilities. It provides students with immersive experiences that extend beyond theoretical boundaries (Conradty & Bogner, 2020; Lacrin, 2021). By integrating real-world challenges into STEM education, students' understanding of core concepts is deepened, and they acquire the problem-solving skills necessary to navigate the complexities of the modern world effectively (Morris et al., 2021). Through hands-on projects and experiments, students can strengthen their grasp of scientific principles and mathematical concepts while simultaneously honing their problem-solving abilities (Imaduddin et al., 2020).

Although STEM learning approaches have been widely recognized for their effectiveness in enhancing students' critical thinking skills (Moore et al., 2016; Astawan et al., 2023), most previous studies have concentrated on urban contexts with adequate educational facilities, thereby overlooking the complexities of rural education, which often faces infrastructural limitations and restricted access to technology (Hellman et al., 2024; Mueller, 2025). Systematic reviews, such as those by Sungur Gül et al. (2023), highlight the limited incorporation of local contexts in STEM learning designs, despite increasing evidence that community- and place-based approaches can significantly enhance student engagement and the meaningfulness of learning (Quang et al., 2015; Sánchez Milara & Orduña, 2024). Furthermore, many studies remain conceptual or laboratory-based, providing little empirical insight into real-world classroom implementations in rural settings (Jang, 2015). This study addresses these gaps by presenting empirical data drawn from classroom observations and the analysis of learning artifacts in rural Indonesian secondary schools. The findings indicate that integrating local context with problem-based contextual STEM, including e-modules and virtual experiments (Husna et al., 2024), effectively improves students' ability to identify problems, design feasible solutions, and reflect on their reasoning processes. Thus, this research contributes to the development of inclusive, evidence-based, and contextually adaptive STEM learning models (Sungur Gül et al., 2023; Hellman et al., 2024).

This study investigates the transformative potential of contextual STEM learning in advancing critical thinking skills, with a specific focus on the creation of non-electric water pump projects. Situated in Sumedang, West Java, this case study examines an educational landscape where students grapple with the tangible issue of water scarcity. By engaging in the design and implementation of non-electric water pump projects, students not only participate in hands-on STEM activities but also confront the socio-economic realities of their local community.

Ultimately, this study seeks to demonstrate the transformative role of contextual STEM learning as a catalyst for cultivating critical thinking skills in students. By presenting empirical evidence from the

Sumedang context, it contributes to the growing discourse on innovative pedagogical approaches and provides insights for educators seeking to harness the potential of contextual STEM learning in nurturing the next generation of critical thinkers.

Methodology

This study employed a qualitative descriptive approach with a single case study design. A single case study was considered appropriate to enable an in-depth, context-specific investigation of students' critical thinking development during the implementation of a contextual STEM-based project. This methodological choice aligns with the exploratory nature of the research, which aimed to uncover nuanced patterns of student interaction, reasoning, and reflective behavior within a naturally occurring classroom environment. Focusing on a single case allowed the study to capture the complexity and richness of the learning process in a real-world setting, thereby providing detailed insights into how and why critical thinking skills emerge in response to authentic problem-solving tasks. Data were collected through observations of verbal interactions and behavioral indicators during the learning sessions and were subsequently analyzed to reveal the dynamics of critical thinking throughout the project-based learning experience.

This study was conducted at a State Junior High School in Sumedang Regency. The participants were 16 seventh-grade students selected through purposive sampling based on their willingness to participate and their availability during the intervention period. Seventh-grade students were chosen because they were in the early stages of learning basic science and technology concepts, which made them suitable for introducing foundational STEM principles. These students engaged in a contextual STEM project to develop a non-electric water pump that addressed the issue of water scarcity in their daily lives. The project employed a science, technology, engineering, and mathematics (STEM) framework to guide students in designing functional, real-life solutions tailored to local environmental challenges. The STEM analysis of Non-Electricity Water Pump Project is shown in Table 1 and the working principle of the non-electric water pump designed by the students is illustrated in Figure 1.

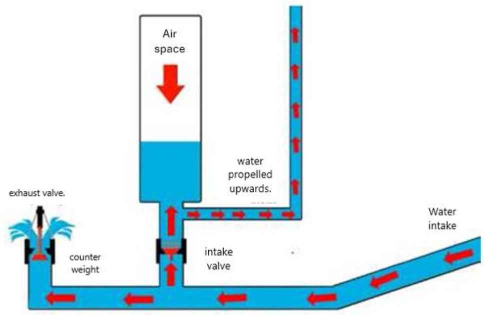

Figure 1. Operational Principle of the Non-Electricity Water Pump Developed by Students in STEM Project.

In the non-electric water pump project, students were challenged to design a prototype using a STEM approach that was adapted to their local environment for practical use in everyday life. The 16 students were divided into six groups, each consisting of two to three members. Each group presented its design, constructed a prototype based on that design, and conducted on-site testing at the school to measure the volume of water flow generated by the non-electric water pump.

The study methodology will consist of three main phases: preparatory, data collection, and data analysis. The preparation phase involved conducting a literature review and designing the research framework. The data collection phase focused on gathering information during STEM learning activities through a project on non-electric water pumps.

Data were collected and analysed using multiple qualitative techniques, including classroom observations, document analysis (such as lesson plans and student worksheets), and audio or video recordings of classroom activities. To ensure credibility and triangulation of findings, each data source was cross-referenced and analysed using thematic analysis techniques. The analysis procedure in the didactic design study comprised three stages: (1) pre-instructional analysis, which examined the anticipated didactic situation based on lesson plans and teacher intentions; (2) instructional analysis, which focused on real-time classroom interactions, student responses, and teaching strategies during the STEM project; and (3) post-instructional analysis, which evaluated learning outcomes, student reflections, and teacher feedback to identify discrepancies or alignments with the intended design. The instruments included an observation protocol emphasizing critical thinking indicators, which was validated through expert review and pilot-tested to ensure clarity and relevance to the research objectives.

Before analysing students' critical thinking activities, the researcher transcribed all learning recordings using instant transcripts produced by observers on observation sheets, together with audio and video recordings of the lessons. Students' critical thinking activities, based on Paul and Elder's eight essential indicators of thinking (2006), were then analysed using *Transcript-Based Lesson Analysis* (TBLA).

Table 1. STEM Analysis of the Non-Electricity Water Pump Project.

Science	Technology
- Factual (Pressure application in liquid substances) - Conceptual sciences 1. Pressure in substances. 2. Capillarity 3. Gravitational & potential energy 4. Alternative energy 5. Energy transformation	1. Internet for searching information related to non-electricity water pump technology. 2. Computer for creating tables or charts or diagrams of observations and reports on the construction of non-electricity water pump
Engineering	**Mathematics**
1. Designing a prototype of a non-electricity water pump 2. Building a prototype of a non-electricity water pump 3. Conducting testing of the prototype of a non-electricity water pump 4. Evaluating the prototype of a non-electricity water pump	1. Calculating the scale and dimensions of the non-electricity water pump 2. Measuring the height of the water source 3. Creating a graph depicting the relationship of dimensions of the non-electricity water pump

Result

This results section presents an integrated and comprehensive analysis derived from multiple data sources, including systematic observations, document analyses, and detailed audio and video recordings. Quantitative data on the frequency of critical thinking indicators were complemented by qualitative insights that illuminated the processes underlying critical thinking. These converging strands of evidence collectively provided a robust foundation for understanding the complex and dynamic nature of learning outcomes within authentic, contextually grounded STEM education.

A key contextual issue in STEM learning is water scarcity, which is closely connected to the students' environment. In particular, it reflects the challenge of accessing clean water faced by residents living near river streams in Sumedang. This issue is highly relevant for integration with technological applications. Moreover, the topic of pressure intersects with related disciplines such as mathematics, engineering, and technology. Figure 2 shows the STEM project process carried out by students.

Figure 2. Students conducting testing of the non-electricity water pump they have built using the STEM approach.

The critical thinking skills outcomes from STEM learning through the non-electric water pump project are classified according to Paul and Elder's eight indicators, as shown in Figure 3.

The most frequently observed indicator was asking questions, with students posing a total of 203 questions during the learning process. These questions were categorised, based on Paul and Elder's Universal Intellectual Standards (2006), into four sub-indicators: asking questions clearly (2a), asking questions relevantly (2b), asking deep questions (2c), and asking questions from different perspectives (2d). Among these, the most frequent was asking questions clearly (2a), with 79 occurrences, followed by asking questions from different perspectives (2d), which occurred 37 times. Most of the questions posed by students were directed towards their peers during the group discussion phase, particularly when determining the design of the non-electric water pump.

G: Once you're done, let's chat about how to solve the problems in the workbook, alright? S2: Oh, this one... So, is Sumedang mostly flat or mountainous?

S3: Mostly highlands

S2: Oh, so if people have difficulty getting water, is it because Sumedang's city. topography is mostly highlands.

S3: Yeah, that's right. Write that down.

S2: How does it work then? So, the water is pumped from the source using that pump, is

that the solution?

S3: Yep.

The second most frequently observed indicator was indicator 6, *conveying assumptions to form perspectives*, with a total of 148 instances. Within this indicator, the most frequent sub-indicator was 6a, *clearly conveying assumptions about agreement or disagreement*, which occurred 84 times. The distribution of sub-indicator 6a is presented in the graph below.

Based on the analysis of sub-indicator 6a, it first appeared at learning index 28 and reached its peak at learning index 325. Learning index 28 corresponds to the phase in which the teacher reviewed the design of the non-electricity water pump, while index 325 coincided with the testing of the constructed device. During this phase, group discussions stimulated students to convey more assumptions. This contrasts with the first meeting, where the occurrence of sub-indicator 6a was not tied to the learning phase but rather to opportunities provided by the teacher or peers to express opinions clearly. In the second meeting, however, the frequency of sub-indicator 6a increased during experiment- or testing-related discussions. This pattern suggests that experimental or testing phases encouraged students to think more critically when conveying data from their experiments. An example of sub-indicator 6a can be seen in the dialogue from Group Discussion 1 during the testing of the non-electricity water pump.

S2: So, it's 'cause the load was too heavy and the air tank sprung a leak.

S3: Yeah, spot on. It leaked 'cause I messed up installing the gear. Should've done it right *to avoid leaks. Made a mistake with it this morning.*

S3: That's why the pump didn't work.

S2: Yeah, wrong installation.

Based on the analysis of critical thinking skills across the indicators in STEM learning through the construction of a non-electricity water pump, the least frequently observed indicator was *setting goals*.

This indicator comprises two sub-indicators from the Universal Intellectual Standards: (1a) clearly stating learning objectives and (1b) stating objectives relevant to the problem. Clear communication of objectives refers to articulating the overall project aim, namely solving the water problem, whereas relevant communication denotes students expressing the objectives of specific learning activities in relation to the problem presented by the teacher during the learning process.

Analysis of the occurrence of the *communicating goals* indicator revealed that students paid limited attention to articulating objectives. They rarely expressed either the general project goals or the specific activity objectives unless explicitly prompted during group discussions. Descriptive analysis of the STEM learning project on constructing a non-electricity water pump further indicated that the most frequently demonstrated critical thinking skills were posing questions, presenting assumptions, and open-mindedness, whereas the least frequently observed was communicating learning objectives or project completion goals.

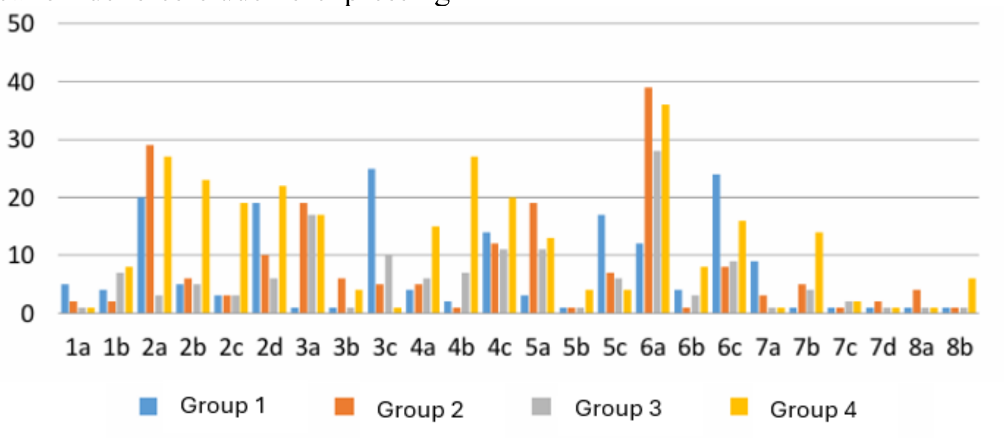

Figure 3. Graph of students' critical thinking skills outcomes over 1 semester of project work.

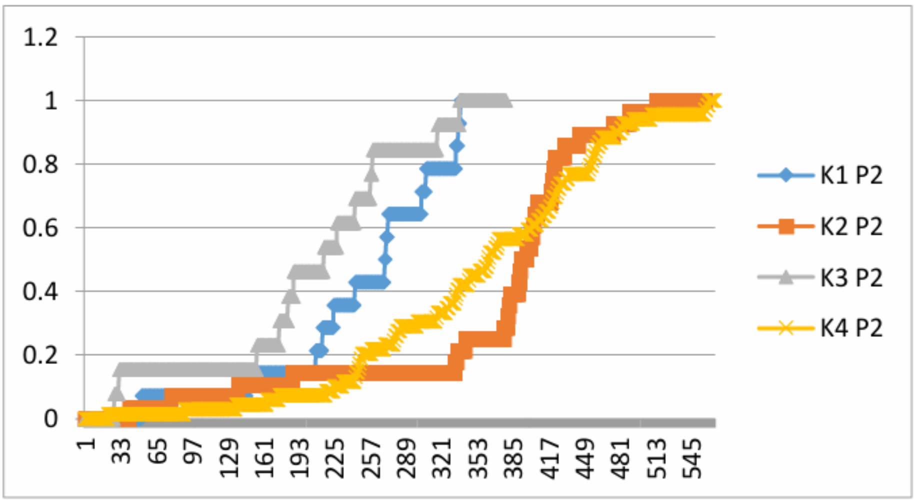

Figure 4. The Frequency of Sub-indicator "Conveying Assumptions" in the Learning Index.

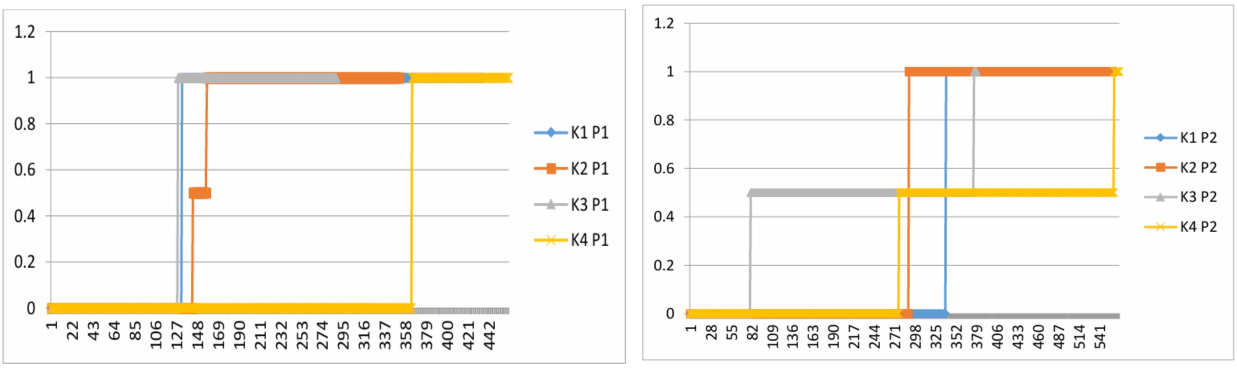

Figure 5. The Occurrence of Sub-indicators Communicating Problem-Solving Goals and Communicating Learning Objectives.

Discussion

An analysis of the frequency and distribution of critical thinking indicators in the STEM learning project on constructing a non-electric water pump revealed that their occurrence was influenced by the stages of STEM activities. In the initial meeting, when students identified fundamental questions related to real-life issues such as water scarcity in Sumedang Regency, there was a marked increase in questioning, with this indicator appearing 203 times—significantly more than any other. During subsequent group discussions on designing a non-electric water pump to address water scarcity, the indicator *identifying and explaining concepts* occurred 124 times, reflecting students' efforts to discuss and clarify relevant operational principles.

This frequent occurrence highlights students' active involvement in conceptualising and clarifying technical aspects of the project. Document analyses of group notes and design sketches revealed iterative refinements of understanding, corroborating the quantitative data and demonstrating cognitive engagement beyond simple indicator counts. Triangulating findings across multiple data sources thus enriches interpretation, offering a more holistic account of how students' critical thinking skills develop in authentic STEM learning contexts.

The initial stages of the non-electric water pump project demonstrated promising outcomes in the development of students' critical thinking skills. As they addressed the real-world issue of water scarcity and engaged in the design and implementation of prototypes, students not only applied STEM knowledge but also refined their critical thinking abilities (Stembridge Labs, 2023). Beyond the high frequency of questioning and concept clarification, their engagement in the project also led to frequent demonstrations of problem-solving and decision-making skills (Husain, 2023). The collaborative nature of the project, in which students worked in groups to present designs and conduct on-site testing, provided multiple opportunities to analyse problems, evaluate alternatives, and make informed decisions (Golden, 2023; Nguyen & Habók, 2023)

In addition, students' immersion in the socio-economic realities of their local community encouraged them to reflect on the ethical and environmental implications of their designs (Golden, 2023). This holistic approach to STEM learning not only deepened their understanding of the practical applications of STEM concepts but also fostered a sense of responsibility and awareness of the broader consequences of their work, aligning with the objectives of contextual STEM education (Castle et al., 2024). As the project progresses, it will be important to continue monitoring the development of students' critical thinking skills and to investigate how these are translated into their problem-solving approaches (Karampelas, 2023). Such monitoring can provide valuable insights into the transformative potential of contextual STEM learning in cultivating well-rounded, socially conscious individuals with strong critical thinking abilities (Asher et al., 2023).

The iterative process of testing and redesigning the non-electric water pump project actively engaged students in systematically collecting and analysing experimental data. This engagement extended beyond data gathering to encompass higher-order cognitive activities such as hypothesis formulation, developing assumptions, and reflective evaluation of observed results (Totten et al., 2020). Tasks such as observing, recording data, and repeatedly evaluating test outcomes provided students with opportunities to strengthen their data interpretation and causal reasoning skills, which are key indicators of critical thinking ability.

Observational data from the first and second sessions demonstrated a consistent frequency of these activities, revealing a clear pattern closely aligned with the structured sequence of learning tasks. This indicates that the emergence of critical thinking indicators was not incidental but was strongly shaped by the design and sequencing of authentic learning experiences (Kamarrudin et al., 2023). In other words, critical thinking skills developed through dynamic interactions between learners and a well-structured, contextually relevant learning environment.

The teacher's role in this context was pivotal, functioning as both facilitator and scaffold provider (Patel & Johnson, 2023). Through structured guidance, the teacher supported students in managing complex information and directed their thought processes from basic data collection towards deeper analysis and evidence-based decision-making (Vance et al., 2016). The observed pattern of critical thinking development further highlights the importance of sustained, inquiry-based, and contextually grounded learning experiences (Lacrin, 2021). The emergence of these skills varied according to the learning phase, individual characteristics, and group dynamics (Karampelas, 2023). Contextual STEM learning is specifically designed to strengthen students' life skills for global competition in the twenty-first century by equipping them to solve everyday problems effectively (Saleh et al., 2023). Findings from this study's STEM learning project may therefore offer valuable guidance for teachers in developing a more meaningful science education curriculum for the future.

Conclusion

The design of STEM learning with the theme of non-electric water pumps is characterised by the use of contextual problems drawn from students' daily lives, particularly the issue of water scarcity in Sumedang Regency. This approach fosters a deeper understanding and application of knowledge gained in classroom discussions. The stages of prototype design and experimentation further promote active engagement in practical problem-solving, enabling students to achieve a more comprehensive grasp of concepts. Frequent group discussions also create opportunities for the emergence of critical thinking indicators essential to students' holistic development. The development of these skills is influenced by learning phases, individual characteristics, and group dynamics, all of which are integral aspects of STEM education. Moreover, teacher instructional practices play a crucial role; the findings and discussions arising from this project should encourage teachers to reflect on their methods and to train students more effectively to solve everyday problems critically and innovatively.

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2025

SEAQIS Journal of Science Education (SciEd)
ISSN: 2987-8101 | E-ISSN: 2964-7533
Vol: 5, No: 2, PP: 11-22
www.journal.qitepinscience.org

Research Paper Open Accsess

Integrating STEAM4Innovator Learning, Gamification, and Design Thinking to Enhance Students' Innovative Skills

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Article history:
Received: March 10, 2025
Revised: May 19, 2025
Accepted: June 24, 2025

Abstract

This study aimed to develop an integrated learning approach that combines STEAM4Innovator, gamification, and design thinking to enhance students' innovative skills. The approach was created through a four-step process, including empathising and defining insights with learners, ideating and generating WOW! ideas, prototyping and developing a business model, and testing and producing the final solution. The approach was implemented with 109 Year 12 students, and the results indicated substantial improvements in their academic performance (78.47% improvement), innovative skills (62.09% improvement), and satisfaction with the learning process (86.97 out of 100), thereby highlighting the effectiveness and appeal of proposed approach. In addition, the success of approach is attributed to its capacity to foster learning and innovation skills, namely inspiration, imagination, creativity, integration, and hands-on implementation. This study demonstrates the effectiveness of integrating STEAM4Innovator, gamification, and design thinking in enhancing learning outcomes and encouraging the development of innovative skills.

Keywords: STEM, STEAM4Innovator, Gamification, Design thinking

Introduction

Education plays a crucial role in national development and is entrusted with the vital responsibility of developing human resources, promoting social equality, and driving economic growth and prosperity. In 2015, Thailand joined the ASEAN community to create regional stability and peace, foster economic cooperation, and improve the quality of life for ASEAN citizens (Foreign Affairs Division, 2021). This regional integration has implications for education systems in member countries, requiring them to develop individuals to their full potential and contribute to sustainable societal development (Pimmas, 2018).

Thailand should enhance its workforce to meet international standards and prepare for the twenty-first century. This requires not only core academic knowledge but also essential competencies such as learning and innovation, information and technology literacy, and life and career skills. The country's 20-year National Strategy (2018–2037) prioritises human resource development, with the aim of improving the quality of education and ensuring its accessibility for all (The Office of the National Economic and Social Development Council, 2018). The Ministry of Education is responsible for developing a competitive workforce and has introduced educational reforms to achieve this objective. The Office of the Permanent Secretary for the Ministry of Education has established policies that place emphasis on active learning, digital literacy, and communication skills (The Office of the Education Council Secretariat, 2017).

Learning and innovation skills are crucial in today's rapidly changing world, enabling individuals to adapt and thrive. Teachers play a vital role in cultivating these skills, fostering inquiry, creativity, and innovation in their students. Such skills emphasis on analytical thinking, problem-solving, and cross-disciplinary knowledge integration, essential for preparing students to succeed in the twenty-first-century workforce (Chompoo *et al.*, 2023).

However, the current education system faces challenges, including a lack of student motivation, inadequate analytical and problem-solving skills, and insufficient integration of knowledge across disciplines. The 2018 PISA results indicated that Thai students scored below the OECD average in reading, mathematics, and science, particularly in analytical thinking and problem-solving (The Institute for the Promotion of Teaching Science and Technology, 2021). This underscores the need to strengthen students' higher-order thinking skills and integrate knowledge from multiple subject areas.

Design thinking, a twenty-first-century teaching approach, can be used to develop these skills (Mayuree & Pichaya, 2021). It is a systematic process that begins with understanding the needs of others, followed by collaborative brainstorming and hands-on implementation. One practical approach is the STEAM4Innovator model, which combines STEAM (Science, Technology, Engineering, Arts, and Mathematics) with entrepreneurship skills (The National Innovation Agency, 2022). This model enhances students' twenty-first-century competencies, promotes creative learning through experiential activities, and cultivates both innovative thinking and entrepreneurial potential. Furthermore, gamification can be used to increase motivation and engagement in the learning process (Natchaporn, 2022).

Takpittayakhom School, where this innovation was developed, is a large school in Tak Province, Thailand. Despite being one of the leading schools in the province, the 2022 Self-Assessment Report (SAR) indicated that students' abilities to gather knowledge independently, work collaboratively, and apply knowledge creatively was below the target (Takpittayakhom School, 2022). This highlights the need for integrated learning approaches that foster innovation and its practical application.

In this study, the integration of STEAM4Innovator learning, gamification, and design thinking is of central improtance. This approach draws on the strengths of STEAM, gamification, and design thinking to create a learning environment that promotes creative thinking, problem-solving, and the development of students’ innovative potential. Such skills are essential for preparing students to succeed in the twenty-first-century workforce and to contribute to Thailand's 4.0 economic development goals.

Methodology

The approach was developed by empathising with learners and understanding their needs, followed by a thorough research phase. Learners’ needs, interests, and prior learning styles were identified through questionnaires administered to students during the first semester of the 2022 academic year. Analysis of the data revealed key challenges and motivational factors influencing students’ learning experiences. These insights helped to clearly define specific problems, which in turn informed the design of a learning approach aimed at addressing the identified needs and challenges. Subsequently, extensive research was conducted, including a review of relevant documents such as the learning standards for Physics. In addition, concepts, theories, and prior research related to design thinking, STEAM4Innovator, gamification, and twenty-first-century skills were examined.

A prototype of the approach was then developed. This phase involved setting clear objectives and designing activities that integrated STEAM4Innovator, gamification, and design thinking. Gamification was implemented using ClassPoint® software to enhance student engagement and motivation. The prototype was tested with a pilot group of students in the first semester of the 2022 academic year. Learning activities in Physics subject for Year 12 were implemented with one class (n = 30), and data were collected through questionnaires, classroom observations, and student interviews. This pilot study allowed for the evaluation of the feasibility and effectiveness of learning approach. Feedback from the pilot indicated that certain activities required more time, particularly the brainstorming and testing phases. Students also recommended clearer task instructions during prototype construction. Based on this feedback, the learning activities were refined to improve pacing, clarity, and instructional support before the full-scale implementation in the 2023 academic year.

The approach was implemented in Physics, specifically in the Heat and Gas unit, for Year 12 students during the first semester of the 2023 academic year. This study employed a quasi-experimental research design using a one-group pre-test–post-test method to examine the effects of the integrated learning approach. All four Year 12 classes (12/1 to 12/4) participated under the same instructional conditions. The integrated learning approach was implemented uniformly across all classes, following the same sequence of activities, materials, and assessment tools. All sessions were facilitated by the same teacher (the author), ensuring consistency in delivery, classroom management, and data collection procedures. To provide a clearer insight into the classroom implementation, the integrated learning approach was applied to the Heat and Gases unit in Physics 5 (W33205), taught to 109 Year 12 students across four classes (Grade 12/1–12/4). The learning design followed a structured, four-phase framework that merged the STEAM4Innovator process with design thinking and gamification via ClassPoint®. Each phase was aligned with the physics content and targeted innovation competencies. The instructional design emphasized real-world relevance by assigning students to solve problems related to heat and gas in everyday contexts. To illustrate this, gamification was specifically integrated into each lesson through targeted ClassPoint® tools. For instance, during the exploration of heat transfer mechanisms, students participated in interactive multiple-choice quizzes covering conduction, convection, and radiation, earning points for speed and accuracy. A live leaderboard was displayed at the end of each session to recognize top-performing teams and to promote friendly competition, reinforcing both content mastery and engagement. Lessons spanned ten 60-minute sessions, integrating inquiry-based learning, group work, and digital tools. The instructional phases, sample classroom activities, and gamification tools used in this unit are summarized in Table 1. This structure offers practical guidance for educators seeking to apply the approach in their own classrooms. Each phase and activity can be adapted to fit different time frames, student abilities, and resource settings, making the design highly transferable. This approach diverged from traditional instruction in both form and function, emphasising collaborative innovation, iterative problem-solving, and hands-on experimentation. Students were not passive recipients but co-creators of knowledge, learning through design cycles, experimentation, and peer review. By incorporating gamified elements and entrepreneurial thinking into a physics context, students developed not only subject mastery but also innovation-oriented mindsets, aligned with the five core competencies of STEAM4Innovator: inspiration, imagination, creativity, integration, and hands-on implementation.

Table 1 Instructional Phases, Sample Activities, and Gamification Tools in the Heat and Gases Unit.

Phase	Focus	Sample Activities	Gamification Tools (via ClassPoint®)
Empathising with learners and defining insights	Empathise with real-world problems and define clear challenges	- Students interviewed peers about heat-related issues at home - Explored inefficiencies in thermal insulation	- Polls to rank challenges - Quiz on thermal basics
Ideating and generating WOW! ideas	Generate innovative ideas based on physics principles	- Brainstorm ideas for low-cost heat retention devices - Select feasible concepts	-
Prototyping and developing a business model	Develop prototypes and consider value creation	- Build simple models like insulated walls, thermochromic products - Simulate market pitch	-
Testing and producing the final solution	Test, refine, and present ideas to peers and community	- Present solutions to classmates - Reflect and improve via feedback	- Badges for best presentation, creativity, and teamwork

The academic performance, learning, and innovation skills were evaluated, including inspiration, imagination, creativity, integration, and hand-on implementation. The students' satisfaction with learning activities using this approach was also assessed and discussed.

Results and Discussion

Table 2 shows the results of the survey on students' learning needs, interests, styles, prior experiences and learning challenges, based on responses from 114 students in the first semester of the 2022 academic year. The majority of students were female (66.67%). The most preferred learning style was hands-on experiments (65.79%), followed by group activities (19.30%) and learning through digital media (4.77%). The most popular subjects were science (48.24%), technology (17.54%), and engineering (8.77%). The most effective learning methods for understanding were watching videos or teaching materials (37.72%), participating in discussions or exchanging ideas (21.93%) and completing exercises or activities (17.54%). Most students (96.49%) believed that technology played a significant role in their learning. The most common obstacles identified were lack of motivation (64.22%), lack of interaction with peers or teachers (62.82%), and unchallenging activities (58.24%).

Based on these observations, the main areas for improvement in the learning process were enhancing active learning, adjusting activities to be more motivating and interactive, and integrating games and technology to support learning. To address these areas, an integrated learning approach was developed that incorporated design thinking, STEAM4Innovator, and gamification elements.

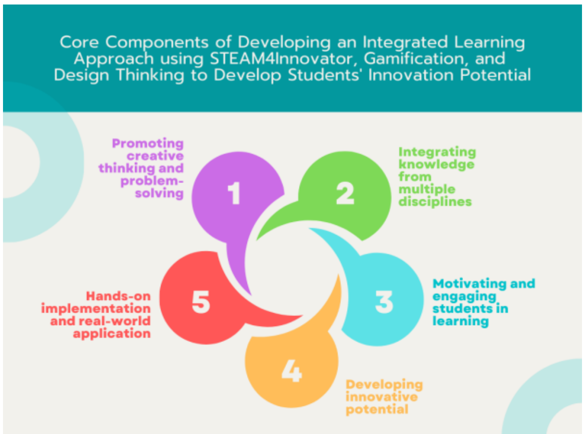

Figure 1 Core components of developing an integrated learning approach using STEAM4Innovator, gamification and design thinking to develop students' innovation potential.

The approach was developed based on the core elements shown in Figure 1, which include promoting creative thinking and problem-solving, integrating knowledge from multiple disciplines, motivating and engaging students in learning, fostering innovative potential, and emphasising hands-on implementation and real-world application. These elements were derived from analysing student needs and existing research, forming the foundation for the integrated learning approach.

Table 2 Learning preferences, interests, prior learning experiences and problems in learning of Students in the first academic year 2022.

Question	Percentage
1. Gender	
• Male	33.33
• Female	66.67
2. What learning style do you prefer the most?	
• Lecture	1.75
• Group activities	19.30
• Self-directed learning	4.39
• Learning through digital media	4.77
• Hand-on experiment	65.79
• Others	4.00
3. What subject do you enjoy learning the most?	
• Science	48.24
• Technology	17.54
• Engineering	8.77
• Art	1.75
• Math	7.01
• Language	7.93
• Business	7.01
• Others	1.75
4. What learning method do you think helps you understand the content the best?	
• Listening of explanations	14.04
• Reading books/articles	8.77
• Watching videos/teaching materials	37.72
• Doing exercises/activities	17.54
• Discussions/exchanging ideas	21.93
5. What learning method do you think makes you feel the most engaged and interested?	
• Playing games/competitions	30.70
• Working in teams	15.79
• Receiving rewards/praise	19.30
• Creating work	28.07
• Others	6.14
6. What role do you think technology plays in your learning?	
• Very Important	96.49
• Important	3.51
• Moderate	0.00
• Less important	0.00
• Not important at all	0.00
7. What challenges have you encountered in your learning experiences? (multiple answers allowed)	
• Lack of motivation to learn	64.22
• Uninteresting content	48.75
• Unchallenging activities	58.24
• Lack of interaction with peers/teachers	62.82
• Inappropriate learning materials	33.78
• Learning environment not conducive to learning	12.15
• Others	7.23

Table 3 Mean, standard deviation, and percentage of improvement in learning achievement in Physics, heat and gas unit, grade 12 before and after learning with the integrated learning approach.

Topic	Before learning			After learning			% Improvement
	Mean	**S.D.**	**Interpretation**	**Mean**	**S.D.**	**Interpreation**	
Learning Achievement (Total score of 20)	4.85	2.20	Not passed	15.83	1.61	Passed	78.47

Figure 2 The designed approach integrates STEAM education, gamification, and design thinking to develop students' innovation potential.

As illustrated in Figure 2, the designed approach integrates STEAM education, design thinking, and gamification using ClassPoint® to foster students' innovative potential. The approach includes four steps, i.e.,

1. Empathising with learners and defining insights: This initial step combines the 'Empathize & Define' phases of design thinking with the 'Insight' stage of the STEAM4Innovator model. Students explore the problem's context, exploring relevant principles, theories, and definitions. Through interviews, they pinpoint the core issue and formulate potential solutions. Gamification, implemented via ClassPoint®, injects fun and engagement, encouraging active participation and deeper comprehension.

2. Ideating and generating WOW! ideas: This step merges the 'Ideate' stage of design thinking with the 'WOW! Idea' phase of STEAM4Innovator. Students engage in brainstorming sessions, collectively generating diverse potential solutions. They then critically evaluate these ideas and select the most promising approach to tackle the problem.

3. Prototyping and developing a business model: This stage connects the 'Prototype' phase of design thinking with the 'Business Model' component of STEAM4Innovator. Students translate their chosen solution into a tangible prototype, rigorously testing and refining it. Additionally, they assess the feasibility of their solution in a business context, considering its potential for real-world application.

4. Testing and producing the final solution: This final step links the 'Test' phase of design thinking with the 'Production & Diffusion' stage of STEAM4Innovator. Students finalise their product or solution, putting it to the test in a competitive setting. They showcase their work, comparing its effectiveness and business viability with other teams. Gamification, using ClassPoint®, adds a layer of challenge and competition, motivating students to strive for excellence.

To clarify how the instructional model in Figure 2 was implemented in the actual lessons, the classroom activities aligned with each phase are detailed in Table 1, located in the Methods section.

Table 3 presents the academic average scores, standard deviations, and percentage of the progress of pre- and post-tests in Physics subject (Heat and Gas unit) using an integrating STEAM4Innovator, gamification, and design thinking approach. This integrated learning approach was implemented with 109 students in the first semester of the 2023 academic year. The total score was 20 points, assessed through a teacher-developed test consisting of 20 multiple-choice questions (0.5 points each), 5 short-answer questions (1 point each), and 2 problem-solving questions requiring written solutions (2.5 points each). The items were designed to assess a comprehensive understanding of the key physics concepts in the Heat and Gases unit, including heat transfer, specific heat capacity, thermal equilibrium, and gas laws.

The results showed that the students' average score on the pre-test was 4.85 out of 20, which was below the passing threshold of 70%. However, after implementing the integrated learning approach, the average score on the post-test increased to 15.83, exceeding the passing threshold. Compared to the previous academic year (2022), where the same content on heat and gases was taught using conventional instruction, the integrated learning model demonstrated a substantially greater improvement in academic performance. Specifically, the traditional approach yielded only a 48.25% improvement between pre- and post-tests, whereas the integrated approach in 2023 resulted in a 78.47% improvement. This significant improvement in academic performance can be attributed to the effectiveness of the integrated learning approach in enhancing the students' understanding of the subject matter. By integrating elements of STEAM4Innovator, gamification, and design thinking, the approach actively engages students in the learning process, encouraging them to participate in hands-on activities, group discussions, and problem-solving exercises. This dynamic and interactive learning environment motivates students and allows them to apply theoretical concepts to real-world scenarios, enhancing their comprehension and retention. Active learning techniques, such as collaborative group work and interactive problem-solving, led to higher student performance and lower failure rates than traditional lecture-based instruction (Freeman *et al.*, 2014). Similarly, Prince (2004) highlighted that active learning strategies, including experiential and project-based learning, are associated with better student outcomes and increased engagement.

Table 4 Results of students' innovative skills development in Physics, heat and gas unit, grade 12 before and after learning with the integrated learning approach.

Topic	Before learning			After learning			% Improvement
	Mean	S.D.	Interpretation	Mean	S.D.	Interpretation	
Total Innovative Skills Score (Total score of 100)	51.38	1.40	Medium	83.28	2.20	Excellent	62.09

Table 4 shows the students' innovative skills development using the STEAM4Innovator framework, which consists of five aspects: inspiration, imagination, creativity, integration, and hands-on implementation. The 100-point scale was based on five equally weighted dimensions from the STEAM4Innovator model: inspiration, imagination, creativity, integration, and hands-on implementation. Each dimension was assessed using a 5-point Likert-scale observation rubric (1 = Not Demonstrated, 5 = Exceptional), resulting in a maximum of 20 points per dimension. The rubric was developed by the researcher and validated by three subject-matter experts to ensure content accuracy and relevance.

The classroom teacher conducted the assessment through structured observation during key activities such as brainstorming, group collaboration, prototyping, and testing. By applying a consistent and clearly defined rubric, reliable assessment was achieved even with a single evaluator. The results showed that the students' average score on the pre-test was 51.38 out of 100, which falls under the 'medium' level of innovator skills. However, after implementing the approach, the average score on the post-test increased to

83.28, reaching the 'excellent' level. This improvement showed the effectiveness of the approach in enhancing innovative skills. Increasing students' innovative skills due to a creative and interactive learning environment enhances students' problem-solving abilities and engagement. The improvement in students' innovative skills in this study—reflected by a normalized gain (N-gain) of 0.656—is comparable to findings from Witdiya *et al.* (2023), who reported a moderate N-gain of 0.55 in creative thinking skills among Grade 11 students through STEAM-based project learning in Indonesia. While their study emphasized project-based learning, the present study incorporated STEAM4Innovator, gamification, and design thinking, which may explain the relatively higher gain observed in this research. This comparison supports the effectiveness of well-designed STEAM learning environments in enhancing innovation capabilities. Research by Hwang *et al.* (2015) also supports that integrating gamification in education improves students' engagement and motivation, leading to higher learning outcomes.

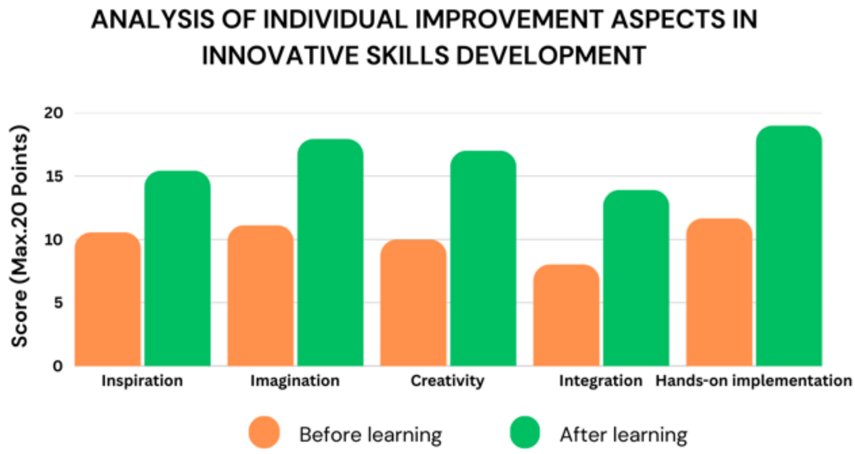

Figure 3 Average individual scores of students' innovative skills before and after the implementation of the integrated learning approach.

Figure 3 shows the analysis of individual improvement aspects in innovative skills development. It was revealed that there was improvement in all five areas. 'inspiration' increased from 10.56 to 15.43, demonstrating a more remarkable ability to inspire and motivate others. 'Imagination' improved from 11.12 to 17.44, indicating enhanced creativity and the ability to envision possibilities. 'Creativity' rose from 10.00 to 17.01, reflecting a greater capacity for generating novel ideas and solutions. 'Integration' increased from 8.03 to 13.91, suggesting a better understanding of combining different concepts to create innovative solutions. Finally, 'hands-on implementation' improved from 11.67 to 18.99, demonstrating an increased ability to put ideas into action and produce tangible results. These findings highlight the effectiveness of the integrated learning approach in fostering the development of well-rounded innovators. According to Guerzon & Busbus (2023) highlights that STEM integration fosters creativity and problem-solving skills by encouraging students to empathize, ideate, and prototype solutions. Furthermore, Zeybek and Saygi (2024) integrate gamification into education, which enhances student engagement and motivation, improving learning outcomes. These elements collectively create an interactive and dynamic learning environment that supports the development of innovative skills.

Figure 4 Student-designed thermal insulation prototypes (A) and an in-class test of heat insulation performance using a heat lamp and temperature sensor (B).

Table 5 Students' satisfaction with the integrated learning approach.

Item	Very satisfied (%)	Satisfied (%)	Neutral (%)	Dissatisfied (%)	Very dissatisfied (%)
1. Overall, I like the learning activities that I have participated in.	81.65	16.52	1.83	0.00	0.00
2. The learning activities are interesting and make me want to learn and participate.	85.32	13.76	0.92	0.00	0.00
3. The learning activities help me think of new ideas and feel more confident in presenting my own ideas.	80.73	14.68	4.59	0.00	0.00
4. The learning activities help me think of new ideas and feel more confident in presenting my own ideas.	91.74	8.26	0.00	0.00	0.00
5. The learning activities help me improve my problem-solving skills and learn to find solution on my own.	90.83	9.17	0.00	0.00	0.00
6. The learning activities help me work better with my friends and learn more from them.	86.24	10.09	3.67	0.00	0.00
7. I enjoy learning in this way and would like to have activities like this more often.	92.66	6.42	0.92	0.00	0.00
8. I have learned new and useful things from these activities.	85.32	7.34	7.34	0.00	0.00
9. The learning activities are challenging but not too difficult or too easy for me.	87.16	3.76	9.08	0.00	0.00
10. I feel that this activity helps me understand the connections between different subjects better.	88.07	6.43	5.50	0.00	0.00
Overall average	**86.97**	**9.64**	**3.39**	**0.00**	**0.00**

In addition to the quantitative findings, student-created outputs were collected as tangible evidence of learning outcomes. During the Prototype and Test phase, students applied concepts of heat transfer by designing thermal insulation devices using everyday materials. These hands-on projects allowed students to demonstrate their understanding of conduction, convection, and radiation through real-world applications. An example of such a product is shown in Figure 4, which displays a student-designed thermal insulation container. The project was assessed based on a performance rubric covering thermal effectiveness, creativity, material selection, and teamwork. These outputs serve as authentic evidence of the students' ability to synthesize content knowledge and innovation skills.

In addition, Table 5 shows the evaluation of the students' satisfaction with the integrated learning approach. The results showed an average satisfaction score of 86.97 out of 100, indicating high satisfaction with the learning process. The incorporation of various innovative elements contributed to this positive outcome. The study's findings highlight the effectiveness of the integrated learning approach in enhancing academic performance, developing innovative skills, and improving student satisfaction. The approach's success is attributed to its ability to create a dynamic and engaging learning environment that fosters active participation, collaboration, and creativity. Dym *et al.* (2005) and Dichev *et al.* (2020) revealed that design thinking and gamification enhance student satisfaction by promoting understanding of design and boosting motivation through active participation in experiential learning activities. These approaches create engaging, interactive learning experiences that foster a better understanding of the material. This aligns with the approach described earlier, which integrates design thinking and gamification elements, leading to higher satisfaction levels among students through active participation, collaboration, and creative problem-solving in real life.

While overall satisfaction was high, a small number of students selected 'neutral' responses for some items. Further analysis suggests that these students—typically in upper secondary school—may possess self-regulated learning abilities that allow them to focus directly on academic content. As such, they might perceive structured activities such as gamification or design thinking as unnecessary for their learning process. Panadero (2017) notes that learners with strong self-regulation skills tend to rely on their personal strategies and autonomy, often favoring direct content access over externally guided interventions. These findings underscore the importance of designing flexible instructional models that can accommodate both structured engagement and independent learning preferences.During implementation, several practical challenges emerged that may inform future applications. For example, when students encountered difficulty with the mathematical aspects of gas laws, visual simulations such as the PhET Interactive platform were used to illustrate the relationships between pressure, volume, and temperature more intuitively. To address student engagement—particularly in repetitive or abstract segments—gamification strategies were applied using ClassPoint®, including live quizzes, point-based competition, and digital badge rewards. These elements significantly increased student motivation and participation by transforming conventional activities into goal-oriented challenges.

Additionally, some upper secondary students initially viewed the innovation process as secondary to mastering content. This highlights the need for clear communication of the model's purpose. Teachers are advised to plan time allocations carefully, prepare materials in advance, and incorporate low-cost alternatives to ensure smoother implementation.

Although this study focused on the topic of Heat and Gases in Grade 12 physics, the integrated learning approach combining STEAM4Innovator, gamification, and design thinking has the potential to be adapted for other scientific topics and different educational levels. For instance, in physics, it can be applied to topics such as electricity or mechanics, while in biology, it may be used to explore environmental systems or health-related innovations. Moreover, the emphasis on student-centred learning and innovation makes it suitable for use with younger learners through scaled-down activities that match their developmental stage.

Conclusion

The integrated learning approach successfully incorporated the concepts of STEAM4Innovator, gamification, and design thinking into the learning process. This resulted in the development of learning activities that enhanced the students' creative thinking, problem-solving, and innovative skills. The approach's four main steps are empathising with learners and defining insights, ideating and generating WOW! ideas, prototyping and developing a business model, and testing and producing the final solution are integrated with the design thinking of STEAM4Innovator and incorporate gamification to improve student motivation and engagement. The approach's effectiveness is evident in the significant improvement in the student's academic performance in physics subject. Furthermore, the students' innovative skills significantly improved. The students also expressed high satisfaction with their approach.

In conclusion, the integrated learning approach's success is attributed to its ability to create a dynamic, engaging learning environment that fosters active participation, collaboration, and creativity. It is a valuable contribution to Thailand's education system, supporting the development of a skilled and innovative workforce for the 21st century. Given its strong alignment with national core curricula and twenty-first-century competencies, this approach holds promise for broader adoption across schools in Thailand and ASEAN. However, as the present study involved a single school and short-term measurement, future research should consider long-term implementations and test its adaptability across diverse educational settings and subjects. To support broader adoption, the approach can be flexibly adapted to different classroom settings. For larger class sizes, teachers can conduct whole-class activities instead of small-group tasks or rotate stations to ensure participation. In resource-constrained environments, low-cost alternatives such as DIY thermometers can substitute standard lab tools. The model's core structure—based on problem-solving through design thinking—can also be applied to other science topics like electricity or mechanics by redesigning the problem context. This adaptability enhances the model's relevance across diverse learning conditions while maintaining its focus on innovation skill development.

Acknowledgments

The author would like to thank the administrators, teachers, and students of Takpittayakhom School who participated in this study. The author also thanks the National Innovation Agency (NIA) for their support in developing the STEAM4Innovator model.

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2025

SEAQIS Journal of Science Education (SciEd)
ISSN: 2987-8101 | E-ISSN: 2964-7533
Vol: 5, No: 2, PP: 23-33
www.journal.qitepinscience.org

Research Paper
Open Accsess

The Impact of Experiential Learning on Climate Change Awareness in Sustainability Education: A Systematic Review

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Article history:
Received: February 12, 2025
Revised: June 2, 2025
Accepted: June 24, 2025

Abstract

This systematic review evaluates the effectiveness of experiential learning methods, including hands-on activities, in enhancing climate change awareness among high school students within sustainability education. By comparing these approaches to traditional lecture-based instruction, the review identifies key facilitators and barriers to their implementation in educational settings. The study follows the PICO framework to define the Population, Intervention, Comparison, and Outcome, and uses the PROMPT mnemonic to assess the Presentation, Relevance, Objectivity, Methodology, Provenance, and Timeliness of the included studies. From 579 initial records, 25 studies met the inclusion criteria, spanning a range of geographic regions and intervention types. The findings indicate that experiential learning significantly improves students' climate change awareness by fostering engagement, real-world application, and collaborative learning. However, challenges such as limited resources, insufficient teacher training, and curricular constraints hinder broader adoption. This review highlights the value of integrating experiential learning into high school sustainability curricula and calls for further research on long-term impacts, culturally responsive practices, and the development of effective assessment tools and teacher support systems.

Keywords: Sustainability education, hands-on activities, experiential learning, climate change awareness, high school education

Introduction

Climate change represents one of the most critical challenges of our time, with profound environmental, economic, and social implications. As global temperatures rise and extreme weather events become increasingly common, equipping future generations with the knowledge, skills, and motivation to address these issues is more urgent than ever (Mebane et al., 2023). Education plays a central role in cultivating climate change awareness, particularly among students in both K–12 and higher education settings, who are at formative stages of cognitive and social development. Embedding sustainability education into school and campus curricula offers a strategic pathway to foster environmental literacy and promote meaningful engagement with climate-related challenges (Campos-Ugaz et al., 2022).

Traditional pedagogical approaches—characterized by passive learning, textbook reliance, and a focus on rote memorization—

often fall short in engaging students with the complexity and urgency of climate change (Tumanggor et al., 2022). These methods can create a disconnect between theoretical content and real-world application, limiting students' ability to internalize and act upon sustainability concepts (Harıadı et al., 2024). In contrast, experiential learning—including hands-on activities, project-based learning, field experiences, and simulations—provides interactive, student-centred alternatives that actively involve learners in constructing knowledge (Jiang et al., 2024). Such approaches have been shown to enhance engagement, critical thinking, and the retention of climate-related concepts by grounding learning in authentic contexts (Cabello & Savec, 2018).

Numerous studies highlight how experiential learning fosters deeper understanding, environmental responsibility, and proactive attitudes (Handoko et al., 2019). Activities such as outdoor education, community-based projects, or environmental simulations not only clarify abstract climate concepts but also help students recognize their role in contributing to sustainable solutions (Chen & Chang, 2024). These immersive experiences can cultivate a lasting sense of agency and stewardship that traditional methods often fail to achieve.

However, despite these documented benefits, experiential learning remains underutilized in many educational institutions. Barriers such as insufficient resources, limited teacher training, and institutional resistance to pedagogical innovation can hinder broader implementation. Additionally, much of the existing literature is fragmented, with studies varying in educational level, geographic scope, and intervention type (Abulibdeh, 2024).

To address this gap, this systematic review synthesizes current evidence on the impact of experiential learning methods, including hands-on activities, in enhancing climate change awareness across both school and university settings. By evaluating key facilitators and barriers, this review aims to provide actionable insights for educators, administrators, and policymakers seeking to strengthen sustainability education through active learning strategies.

Methodology

1. Protocol:

This systematic review was conducted in accordance with the PICO framework, with an initial protocol outlining the review's objectives, eligibility criteria, and methodology (Thapa et al., 2024). To ensure a structured and critical appraisal of the included studies, we employed the PROMPT mnemonic, which evaluates Presentation, Relevance, Objectivity, Method, Provenance, and Timeliness (Santos-Hermosa & Sánchez, 2010). The review focuses on assessing the effectiveness of hands-on activities and experiential learning methods (Intervention) in enhancing climate change awareness (Outcome) among school and university students (Population), in comparison to conventional learning methods (Comparison). This population is particularly important, as students in both K–12 and higher education are at a formative stage in developing sustainability attitudes and will play a pivotal role in future environmental decision-making.

2. Eligibility Criteria:

Studies included in this review were required to meet specific eligibility criteria. First, the population of interest was school and university students. Second, the intervention must involve hands-on activities or experiential learning methods aimed at promoting sustainability education and climate change awareness. Third, studies needed to include a comparison group utilizing conventional learning methods, such as lectures or textbook-based instruction. Finally, eligible studies were required to report measurable outcomes related to students' climate change awareness, knowledge, attitudes, or behaviours. We included both quantitative (e.g., randomized controlled trials, quasi-experimental designs, surveys) and qualitative studies (e.g., case studies, interviews, focus groups) that provided empirical evidence. Only studies published in English between December 2014, and December 2024 were considered, reflecting a decade of research following the 2015 Paris Agreement, which marked a global shift toward integrating climate change education into policy and curricula (Jamarani et al., 2024).

3. Information Sources and Search Strategy:

A comprehensive search strategy was developed to identify relevant studies across multiple databases, including Scopus, and Sinta. The search terms included combinations of keywords such as "sustainability education," "hands-on activities," "experiential learning," "climate change awareness," and "school." Boolean operators (AND, OR) were employed to refine the search results. The search was conducted in two phases: an initial search in November 2024 to develop the study protocol, followed by a more extensive search in December 2024 to capture any additional relevant studies published during that period (Jamarani et al., 2024).

The search yielded a total of 579 records, which were imported into Mendeley Desktop for reference management. Duplicate entries were removed, and the remaining records were screened for relevance based on titles and abstracts. The search strategy was designed to be inclusive, capturing a wide range of studies related to the impact of hands-on and experiential learning on climate change awareness. Additionally, a manual search of the reference lists of included articles was conducted to identify any further relevant studies that may not have been captured in the initial database search (Santos-Hermosa & Sánchez, 2010).

4. Data Charting and Synthesis of Results:

Data extraction was performed using a standardized charting form to ensure consistency and comprehensiveness. Key information was collected from each study, including author(s), year of publication, study design, sample size, intervention details, comparison methods, and outcomes related to climate change awareness. The extracted data were then synthesized qualitatively, focusing on the themes and patterns that emerged from the studies. This synthesis aimed to highlight the effectiveness of hands-on and experiential learning methods in enhancing students' understanding of climate change and their attitudes toward sustainability (Mebane et al., 2023).

In addition to qualitative synthesis, a descriptive analysis was conducted to summarize the findings across studies. This included calculating effect sizes where applicable and categorizing the outcomes based on the type of intervention and the context in which it was implemented. The synthesis of results aimed to provide a comprehensive overview of the current state of research on this topic, identifying both the strengths and limitations of existing studies. By analysing the data in this manner, the review sought to draw meaningful conclusions about the impact of innovative teaching methods on climate change awareness among school and university students, ultimately informing future educational practices and policies (Pena-Vega et al., 2022).

Results and Discussion

The search of the database, along with the manual examination of reference lists and hand searching, yielded 579 reports. After eliminating duplicates and completing the title and abstract screening, 43 papers were found to be eligible for review (Thapa et al., 2024). The eligibility assessment process resulted in the inclusion of 25 papers in this scoping review (see Table 1 and Figure 1).

Table 1 Summary of included publications.

Author(s), Year, Country	Article Type	Sampling Methods, Study Design, Data Collection Tools	Participant Profile
Kinoshita et al., 2019, Indonesia	Empirical Study	Convenience sampling, Cross-sectional design, Questionnaire surveys	University students
Zidny & Eilks, 2020, Indonesia	Conceptual Paper	Purposive sampling, Case study, post-intervention questionnaire	High school and university students
Paristiowati et al., 2022, Indonesia	Empirical Study	Purposive sampling, Qualitative design, Interviews, observations, reflective journals	Preservice chemistry teachers
Antronico et al., 2023, Italy	Empirical Study	Voluntary questionnaire, Survey design, Descriptive statistics	High school students
Ika Sari et al., 2024, Indonesia	Quantitative Study	Stratified sampling, Regression analysis, Questionnaire surveys	Early childhood educators and students
Bailey et al., 2022, USA	Mixed Methods Study	Purposive sampling, Pre-post design, Structured surveys and focus groups	High school students
Piscitelli & D'Uggento, 2022, Italy	Empirical Study	Convenience sampling, Cross-sectional design, Questionnaire surveys	High school students
Harris et al., 2022, USA	Empirical Study	Purposive sampling, Mixed-methods design, Tactile teaching tools	Middle school to master's level students
Bishoge et al., 2022, Tanzania	Empirical Study	Convenience sampling, Cross-sectional design, Questionnaire surveys	Secondary school students
Giardino et al., 2022, EU	Review Paper	Stratified sampling, Case study, Pedagogical documentation	High school students
Haimovich et al., 2022, Israel	Review Paper	Purposive sampling, Case study, Virtual Escape Room evaluation	High school chemistry students
Tumanggor et al., 2022, Indonesia	Qualitative Study	Purposive sampling, Structured interviews, Observations	High school students
Zjalic et al., 2023, Italy	Pilot Study	Convenience sampling, Pre-post survey, Structured questionnaires	High school students
Martinez-Mirambell et al., 2023, Spain	Empirical Study	Semi-structured interviews, Active learning sessions	Secondary school students
Goel et al., 2023, India	Empirical Study	Convenience sampling, Cross-sectional design, Offline questionnaire surveys	Middle and high school students
Kluczkovski et al., 2024, UK	Program Evaluation	Teacher surveys, Student blogs, Mixed-data collection	High school students
Abulibdeh et al., 2024, Global Perspective	Scoping Review	Literature review	Institutions transitioning to zero-carbon campuses
Chen & Chang, 2024, Taiwan	Mixed Methods Study	Purposive sampling, Quasi-experimental design, pre-post-tests, Interviews	Graduate students
Martinez-Mirambell et al., 2023, Spain	Empirical Study	Semi-structured interviews, Active learning sessions	Secondary school students
Jiang et al., 2024, USA	Technology Evaluation	Usability testing, Mixed-methods evaluation, Observations	University students
Wekerle et al., 2024, Germany	Quantitative Study	Structural equation modelling, Student evaluations	University students
Harıadı et al., 2024, Indonesia	Comparative Study	Statistical surveys, TGMD-2 instrument	Preschool children

Hsiao et al., 2022, Taiwan	Empirical Study	Mixed-methods approach; surveys and interview	High school students
Mebane et al., 2023, Italy	Empirical Study	Quantitative study; Surveys and educational programs	High school students
Campos-Ugaz et al., 2022, Peru	Review Paper	Qualitative approach; bibliometric	Across institutions

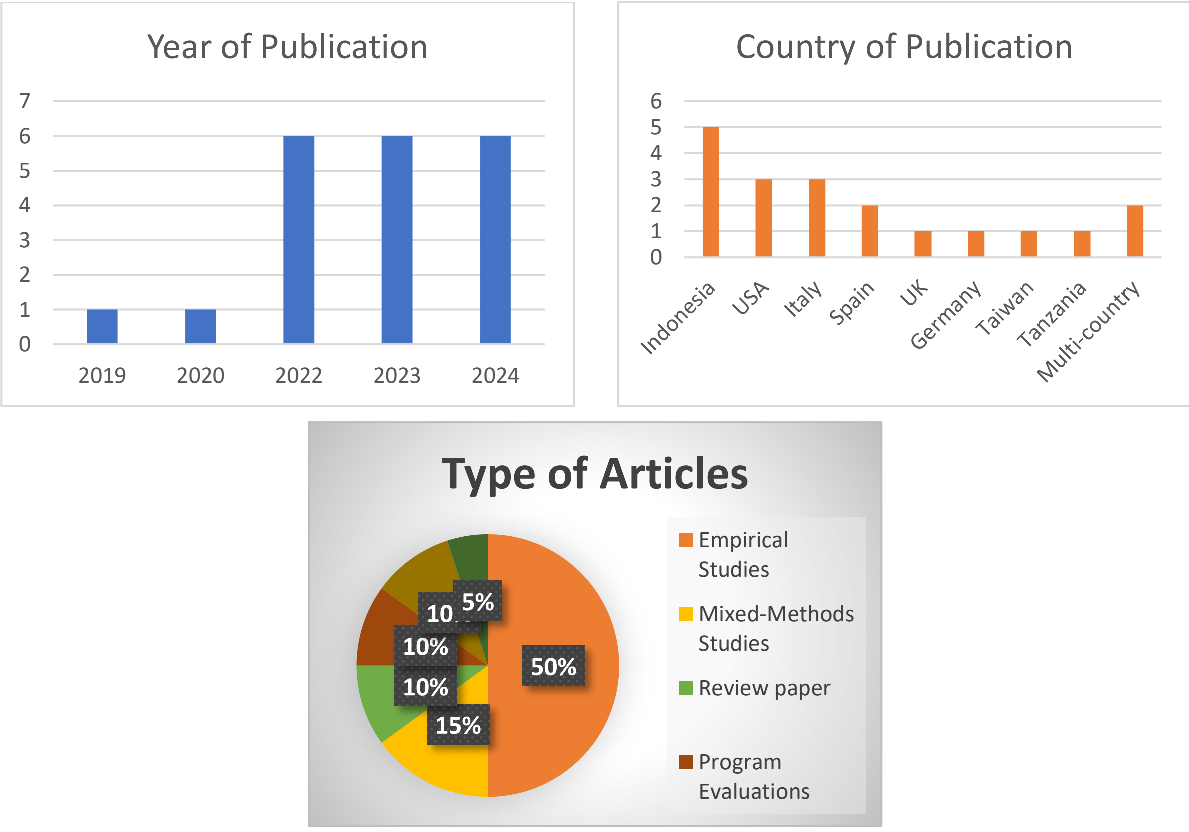

Figure 1 Characteristics of included publications. a. Year of publication. b. Country of publication. c. Type of articles.

a. Characteristics of included publications

1. Year of Publication

The research studies span a wide timeframe from 2019 to 2024, reflecting a growing interest in sustainability and education. Early studies, such as those by Kinoshita et al (2019), lay foundational insights, while more recent publications, including (Harıadı et al., 2024) and (Jiang et al., 2024), emphasize advanced approaches like experiential learning and mixed-reality science labs. There is a notable surge in publications from 2022 onward, showing an increased global recognition of integrating sustainability concepts in education.

2. Country of Publication

The studies represent diverse geographical contexts, including Indonesia (Zidny & Eilks, 2020); (Ika Sari et al., 2024), the USA (Harris et al., 2022); Jiang et al., 2024), and Italy (Antronico et al., 2023); Zjalic et al., 2023). Other contributions come from Spain, the UK, Germany, and Taiwan, highlighting the global scope of sustainability education. This diversity reflects the universal importance of addressing climate change through educational interventions tailored to regional needs.

3. Article Types

The reviewed articles include a mix of empirical studies (Kinoshita et al., 2019; Martínez-Mirambell et al., 2023), program evaluations (Kluczkovski et al., 2024), and scoping reviews (Abulibdeh, 2024). Mixed-methods and qualitative approaches (Chen & Chang, 2024; Tumanggor et al., 2022) provide a robust understanding of both the outcomes and contextual influences of these educational practices.

4. Sampling Methods, Study Design, and Data Collection Tools

Sampling methods vary from purposive sampling (Chen & Chang, 2024) to convenience sampling (Harris et al., 2022), reflecting flexibility in study designs. Data collection tools include pre-post-tests, structured surveys, and observational techniques, ensuring comprehensive data triangulation. Quasi-experimental designs (Chen & Chang, 2024) and usability evaluations (Jiang et al., 2024) offer advanced methodological insights for measuring educational impact.

5. Participant Profile

The participants range from preschoolers (Harıadı et al., 2024) to university students (Kinoshita et al., 2019; Jiang et al., 2024), with a significant focus on high school students (Piscitelli & D'Uggento, 2022; Zjalic et al., 2023). Educators and pre-service teachers (Zidny & Eilks, 2020) also feature prominently, emphasizing the need to equip teachers with the tools and knowledge for sustainability education.

b. Exploring the Importance of Hands-on and Experiential Learning in High School Sustainability Education

1. Effectiveness of Hands-on and Experiential Learning

Hands-on and experiential learning methods, as demonstrated in several studies, effectively enhance student engagement and awareness of sustainability issues. For instance, research on aquaponics in schools (Kluczkovski et al., 2024) highlighted how interactive activities fostered environmental awareness and practical knowledge about sustainability. Similarly, the use of clay modelling to teach biology vocabulary (Bailey et al., 2022) showed that students were actively engaged and experienced positive emotional and behavioural outcomes. Plogging, which combines physical activity with litter collection (Martínez-Mirambell et al., 2023), not only raised environmental awareness but also encouraged students to reflect on their role in improving their surroundings. These examples illustrate that hands-on learning creates an immersive environment where students can connect theoretical knowledge to tangible actions, making sustainability concepts more relatable and memorable.

2. Comparison of Hands-on vs. Traditional Methods

Studies comparing hands-on learning to traditional methods provide compelling evidence for the superiority of experiential approaches. For instance, research involving STEAM education (Hsiao et al., 2022) compared traditional project-based learning (PBL) with a cognitive-affective interaction model (CAIM) and found that hands-on activities significantly enhanced students' creativity, critical thinking, and hands-on performance. Similarly, the use of clay modelling in research (Bailey et al., 2022) was compared to traditional sentence-writing exercises, revealing that kinesthetic activities fostered equal or better learning outcomes while also engaging students emotionally. These comparisons highlight how experiential methods go beyond rote memorization, allowing students to develop deeper connections to the material and fostering skills that are essential for addressing complex sustainability challenges.

3. Participant Engagement

Hands-on and experiential methods have been shown to significantly enhance participant engagement across different demographics. In research involving high school students in Jakarta (Tumanggor et al., 2022), ecological behaviour was explored through structured interviews and observations, demonstrating that hands-on interventions, like building eco-projects, improved students' environmental consciousness. Similarly, an urban health education program in Italy (Zjalic et al., 2023) used interactive sessions to boost student awareness of urban health challenges, with post-intervention assessments revealing a significant improvement in knowledge retention. Such methods actively involve students in the learning process, transforming them from passive recipients of information to active participants, which is crucial for cultivating long-term interest in sustainability education.

4. Behavioural and Attitudinal Changes

Behavioural and attitudinal shifts are critical outcomes of hands-on learning. Research on youth climate action (Pena-Vega et al., 2022) revealed that participatory projects led by students often achieved higher success rates, fostering a sense of civic responsibility. Another study (Piscitelli & D'Uggento, 2022) on sustainable behaviours among high school students showed that activities like turning off faucets or volunteering significantly influenced their daily choices. Plogging interventions (Martínez-Mirambell et al., 2023) further demonstrated how hands-on activities could shift students' attitudes towards environmental care. These findings underscore the power of experiential learning in not only imparting knowledge but also in shaping behaviours and attitudes necessary for climate action.

5. Development of Environmental Competencies

Experiential learning directly supports the development of essential environmental competencies. For example, research involving a summer course for preservice chemistry teachers (Paristiowati et al., 2022) found that project-based learning enhanced skills such as collaboration, communication, and critical thinking. Similarly, aquaponics education (Kluczkovski et al., 2024) equipped students with practical skills in food sustainability and climate change mitigation. By participating in hands-on projects, students gain competencies that prepare them to address real-world environmental challenges, bridging the gap between theoretical knowledge and practical application.

6. Link to Climate Change Awareness

Several studies explicitly link hands-on methods to improved climate change awareness. A pilot program in Italy (Mebane et al., 2023) used participatory workshops to enhance students' understanding of climate change's emotional and environmental impacts. Another study (Zjalic et al., 2023) on urban health education highlighted how interactive interventions fostered a deeper comprehension of climate-related health issues. These findings suggest that experiential methods make abstract climate change concepts more accessible, enabling students to connect global issues to their personal lives and communities. This contextual understanding is essential for fostering proactive attitudes toward climate action.

7. Cultural and Contextual Relevance

Integrating local cultural and environmental contexts into experiential learning enhances its relevance, relatability, and impact by connecting abstract sustainability concepts to students lived experiences. This contextual grounding fosters deeper engagement and a stronger sense of ownership over environmental issues. For example, one study integrated Indigenous knowledge into chemistry education, illustrating how blending Indigenous and Western scientific perspectives enriched students' understanding of sustainability and promoted respect for traditional ecological wisdom (Zidny & Eilks, 2020). Another study focused on geoheritage-based activities in European geoparks, where students explored local geological features and environmental challenges, fostering both local engagement and broader environmental consciousness (Giardino et al., 2022). These examples show how culturally and geographically grounded learning can deepen students' appreciation of the interconnected nature of environmental challenges and solutions, ultimately strengthening the effectiveness of climate change education.

8. Policy Implications and Scalability

Program evaluations provide valuable insights into scaling hands-on learning methods for broader impact. For example, research on aquaponics education (Kluczkovski et al., 2024) identified logistical challenges and proposed solutions for integrating such programs into national curricula. Similarly, a bibliometric review of environmental education (Campos-Ugaz et al., 2022) emphasized the need for policy frameworks that prioritize experiential learning. By addressing challenges and leveraging these insights, policymakers can create scalable programs that integrate hands-on methods into sustainability education, thereby achieving systemic improvements in climate awareness and action.

9. Challenges and Recommendations

While hands-on methods are highly effective, they come with challenges such as logistical complexities (Kluczkovski et al., 2024) and increased cognitive load (Bailey et al., 2022). Addressing these challenges requires careful planning, such as providing teacher training and designing age-appropriate activities. For example, research on clay modelling (Bailey et al., 2022) recommended instructional strategies to reduce cognitive load, while studies on aquaponics (Kluczkovski et al., 2024) suggested improvements in logistical support. By overcoming these hurdles, educators can maximize the benefits of experiential learning for sustainability education.

10. Interdisciplinary Connections

Hands-on learning naturally supports interdisciplinary education, combining science, technology, social studies, and arts. For instance, research on STEAM education (Hsiao et al., 2022) showed how integrating science and art through project-based learning fostered creativity and problem-solving skills. Similarly, indigenous knowledge integration in chemistry lessons (Zidny & Eilks, 2020) bridged cultural and scientific perspectives. These interdisciplinary approaches not only make learning more engaging but also equip students with the diverse skills needed to tackle multifaceted environmental challenges.

Limitations

This review has several limitations. First, the scope of studies was constrained to those available in specific databases, potentially excluding relevant research from less accessible sources. Second, the variability in study designs and methodologies, such as sampling methods and data collection tools, limited direct comparisons between studies. Lastly, the geographical representation was uneven, with a significant focus on specific regions like Southeast Asia and Europe, while other regions were underrepresented.

Conclusion

Hands-on and experiential learning methods are essential for fostering meaningful and impactful sustainability education. The studies reviewed provide compelling evidence that these approaches enhance climate change awareness by making abstract concepts more relatable and actionable. Activities like aquaponics, plogging, and indigenous knowledge integration not only educate students but also inspire them to take practical steps toward addressing environmental challenges.

Moreover, experiential learning cultivates critical thinking, creativity, and collaboration skills that are vital for solving complex sustainability problems. By actively engaging students in the learning process, these methods ensure deeper knowledge retention and a stronger emotional connection to environmental issues. This emotional engagement is key to instilling long-term behavioural changes that support climate resilience and sustainable living.

Integrating experiential learning into educational frameworks requires strategic planning and policy support. Scalable models, such as those presented in program evaluations, demonstrate how logistical challenges can be addressed effectively. Policymakers and educators should prioritize these methods to create robust, interdisciplinary curricula that empower students to lead sustainable transformations within their communities.

In conclusion, hands-on and experiential learning methods are not just educational tools but transformative strategies that equip the next generation with the skills, mindset, and motivation needed to confront climate change. Expanding access to these methods across diverse geographical and socio-economic contexts will be crucial for achieving global sustainability goals.

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2025

SciEd
SEAQIS Journal of Science Education

SEAQIS Journal of Science Education (SciEd)
ISSN: 2987-8101 | E-ISSN: 2964-7533
Vol: 5, No: 2, PP: 34-46
www.journal.qitepinscience.org

Research Paper Open Accsess

Empowering Future Biology Teachers: Integrating STEM and Design Thinking for Effective Sustainability Learning

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Article history:
Received: February 8, 2025
Revised: june 10, 2025
Accepted: June 24, 2025

Abstract

This study examines the implementation of a design project in a preservice biology teacher education course titled "Biology Education for Sustainability," aiming to enhance creativity while addressing the United Nations Sustainable Development Goals (SDGs). This work presents a comprehensive framework divided into 10 chapters, spanning approximately 16 weeks (or about three and a half months) of meetings, each corresponding to key lessons designed to empower preservice biology teachers. In addition, the project engages preservice teachers in collaborative teams to identify local environmental challenges related to specific SDGs, such as clean water, climate action, and life on land. Utilizing a design thinking framework, participants engage in brainstorming, prototype development, and iterative feedback that lead to the fostering of innovative solutions. Moreover, data were collected through pre- and post-project surveys, reflective journals, and presentations to assess the impact on creativity, understanding of the SDGs, and confidence in teaching sustainability concepts. The results indicate significant improvements in creative problem-solving skills and a deeper awareness of the SDGs, along with increased motivation to integrate sustainability into their future teaching practices. As a result, this experiment highlights the effectiveness of experiential learning in the "Biology Education for Sustainability" course, preparing preservice teachers to address global challenges through innovative and creative educational strategies.

Keywords: Preservice Biology Teacher Education, Design Thinking, STEM, Sustainability Education

Introduction

In the face of escalating environmental challenges, the role of education in fostering sustainability has become increasingly critical (Biasutti and Frate 2017). The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide a comprehensive framework for addressing global issues such as poverty, inequality, climate change, and environmental degradation. Education is recognized as a fundamental driver for achieving these goals, particularly in empowering future generations to become informed and active participants in sustainable practices (Annan-Diab and Molinari 2017). For instance, biology teacher education programs play a pivotal role in equipping preservice teachers with the knowledge (Atchia 2023), skills, and creativity needed to engage students in sustainability-oriented learning (Brugmann et al. 2019).

Biology, as a discipline, inherently aligns with the principles of sustainability (Adams et al. 2023), exploring the intricate relationships between living organisms and their environments (Hiong and Osman 2013). By integrating sustainability into biology education, future teachers can inspire students to critically examine ecological issues and develop innovative solutions (Batz et al. 2015). However, traditional approaches in teaching biology often fail to cultivate the creative problem-solving skills that are essential for addressing complex sustainability challenges (Ladachart and Ladachart 2022). To bridge this gap, innovative pedagogical strategies, such as Design Thinking (DT), can be employed.

Design Thinking is a human-centered approach to problem-solving that emphasizes empathy, creativity, and iterative processes (Badwan et al. 2018). By engaging preservice teachers in design projects, educators can foster an environment where creativity thrives. This approach encourages students to identify real-world problems (Baran and Al Zoubi 2023), brainstorm potential solutions (Cross 2023), and develop actionable plans that reflect an understanding of the SDGs (Dotson et al. 2020). Furthermore, collaborative learning experiences promote communication and teamwork (Baniya et al. 2019), which are vital skills for future educators who will need to work with diverse groups of students and stakeholders.

This study focuses on the implementation of a design project within a preservice biology teacher education course titled "Biology Education for Sustainability." The courseaims to enhance participants' understanding of sustainability concepts while fostering creativity and innovative thinking. By tackling local environmental challenges linked to specific SDGs,preservice teachers not only deepen their knowledge of sustainability but also gain practical experience in applying their learning to real-world contexts (Adams, Kewell, and Parry 2018). Through this project, we seek to investigate the impact of experiential learning on preservice teachers' creativity, confidence, and understanding of sustainability. By employing a mixed-methods approach, we will collect data on participants' experiences and outcomes, providing insights into the effectiveness of integrating Design Thinking into biology education. In the analysis, this research aims to contribute to the growing body of literature on sustainability education, offering valuable implications for teacher preparation programs and strategies for empowering future biology educators.

Literature Review

1) STEM Education in Biology Teacher Preparation

STEM (Science, Technology, Engineering, and Mathematics) education has become a cornerstone of 21st-century teaching and learning. In biology teacher education programs, STEM integration is essential for equipping future teachers with the skills that are necessary to address complex real-world problems (Batty and Reilly 2023; Ben-Eli 2018). Research highlights that STEM-based learning promotes critical thinking, interdisciplinary knowledge, and scientific literacy (Brunelli and Macirella 2021; Suwono et al. 2023). For future biology teachers, this approach helps in making biology content more relevant, applied, and connected to everyday life and global challenges.

2) Design Thinking in Education and Teacher Training

Design Thinking (DT) is a human-centred iterative process involving empathy, ideation, prototyping, and testing to solve complex problems (Atchia, Chummun, and Luckho 2024; Blundell 2024). In teacher education, DT offers a framework that nurtures creativity, problem-solving, and collaboration (Fei 2024; Goldman and

Zielezinski 2016; Wingard et al. 2022). When integrated into biology teacher training, DT encourages preservice teachers to design meaningful and engaging learning experiences that go beyond textbook content and foster innovation. Studies show that using DT helps future educators feel more confident in managing uncertainty and ambiguity in classroom practices (Honra and Monterola 2024; Trung et al. 2024).

3) Sustainability Learning in Science Education

Sustainability education focuses on equipping students with the knowledge, skills, attitudes, and values needed to address environmental, social, and economic challenges (UNESCO, 2017). In science education and particularly biology, sustainability themes, such as climate change, biodiversity, and ecosystems, are highly relevant. Studies emphasize the role of teachers as agents of change in promoting sustainability literacy (Sterling, 2001; Wals, 2010). However, research also reveals that many preservice teachers feel inadequately prepared to teach sustainability issues effectively (Evans et al., 2017), which is signalling the need for pedagogical innovation in teacher training programs.

4) Integration of STEM and Design Thinking for Sustainability

Integrating STEM with Design Thinking offers a transformative learning approach that combines technical knowledge with empathetic and solution-oriented thinking (Lande & Leifer, 2010; Watson, 2020). This integration fosters transdisciplinary competencies and enhances students' and teachers' abilities to engage in authentic problem-solving. In the context of sustainability, this approach enables future biology teachers to design projects that are locally relevant and globally significant—such as eco-enzyme creation, school composting, or urban gardening—making sustainability concepts tangible and actionable (Tosun & Taskesenligil, 2013; Mishra et al., 2022).

5) Empowering Preservice Biology Teachers through Innovative Pedagogies

Empowerment in teacher education refers to fostering agency, autonomy, and capacity to lead change in educational practices (Zimmerman, 1995). Innovative pedagogies like STEM-DT integration empower preservice biology teachers by enhancing their confidence, pedagogical creativity, and content mastery. Research by Finkelstein et al. (2021) suggests that when preservice teachers are involved in real-world, design-based STEM projects, they not only deepen their subject understanding but also develop a stronger sense of ownership over their teaching methods and purposes. Empowerment also includes developing reflective practices, collaboration, and ethical decision-making in response to sustainability challenges.

Methodology

This study investigates the implementation of a design project in a preservice biology teacher education course titled "Biology Education for Sustainability". The course is structured to enhance creativity among preservice biology teachers while addressing key United Nation Sustainable Development Goals (SDGs). To improve clarity, specific SDGs are explicitly referenced during each project phase to align with the issues being addressed, such as SDG 13 (Climate Action), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land). The course framework is divided into 10 chapters, each aligned with critical lessons aimed at empowering preservice teachers with sustainability teaching competencies. The participants were 40 preservice biology teachers enrolled in the "Biology Education for Sustainability" course. These preservice teachers were in the latter stages of their teacher education program and had prior experience in biology and educational methods.

The course followed a design thinking

framework to guide the participants through the project stages. The steps included: (1) Empathize: Teams identified local environmental challenges through research and community engagement that tied to SDG 13 and SDG 15; (2) Define: They framed the problem related to SDGs; (3) Ideate: Through brainstorming sessions, teams generated innovative solutions to the defined challenges such as waste management (SDG 12), environmental degradation (SDG 15), and local climate resilience (SDG 13); (4) Prototype: Teams developed initial prototypes of their solutions; (5) Test: Prototypes were refined through iterative feedback cycles from peers and instructors.

Data were collected from multiple sources to assess the impact of the course on participants' skills and perspectives: (1) Pre- and post-project surveys: These surveys measured changes in participants' creative problem-solving skills, understanding of SDGs, and confidence in teaching sustainability concepts; (2) Reflective journals: Participants maintained reflective journals throughout the course, documenting their thought processes, challenges, and learning experiences; (3) Presentations: Teams presented their final prototypes and solutions to their peers and instructors, providing additional qualitative data on their learning outcomes. Quantitative data from the surveys were analyzed using statistical methods to evaluate changes in creativity, SDGs awareness, and teaching confidence. Moreover, qualitative data from journals and presentations were analyzed through thematic coding to identify common patterns in how participants experienced the design process and developed sustainability teaching strategies.

Results and Discussion

Education for Sustainable Development (ESD) is a crucial topic in environmental education; it encompasses significant contexts such as socio-cultural factors and socio-political issues, including equity, poverty, democracy, and quality of life (Scott, 2015; Dotson et al., 2020). ESD serves as both a solution and a requirement for transforming human behavior and addressing the ongoing environmental sustainability crisis (Lestari, Paidi, and Suyanto 2024). As global challenges intensify, ESD encourages individuals and communities to adopt more sustainable practices. In response to these challenges, many countries have incorporated sustainable development issues into their educational curricula at all levels (Chang and Lien 2020), emphasizing the need for a more sustainable and equitable future (Eidin and Shwartz 2023). However, despite the growing inclusion of sustainability topics in curricula, many studies highlight a gap between policy intentions and classroom implementations, especially regarding effective pedagogical strategies that foster higher-order thinking and real-world application (Al-Hazaima, Low, and Sharma 2024; Ben-Eli 2018).

This study contributes to bridging that gap by embedding the **design thinking** framework into a preservice biology teacher education course, providing a structured yet flexible pathway for students to engage in creative problem-solving rooted in real sustainability challenges. This activity offers significant potential for enhancing students' problem-solving and critical thinking skills in multiple ways. First, it engages students in identifying key issues within complex, real-world sustainability challenges, which are often ill-structured and multifaceted. It then guides students to analyze underlying causes and develop sustainable solutions, ultimately improving their capacity to tackle complex problems and address real-world challenges effectively. The design thinking framework guided preservice biology teachers through each phase of the project, enhancing their skills and understanding of sustainability.

Below are the results, broken down by each phase of the design thinking process.

1) Phase 1: Empathize

In the first phase, students engaged with their local communities to identify real-world environmental problems. This stage helped them develop a deeper understanding of the challenges related to sustainability and the SDGs (Durak and Topçu 2023), fostering empathy toward the affected communities (Boncukçu and Gök 2023). Furthermore, students became more aware of local environmental challenges such as water pollution and deforestation, gaining insights into how these issues connect to global goals (Figure 1).

Figure 1. Students collaborated to understand environmental problems by conducting research and engaging with local community data.

Figure 1 shows students from Group 1, Group 2, and Group 3 actively collaborating in this phase. The image captures them discussing community findings, reviewing data collected from interviews with residents, and mapping the environmental problems that are most urgent in their surroundings. This collaborative inquiry process not only increased their engagement but also reflected the real-world scientific practices of data gathering and problem analysis within a socio-environmental context.

2) Phase 2: Define

In this phase, participants worked in teams to clearly define the problems they wanted to solve, narrowing down the root causes of the environmental issues they had identified. This stage required them to critically analyze complex problems (Ericson 2022) and break them down into manageable components (Goldman and Zielezinski 2021). Students learned to frame challenges in a structured way, which led to a more focused approach to creating solutions. The act of defining specific problem statements enhanced their critical thinking and problem-solving skills.

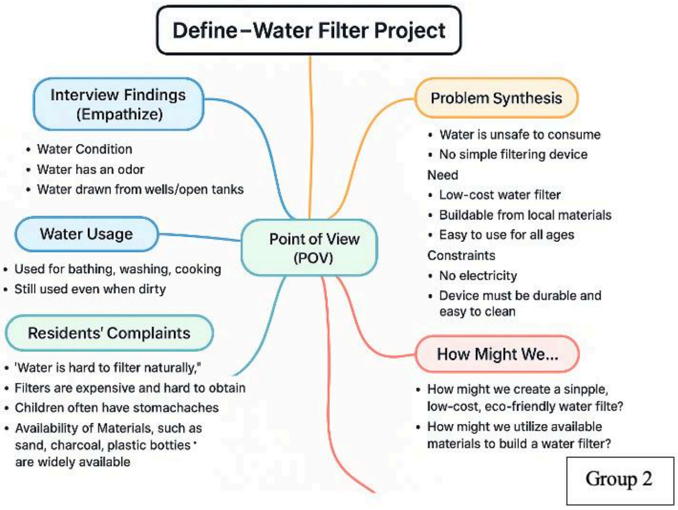

Figure 2. Student's mind map (representation of the Define Stage in the DT process for the Water Filter Project)

Students created a mind map (Figure 2) as a result of their qualitative data, which is obtained from interviews and observations during the Empathize phase. Moreover, it was systematically analyzed to identify key user needs and contextual challenges. The findings revealed that the community relied on murky and odorous water sources for daily activities such as cooking, bathing, and washing, despite the associated health risks. Participants also reported limited access to affordable and user-friendly water filtration tools. These insights were synthesized into a clear point of view (POV) statement: *"The villagers need a simple and affordable water filter that can improve water quality for daily use."* This problem definition served as a foundation for generating targeted "How Might We" (HMW) questions, such as: *"How might we design a low-cost, eco-friendly water filter using locally available materials?"*

The Define Phase is essential in articulating a human-centered problem statement, providing a structured direction for the subsequent ideation and prototyping stages. It ensures that the design process remained grounded in real-world needs, promoting the development of practical and contextually appropriate solutions.

3) Phase 3: Ideate

During the ideation phase, students generated a wide range of potential solutions through brainstorming sessions. This phase encouraged creative thinking (Trung et al. 2024), enabling participants to propose innovative ideas without immediate constraints (Gouseti et al. 2023). Students' creativity flourished as they explored diverse possibilities for solving sustainability challenges. This phase particularly boosted their ability to think outside the box (Kimbell 2011), with participants reporting an increased capacity for generating new ideas.

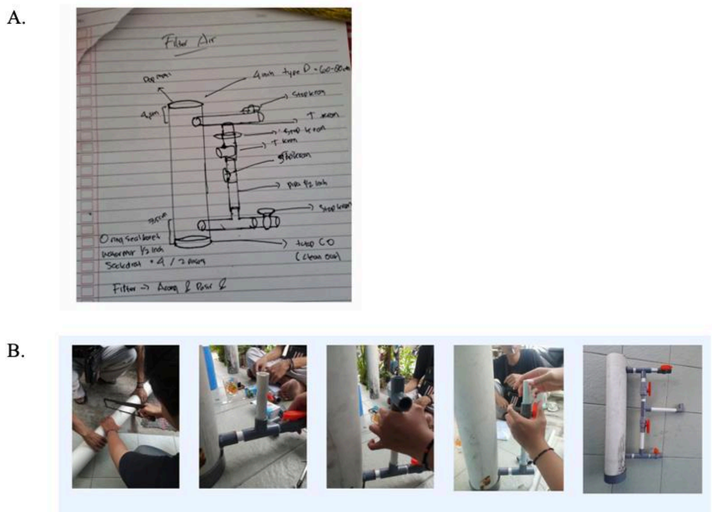

Figure 3. Students demonstrated significant growth in creative and practical problem-solving (A & B: student-designed water filtration systems).

During the ideation phase (Figure 3), students generated a wide range of potential solutions through brainstorming sessions, aligning with the creative divergence stage of the DT process (Miller and Krajcik 2019). This stage facilitated open-ended exploration (Fei 2024), where students were encouraged to think freely without immediate judgment, which is a condition proven to foster creativity (Goldman and Zielezinski 2016; Lee de Wet and Tselepis 2020; Wingard et al. 2022). Prior studies (Atchia et al. 2024; Blundell 2024) have demonstrated that such unconstrained ideation environments significantly enhance learners' creative self-efficacy, particularly when tackling real-world challenges like sustainability issues.

However, while existing research acknowledges the benefits of ideation in promoting creativity, **few studies** have explored how this phase operates **within an integrated STEM–DT framework focused on sustainability literacy at the secondary education level (Goldman and Zielezinski 2016; Trung et al. 2024).** Therefore, this study contributes to the field by providing empirical evidence on how structured ideation activities embedded in interdisciplinary STEM projects can foster not only creativity but also a deeper understanding of complex environmental problems. This fills a notable gap in the literature and offers a new pedagogical model for empowering students with both innovative thinking and sustainability competencies.

4) Phase 4: Prototype

In this phase, students developed prototypes of their ideas using readily available and recycled materials, as illustrated in **Figure 4.** This stage was highly practical, requiring them to transform their abstract ideas into tangible models or systems (Lin et al. 2021). Building prototypes helped students better understand the feasibility and limitations of their solutions (Matthews et al. 2023). It also improved their hands-on problem-solving abilities (Kijima, Yang-Yoshihara, and Maekawa 2021), with participants expressing newfound confidence in turning ideas into real-world applications.

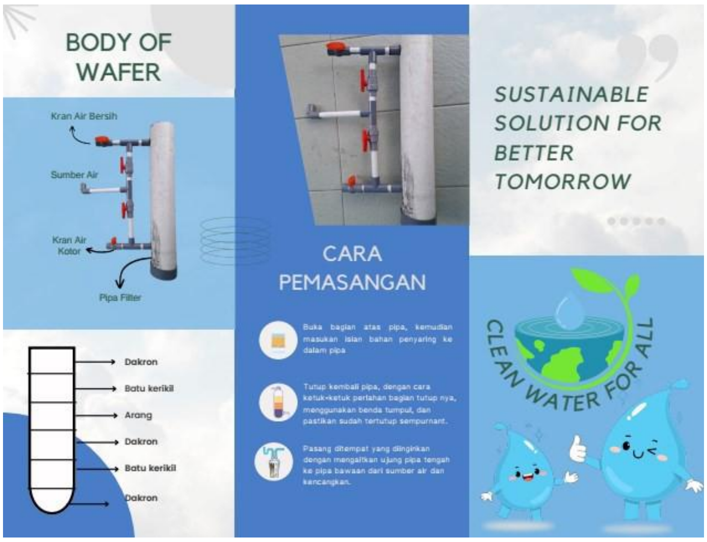

Figure 4. Students created physical prototypes of water filtration systems or sustainableagricultural models, using recycled materials.

5) Phase 5: Test

Finally, students tested their prototypes, presented them to their peers and instructors, and received feedback for further refinement. This phase involved an iterative cycle of improvements based on peer and instructor evaluations. The testing phase helped students refine their solutions, leading to more effective and innovative results. It also fostered resilience, as participants learned to accept constructive criticism and used it to enhance their work. In the *Test* Phase, iterative feedback loops promoted resilience and adaptability—key traits highlighted by Kijima et al. (2021) as central to 21st-century sustainability education.

This research adds to the body of empirical work by quantitatively measuring the impact of the DT approach on preservice teachers' creativity, problem-solving, and confidence. Unlike previous studies that relied on perception surveys alone, this study employed a paired-samples t-test (Table 1) to compare pre- and post-project competencies that revealing statistically significant gains across all measured dimensions. By these positions, the study is not merely an evaluation of a teaching activity, but an original empirical investigation that advances our understanding of how design-based pedagogy can concretely build sustainability competencies.

Overall impact of DT process significantly improved participants' skills in creative problem solving, as the ideation and prototyping phases helped unlock students' creativity and enhanced their ability to generate and develop innovative solutions. Critical thinking by empathizing and defining phases requires participants to delve into the root causes of sustainability challenges, fostering deeper critical analysis (Trung et al. 2024; Wingard et al. 2022). Student confidence in teaching was increased by going through the entire process. Starting from empathizing with local challenges to testing solutions, students gained confidence in their ability to teach sustainability concepts in engaging, hands-on ways.

The integration of the design thinking framework within the "Biology Education for Sustainability" course proved highly effective in enhancing preservice biology teachers' creativity, problem-solving, and sustainability teaching skills. Data from pre- and post-project surveys revealed a 25% increase in creative problem-solving skills, as students engaged in brainstorming, prototyping, and iterative feedback cycles.

Additionally, reflective journals indicated that 85% of participants felt more confident in addressing complex environmental issues after the course. By guiding students through the phases of empathizing, defining, ideating, prototyping, and testing, the project enabled them to tackle real-world environmental challenges related to the SDGs, such as clean water, climate action, and life on land. This hands-on approach deepened their understanding of sustainability, improved critical thinking, and boosted their confidence in teaching these concepts. Overall, the project demonstrated the potential of experiential learning and Design Thinking in preparing future educators to effectively address global environmental challenges and incorporate sustainability into their teaching practices.

To assess the impact on preservice biology teachers' creativity and problem-solving skills, a paired-samples t-test was conducted to compare the pre- and post-project results. The collected data from the surveys indicated significant improvements in both variables after the project. The following table summarizes the t-test results. It shows the changes in participants' creative problem-solving abilities, confidence in addressing complex issues, and understanding of the SDGs. All outcomes were statistically significant, indicating a meaningful enhancement in the participants' skills and understanding.

Table 1. Paired-Samples t-Test Results Comparing Pre- and Post-Project Scores on Creativity, Problem-Solving, and Understanding of SDGs.

Variable	Pre-Project Mean (SD)	Post-Project Mean (SD)	t-value	p-value	Significance
Creative Problem-Solving	60.3 (8.5)	75.4 (7.2)	5.62	0.001	Significant
Confidence in Addressing Complex Issues	58.7 (9.1)	80.5 (6.9)	6.34	0.001	Significant
Understanding of SDGs	65.2 (7.8)	83.0 (6.4)	6.01	0.001	Significant

The table highlights statistically significant improvements ($p < 0.05$) across all categories. It is demonstrating the positive effect of experiential learning through Design Thinking on participants' creative and problem-solving abilities, as well as their understanding of sustainability concepts.

Conclusion

The integration of the design thinking framework within the Biology Education for Sustainability course proved highly effective in enhancing preservice biology teachers' creativity, problem-solving, and sustainability teaching skills. By guiding students through thephases of empathizing, defining, ideating, prototyping, and testing, the project enabled them totackle real-world environmental challenges related to the SDGs, such as clean water, climate action, and life on land. This hands-on approach deepened their understanding of sustainability, improved critical thinking, and boosted their confidence in teaching these concepts. Overall, the project demonstrated the potential of experiential learning and Design Thinking in preparing future educators to effectively address global environmental challenges and incorporate sustainability into their teaching practices.

By integrating Design Thinking into a structured ESD course, this study demonstrates a replicable model for teacher education programs that aim to cultivate creative, critical, and sustainability-literate educators. It responds to calls in the literature for more action-oriented and transformative pedagogies and offers empirical evidence of their effectiveness in real classroom contexts. As such, the findings make a valuable contribution to both **theoretical discourse on sustainability education** and **practical frameworks for curriculum development** in science teacher training.

Acknowledgements

The author would like to express sincere gratitude to Prof. Dr. Hadi Suwono, M.Si., and Prof. Dr. Ibrohim, M.Si., from Universitas Negeri Malang, for their invaluable guidance and support as dissertation promoters. Deep appreciation is also extended to Dr. Agung Wijaya Subiantoro, M.Pd, from Universitas Negeri Yogyakarta, for his insights and contributions as the lecturer of the course "*SDGs for Biology Education*", which significantly enriched the perspectives presented in this article.

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2025

SEAQIS Journal of Science Education (SciEd)
ISSN: 2987-8101 | E-ISSN: 2964-7533
Vol: 5, No: 2, PP: 47-55
www.journal.qitepinscience.org

Research Paper

Open Accsess

Laboratory Anxiety: Prevalence and Overcoming the Challenges among Indian Secondary School Students

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Article history:
Received: December 26, 2024
Revised: July 31, 2025
Accepted: August 6, 2025

Abstract

The association of negative emotions with the triumph of scientific inquiry requires focus as an area of research, since it has long been established that learning by doing is the highest form of engagement in science. This study addresses laboratory anxiety, its prevalence, and the barriers that inhibit students' full participation. It also proposes a self-directed learning strategy to mitigate anxiety. An initial sample of 121 students, selected through purposive sampling, was studied to measure the prevalence in a study primarily conducted using a sequential explanatory mixed-methods approach. Then, 19 students who showed a high level of anxiety were interviewed to understand the cause behind anxiety, and they were further administered a self-directed learning strategy containing elements derived from the conclusions of student interviews. A significant prevalence of laboratory anxiety was found among school students. Based on the self-directed learning strategy, the results revealed a significant decrease in overall laboratory anxiety, and individual improvement was observed for components of the execution of experiment, laboratory safety, use of chemicals, and use of material and equipment. These findings highlight the need for curriculum interventions and revised teaching methodologies that support emotionally safe and effective science learning environments.

Keywords: Laboratory Anxiety; Laboratory Safety; Science Education; Secondary School Students; Self-directed Learning

Introduction

Anxiety, as a concept, is commonly referred to as an unpleasant emotional state characterised by excessive degrees of fear, worry, and apprehension without a specific object or cause; it is initiated by feelings as a response to a perceived threat (Casbarro, 2005; Putwain, 2008). Anxiety is a complex phenomenon that has been defined and understood differently across various fields of study and disciplines. Mallow (1986) defined science anxiety as the disgust or fear of science concepts, scientists, and scientific activities. Mallow (2006) has also shown science anxiety to be a phenomenon that can impede learning. The distinctness of science anxiety from general anxiety lies in the ability of students to stay calm in non-science courses as compared to science courses.

Anxiety has been studied extensively across all three major branches of science, both in the classroom and laboratory environment. These anxieties are accompanied by various causes, such as a fear of chemicals and chemistry classes (McCarthy & Widanski, 2009), incapability to perform experiments involving living specimens, unclear biological concepts, poor handling of laboratory equipment (Kurbanoğlu, 2014), apply theoretical knowledge in situations based on practice, manipulate laboratory materials, and make comments on results (Berber 2013). Moreover, the other causes of science laboratory anxiety include past bad experiences in science classes, exposure to science-anxious teachers who are teaching science in elementary and secondary schools, lack of role models, gender and racial stereotyping, and scientists' stereotyping in the popular media. The symptoms of anxiety are reflected as students' emotional reactions, such as timidity and shyness, and the physical indications of these emotions (Turner & Lindsay, 2003).

Anxiety about the laboratory has been known to influence students' performance (Eddy, 2000; Wynstra & Cummings, 1993). This fear towards laboratory activities can also be characterised by a disappointment among the students regarding the subject (Jegede, 2007), which can also eventually make them lose interest in that subject area (Keeves & Morgenstern, 1992). Though some degree of anxiety may be helpful in the learning process, a high level of anxiety impedes optimum performance on science learning (Udo, Ramsey, & Mallow, 2004). Therefore, to overcome anxiety, it is pertinent to generate a belief in one's ability to perform. Bandura's theory highlights that perceived self-efficacy directly relates to their task performance and choice behaviour (Bandura, 1986). Among high school students, science self-efficacy is a better predictor of achievement and engagement with science-related activities than gender, ethnicity, and parental background (Kupermintz, 2002; Lau & Roeser, 2002; Lodewyk & Winne, 2005).

Many researchers have highlighted and studied methods for overcoming anxiety and its impact on student learning. Ercan (2014) assessed the role of 5E learning cycle and V diagrams in decreasing anxiety. Güven, Cam, and Sülün (2015) used an approach based on case-based laboratory activities in reducing chemistry lab anxiety among preservice teachers. Damo et al. (2020) proposed overcoming anxiety among undergraduate students with the help of technology-related activities. Action research by Sesen and Mutlu (2014) highlighted a strategy to overcome challenges faced by undergraduate students in science laboratories. Although the review suggests implications of research in reducing anxiety, not much research has been conducted that deals with addressing laboratory anxiety among school students. Overall challenges in an integrated science laboratory in the context of laboratory anxiety need to be explored, especially in the context of the Indian education system, since in most circumstances, laboratories remain a very unexplored territory for students.

Most studies have emphasised that the use of a project-based learning process for self-learning in a chemistry laboratory (Alkan & Erdem, 2013) requires a lot of time in the laboratory for performing experiments (Erokten, 2012), and uses effective educational strategies (Kaya & Cetin, 2012). Moreover, approaches or methods in the laboratory, such as argumentation and reflection based on the activities, can reduce anxiety towards laboratory. Apart from these methods, the development of self-belief can play a major role in reducing the anxiety of students related to participation in laboratories (Chan et al., 2021; Ekici, 2011). Research has confirmed that science self-efficacy, which is students' "belief in their ability to succeed in science tasks, courses, or activities" (Britner & Pajares, 2006; Gunes & Ozsoy, 2016), influences a variety of factors related to student achievement. Studies also suggest that students with higher science self-efficacy are more engaged and successful in science than their peers with lower science self-efficacy (Bouffard-Bouchard, Parent, & Larivee, 1991; Lau & Roeser, 2002). Therefore, building self-efficacy was considered a beneficial option for overcoming anxiety among school students (Kapici et al., 2020; Makransky et al., 2020). Pre-laboratory preparations in the form of simulations or discussions can positively affect laboratory participation, as they can promote students' readiness for exploring. Hence, research was designed based on this principle, which could identify and address the gaps associated with the following research questions:

1) What are the anxiety levels of students towards science laboratory?
2) What are the probable causes for the incidence of laboratory anxiety among students?
3) Does a self-directed learning strategy influence laboratory anxiety of students?

Therefore, this study has used an explanatory mixed-method design to measure the anxiety levels and understand the underlying causes for their prevalence. Also, a self-directed learning strategy has been proposed to mitigate anxiety among students. The self-directed learning strategy was devised based on conclusions for probable causes derived from interviews conducted in the qualitative phase of the study. The identified elements of learning strategy can be actively integrated into the curriculum and implemented for the creation of a positive learning environment.

Methodology

Participants

The sample for the study consisted of 57 (47%) girls and 64 (53%) boys from secondary schools. A purposive sampling design was used since only those schools were selected that had a functional laboratory available and were easily accessible to both students and teachers. A nested design of sampling was selected, wherein sample members selected from the quantitative phase were used for conducting interviews and for carrying out the experimental research. Therefore, 19 students falling in the range of higher anxiety levels were selected for the interview. After obtaining necessary consent and permissions, these students also agreed to be a part of the experimental group.

Design

A sequential explanatory mixed-method study design was implemented in which a quantitative descriptive survey was used to assess the prevalence of laboratory anxiety among secondary school students. As a part of the qualitative strand, subsequent follow-up interviews were conducted to establish the causes of anxiety. Taking the causes as a basis, a self-directed learning strategy was implemented as a pretest-posttest design. The 19 participants for the experimental design were selected from the quantitative phase and were the ones reflecting high levels of anxiety. These participants formed part of a single group, which was assessed before and after the intervention.

Instruments

The Laboratory Anxiety Scale was developed to measure the incidence of laboratory anxiety among secondary school students. A pool of 36 items was generated based on the theoretical dimensions of the construct and a review of literature. Items were prepared that dealt with feelings and emotions that can be felt altogether in subjects of Physics, Chemistry, and Biology. A Likert scale was used with options ranging from 1 to 4 (Always to Never). The midpoint or neutral option was not used in the current scale, as it has been recommended that the removal of midpoint acts as a better measure for assessing the intensity of participants' attitude. Moreover, midpoints are used by respondents as dumping grounds (Stone, 2004), so that such respondents tend to appear as non-committal. In total, 15 items were reverse-scored to lessen the acquiescence bias generated by the respondents while answering the scale items. The initial item pool was reviewed by eight experts, including science educators, Psychology professors, and language experts, to establish the content validity of the tool. Items were modified and retained as suggested by experts, and an item-total correlation was used to reveal a final scale with 20 items. The dimensions of scale were as follows: anxiety related to the use of chemicals (6), use of materials and equipment (5), laboratory safety (5), and execution of experiment (4). The reliability coefficient of Cronbach's Alpha was found to be 0.81.

The learning strategy based on Bandura’s theory was used for designing the experimental strategy to be implemented. Development of self-efficacy has been known to reduce laboratory anxiety (Chan et al., 2021). The main idea behind selecting the different components and elements to be a part of the learning strategy was based on the causes of incidence, derived from interviews and extensive deliberation on the review of proven techniques that have been pertinent in overcoming anxiety. To extract elements that were a part of the learning strategy, firstly, coding and categorising raw transcripts of information into meaningful phrases, sentences, and categories was done. Secondly, comparisons and linkages between various categories were carried out to draw major themes. Lastly, theoretical conclusions in the form of discussions were drawn out from the data (Cohen et al., 2002).

Therefore, the self-directed learning strategy comprises elements drawn from research interviews and review of literature that could enhance self-efficacy and allow students to be independent in dealing with anxiety, such as:

- Students were provided with access to web-based simulations in accordance with their curriculum for grades 10 to 12. Lab on laptop, Praxi lab, and virtual labs (Ministry of Education initiative) were a few of the applications used.
- Detailed information was given on lab safety, rules, and regulations.
- Myths about laboratory accidents were clarified, and first aid in case of laboratory accidents was discussed.
- Trips to science laboratories in government-led institutes and universities were planned.
- Information related to materials and equipment used in the laboratory.
- Self-help content about how to analyse and represent data after completion of experiments.
- Talks with researchers sharing significant research experience.

Results and Discussion

Incidence of Laboratory Anxiety among Secondary School Children

The results obtained after administration of the Laboratory Anxiety Scale showed that out of 121 students 16% (n=19) had high levels of anxiety, 28% (n=34) depicted moderate anxiety, and 56% (n=68) reflected low levels of anxiety for science laboratories. Various factors that contributed to the prevalence of anxiety towards science laboratories (the mean percentage as shown in Figure 1) were found to be the highest for execution of experiment (48%), followed by use of chemicals (44%), use of materials and equipment (42%), and lab safety (39%).

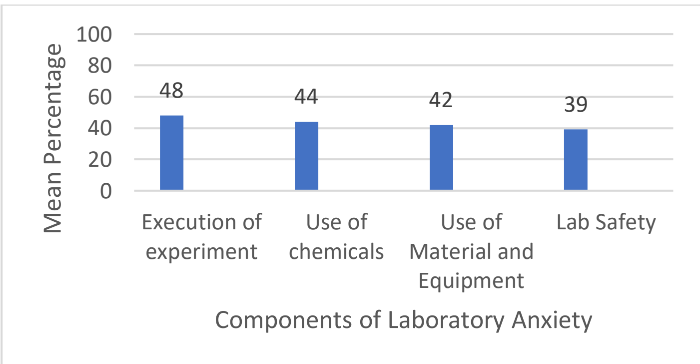

Figure 1. Percentage Distribution of Each Component of Laboratory Anxiety

Causes for the Incidence of Laboratory Anxiety among Secondary School Students

The students with high levels of laboratory anxiety were interviewed to discuss the factors responsible for the incidence of the current problem. On achieving a theoretical saturation, the data were coded and brought together in major themes, which are of the following nature. It was found that initially, the mental resistance of the child to not knowing what to expect was one of the reasons for being anxious. Low motivation prevailed among students as they felt actual learning could only happen from textbooks. The methodology followed for experimenting was a cookbook-type approach, which was considered equivalent to rote learning. They reinforced it into a procedure, involving meticulous recall of chemical quantities or the precise retention of electrical connections essential for a physics laboratory, demanding extensive memorisation. Therefore, the execution of experiment contributed as the highest factor towards laboratory anxiety as represented in Figure 2. Students often found it challenging to interpret the readings, which are crucial for depicting the results of an experiment. This difficulty made them apprehensive about potentially providing an incorrect evaluation of the outcome. Some individuals experienced anxiety merely being near glassware and expensive equipment, feeling ill-prepared to handle potential mistakes, which is reflected as a 42% contribution in mean percentage for use of material and equipment (Figure 2). These instances report nothing else but a lack of awareness of laboratory safety rules and regulations, working with equipment, and a general lack of practical manifestation of science principles. The idea of going to a laboratory was not a matter of hatred for the students, but not knowing what, how, and why things function in a laboratory made them disinterested in the concept.

Influence of Self-directed Learning Strategy on Laboratory Anxiety

By using student interviews as a basis for designing a self-directed learning strategy, the group of 19 students identified as individuals possessing higher levels of laboratory anxiety were administered the strategy as part of the experimental group. Pretest and posttest results showed significant variation (Figure 2). The mean score differences between the two groups were M (Pre) 57.31 and Post (47.84). This shows a decrease in anxiety levels of the students after undergoing a self-directed strategy to control laboratory anxiety. As represented in Figure 2, analysis of component-wise gain score reveals a major decrease in anxiety for lab safety (22%), followed by execution of experiment (19.1%), use of chemicals (11%), and use of material and equipment (7%). Gender differences were not found to be significant M(female)= 44.4 and M(Male)= 43.8.

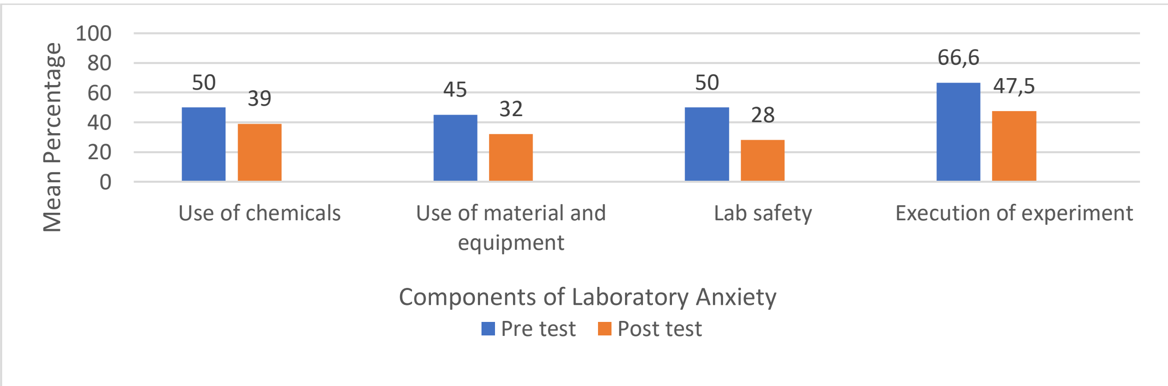

Figure 2. A Difference in Percentage of Laboratory Anxiety for Different Components Measured Before and After Administration of a Self-directed Learning Strategy.

Discussion

The prevalence of laboratory anxiety was reported to be 16% which is not something to be ignored, as increased anxiety is accompanied by a lower self-efficacy that allows for lesser sustainment in a task and lower achievement (Lorsbach & Jinks, 1998; Perry, 2016). Hence, assessment of students scoring lower grades in science can be done by teachers to interpret their anxiety levels towards laboratories.

The study showed anxiety towards the use of chemicals, materials and equipment, and challenges with laboratory safety (Figure 1). These issues have also been experienced and previously discussed in research based on students in India's schools (Sharma & Kumar, 2023). These challenges stem from the root cause of students not being provided with exposure to a laboratory in a true sense. Non-integration of practical and theory as well as using a cookbook approach are certain aspects that disagree with the maxims of inquiry-based learning using laboratory. These are being regularly followed upon in science laboratories and somehow manage to show the unpreparedness of the students (Pareek, 2019; Gupta et al., 2015). Overall, spending more time in the laboratory and performing experiments can help overcome anxiety (Erokten, 2010; Washbourn, 2024). Constructive changes can be brought about, as there was a missing link between the understanding of theoretical concepts and their implementation through a laboratory setup. The timing or duration of experimenting also plays an important role in satiating scientific curiosity (Hofstein & Lunetta, 2004). Since the laboratory classes were not well amalgamated with theory sessions, this seemed to have led to an erosion of interest in students' coherence with the concept, contributing to laboratory anxiety.

The self-directed learning strategy, which was very well supported by the virtual learning environment, has shown a significant improvement in anxiety scores as represented in Figure 2 (Gungor et al., 2022). The findings of the study showed that anxiety related to the execution of experiment and laboratory safety had been overcome in a high percentage (Figure 2). Thus, self-directed learning strategies can be used effectively for addressing anxiety-related issues (Sesen & Mutlu, 2014; Alkan & Erdem, 2013; Kurbangolu & Akin, 2012). The strategy involved technology integration for providing virtual lab experiences, which was less difficult to do as not all students had access to laptops or phones. Therefore, school computer labs were used to provide experience for the students. A detailed laboratory manual prepared for providing information and busting myths was gradually introduced, since immediately burdening students with content will create unnecessary pressure. School alumni were found to have a better connection and approachability with students during research experience sharing. Another observation found that while working with simulations, a few students found confidence initially, but failed to carry this preparedness to a real-life laboratory environment. This can be overcome if the training is provided with a longer duration.

Conclusion

This study confirms that progressive, scaffolded exposure to laboratory settings effectively reduces anxiety and improves competence in science education. Evidence shows that students who tackled increasingly complex lab tasks, with ongoing formative feedback, reported lower anxiety levels and better practical performance—supporting our initial hypothesis about gradual skill development. Based on this data, curriculum designers should incorporate incremental laboratory assignments and regular teacher feedback to boost students' confidence and skills. The findings also support using technology-enhanced simulations—such as augmented or virtual labs—as preparatory tools, especially for students who are initially intimidated by hands-on experiences, since participants who used these tools showed less nervousness during real lab tasks. While educators and curriculum experts can help implement these strategies, this recommendation directly follows from the study's results and not broader assumptions. However, exploratory practices like desensitisation protocols or mindfulness strategies—though promising—were not evaluated here and should be explored in future research. Longitudinal and qualitative studies are needed to understand how anxiety changes over time, identify specific triggers, and evaluate the impact of evidence-based interventions beyond self-directed approaches. Overall, aligning curriculum design with these findings and expanding on them through targeted follow-up research could greatly help reduce laboratory anxiety and promote positive science learning experiences.

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ISSN 2987-8101

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