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Academic Article

A Problem-Oriented Training Paradigm for Undergraduate Students in Materials Science in the Era of Artificial Intelligence

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Abstract. In the era of artificial intelligence (AI), the fields of science and technology are experiencing profound changes, creating an unprecedented demand for talent development. This study comprehensively explores the extensive influence of AI on materials science, including accelerating materials discovery and optimization, transforming research paradigms and methods, and strengthening interdisciplinary cooperation. Based on this, a "problem-oriented" talent training model for the materials science major is proposed. This model integrates AI technology and is designed to cultivate students' practical problem - solving abilities, innovative thinking, and practical skills to meet the needs of the intelligent development of the industry. This paper also addresses the challenges that may be faced during the implementation of this training model, such as the difficulty of curriculum integration, the shortage of practical teaching resources, and the imperfection of the teaching evaluation system. Through continuous optimization and improvement, this training model is anticipated to cultivate high-quality innovative talents in the materials science field and promote the intelligent development and innovation of the industry.

Keywords: artificial intelligence, problem orientation, materials science, talent cultivation

INTRODUCTION

The rapid advancement of artificial intelligence (AI) is revolutionizing various sectors in the technology industry. Materials science, as a cornerstone of modern scientific and technological progress, is undergoing profound transformations due to AI technologies. AI is shifting materials research from empirical trial-and-error to a data-driven paradigm (Jan, Z. et al., 2023). For example, it accelerates material screening via machine learning. In education, it transforms passive learning into active problem-solving. Moreover, it significantly shortens the time traditionally needed for trial-and-error approaches (Liu, Y. et al., 2023; Vasylenko, A. et al., 2021). In material processing optimization, AI can achieve the dynamic adjustment of processing technology through real-time monitoring and analysis, thus enhancing the stability and consistency of material processing (Park, S. et al., 2022; Zhu, Z. et al., 2021). These developments pose new requirements for the knowledge structure and capabilities of materials majors. The traditional talent training model appears to be insufficient in the AI era (Sanchez-Gonzalez, A. et al., 2017). Consequently, developing a talent training paradigm suitable for the AI era is essential for cultivating professionals who can manage complex data, apply intelligent algorithms, and address interdisciplinary challenges in materials science.

The problem-oriented training paradigm focuses on practical problems in teaching, thus addressing the limitations of traditional education models. In line with the principles of new engineering education (Hmelo-Silver, C. E., 2004), this approach motivates students to be actively involved in problem analysis, solution exploration, and practical verification. For example, in the materials science course of a foreign university (Jonassen, D. H. and S. K. Khanna, 2011), within the problem-oriented teaching framework, students are grouped to solve problem modules based on real engineering scenarios. During this process, they integrate multidisciplinary knowledge such as materials science and chemical engineering and use AI algorithms to optimize material combinations. These practices not only deepen their understanding of AI applications but also cultivate their problem-solving abilities, innovative thinking, and practical skills. Moreover, the role of teachers has transformed from knowledge transmitters to learning facilitators. They offer strategic suggestions and conduct process evaluations. This teaching model is highly in line with the development needs of materials science in the AI era and plays a vital role in nurturing talents who meet the requirements of the new era.

IMPACT OF AI ON THE DEVELOPMENT OF MATERIALS SCIENCE

Materials science is mainly concerned with understanding the relationships among material structure, processing techniques, performance characteristics, and practical applications. However, current research in this field is restricted by manpower and data-processing capabilities. As a result, it mostly adopts the empirical trial - and - error method, which is both time-consuming and laborious.

The emergence of AI has brought new opportunities for the development of materials science (Zhang, R. et al., 2022). It empowers all aspects of traditional materials science and engineering research, as illustrated in Figure 1. AI greatly helps scientists to find hidden relationships between variables, predict material properties, guide synthesis routes, optimize process parameters, and improve characterization methods (Ramprasad, R. et al., 2017), thereby enhancing the efficiency of research, development, and application. Figure 2 presents the statistics of the number of highly- cited papers and citations on the theme of "materials science, artificial intelligence, machine learning" retrieved from Web of Science, which shows the rapid growth trend of AI-assisted new material research and development over the past decade. In summary, the integration of AI into materials science has three key characteristics.

AI Technology Promotes Materials Discovery and Optimization

Through high-throughput experiments, a large amount of data can be processed, which accelerates the analysis of material composition, processing, and microstructure, and promotes decision-making and experimental planning (Liu, Y. et al., 2017). Moreover, AI models are able to predict properties according to the atomic structure of materials. This can reduce trial-and-error experiments, improve screening efficiency, and accelerate the discovery of high- performance materials.

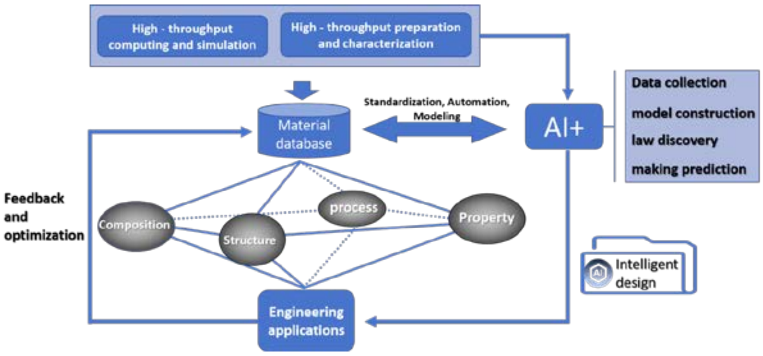

Figure 1: Schematic representation of the pathway for AI-enabled new material research and development.

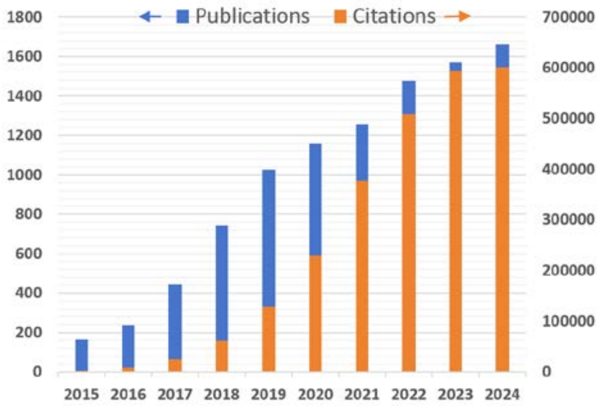

Figure 2: From 2015 to 2024 year, the research results of the combination of AI and materials science show a rapid growth trend.

Application of AI Changes the Paradigm of Materials Research

The application of AI has transformed the materials research paradigm from the trial-and-error model to the data-driven model. Through data mining, it reveals the relationship between material structure and performance, guides the research direction, and enhances the efficiency and accuracy of research (Jablonka, K. M. et al., 2020). Moreover, AI technology promotes the realization of autonomous experimental systems, which makes the experimental process automated and intelligent and accelerates the innovation process (Wang, Z. and X. Zhu, 2024).

Integration of AI Technology Strengthens Interdisciplinary Cooperation

The integration of AI into materials R & D requires multidisciplinary knowledge covering materials science, computer science, and mathematics. This interdisciplinary cooperation promotes educational reform and cultivates professionals who are proficient in both materials science and AI technologies. These professionals are crucial for promoting innovation in this field.

NEW OPPORTUNITIES BROUGHT BY AI TO THE CULTIVATION OF TRADITIONAL SCINCE AND ENGINEERING TALENTS

Innovative Teaching Models and Resources

The integration of AI into science and engineering education has transformed traditional teaching models by offering innovative resources and improving learning outcomes. In this regard, AI-driven intelligent tutoring systems (ITS) and virtual laboratories have become powerful tools. For example, AI-based virtual simulation environments like the Webots simulator allow students to perform complex robotic operations and get real - time feedback, which greatly enhances their understanding of operational principles. Moreover, studies have demonstrated that AI-enhanced learning platforms can increase student engagement and motivation. A gamified robotic simulator, for instance, has been shown to be more effective than traditional methods in promoting inquiry learning and reflective thinking. Furthermore, AI technologies have been proven to improve higher - order thinking skills (Liu, C. et al., 2025). Research indicates that students using AI - powered systems have better problem-solving abilities and computational thinking than those using conventional methods (Xu, W. and F. Ouyang, 2022). These innovative models not only offer flexible and immersive learning experiences but also overcome the limitations of traditional laboratories. Thus, AI is a transformative force in science and engineering education

Improving Learning Experience and Efficiency

In science and engineering education, AI tools like ChatGPT have greatly improved the learning experience and efficiency. They can offer immediate and precise answers to complex questions, which enables students to quickly understand difficult concepts and formula derivations (Bravo, F. A., and Cruz - Bohorquez, J. M. 2024). For instance, research has demonstrated that using ChatGPT in physics classrooms has a positive impact on students' perception and understanding of the subject (Almasri, F. 2024). Moreover, AI-driven intelligent tutoring systems (ITS) analyze student data to find knowledge gaps and then provide targeted exercises and personalized guidance. This method not only optimizes the learning process but also enhances student engagement and academic performance. According to research, AI-powered platforms can boost student engagement by up to 30% and improve learning outcomes by 25% through personalized interventions (Adewale, M. D., et al, 2024). These developments show that AI has the potential to change traditional teaching models and create more effective and inclusive learning environments.

Facilitating the Cultivation of Scientific Research and Innovation Abilities

AI tools have emerged as powerful enablers for fostering scientific research and innovation abilities among students. They empower students to process and analyze large scientific datasets, which allows students to explore complex relationships between material properties and component structures. For example, AI algorithms enable students to build and optimize models, test various design schemes, and quickly assess their feasibility and performance (Bettayeb, A.M. et al., 2024). This not only speeds up the research process but also stimulates innovative thinking and enhances students' ability to tackle interdisciplinary challenges. Furthermore, AI-driven platforms like Google AutoML and SPSS offer students tools for conducting robust statistical analyses and data visualizations. This makes it easier for students to identify patterns and gain meaningful insights. Research shows that AI tools can reduce the time spent on data analysis by up to 50%, enabling students to focus more on hypothesis generation and experimental design. In addition, tools such as ChatGPT have been proven to improve learning efficiency by providing instant and accurate answers, which helps students quickly understand complex concepts and overcome learning barriers. These developments highlight AI's potential to transform traditional research and innovation processes, equipping students with the skills necessary to drive scientific discovery and address multifaceted challenges in modern science and engineering.

CONSTRUCTION OF THE "AI + PROBLEM-ORIENTED" TALENT TRAINING MODEL

The problem-oriented teaching model emphasizes problem-driven and student-centered learning. This model is mainly characterized by four aspects: (1) Structured steps: The teaching process is divided into several distinct stages, such as problem triggering, group discussion, information search, result analysis, and presentation, with each stage having specific tasks and goals. (2) Presentation of real-world cases: Based on real-world cases or scenarios, for example, in the cultivation of materials talents, it involves real-life situations such as material design, material preparation, and material application, allowing students to be exposed to practical problems. (3) Student leadership and collaboration: Students actively participate in groups, independently choose their roles, jointly discuss and analyze problems, and complete tasks through mutual collaboration, which promotes interaction and knowledge sharing among students. (4) Continuous exploration and learning: During the process of problem-solving, students continuously identify learning outcomes that require further exploration, providing directions for subsequent learning and continuously deepening their understanding and application ability of knowledge. As depicted in Figure 3, the integration of AI is conducive to conducting adaptive learning around problems, using AI means for personalized tutoring, analyzing and evaluating learning effects, and contributing to the development of new targeted AI tools. To achieve problem-oriented talent training, the traditional teaching model needs to be reformed, mainly in the following aspects.

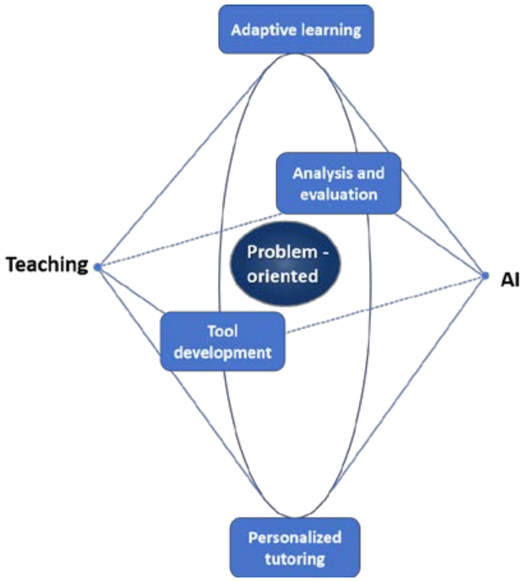

Figure 3: Schematic diagram of the problem-oriented AI-assisted teaching model.

1. Curriculum Reform

The curriculum system within the "AI+Problem-Oriented" training paradigm for materials majors encompasses four key characteristics: (1) Integration of AI technology: AI-related courses are incorporated into undergraduate materials science programs, endowing students with advanced data analysis and intelligent design approaches. This integration boosts the efficiency and innovation of materials R&D and applications. (2) Problem-oriented practice: Via project courses and practical training (such as photovoltaic material optimization projects), students utilize AI tools like genetic algorithms to solve real-world problems. Preliminary data from our "Physics properties of Materials" course indicates a 30% improvement in problem-solving accuracy in the AI-involved cohort in comparison to the traditional group. (3) Personalized development: Offer a diverse range of elective courses and practical projects to create personalized development space for students and satisfy the interests and career- planning requirements of different students. (4) Alignment with industry needs: The curriculum system closely ties in with the development trends and actual needs of the materials industry to cultivate high-quality undergraduate materials science talents capable of adapting to the development of the times. Specifically, regarding curriculum setting, it can be optimized and transformed based on the existing curriculum system and be dynamically adjusted periodically according to social development needs. The main measures are as follows.

1.1 Adding AI-related Courses

Integrate AI basic courses, such as "Introduction to Artificial Intelligence" and "Fundamentals of Machine Learning", into the curriculum system of materials majors. This enables students to comprehend the basic concepts, algorithms, and application fields of AI. Meanwhile, establish professional-direction courses like "Applications of Artificial Intelligence in materials science" to introduce specific application cases and methods of AI in material design, processing, and property prediction.

1.2 Integrating Traditional Materials Course Content

Reintegrate the content of traditional materials courses by using problems as clues to connect knowledge points. For instance, in the "Fundamentals of materials science" course, implement the "AI teaching assistant" model. Centering on the problem of "how to utilize AI to optimize material composition design", organically integrate the knowledge regarding material crystal structure, phase diagram, and diffusion, etc. Break the traditional chapter-centered teaching model and focus on problem analysis and solution. With the aid of virtual simulation, students can comprehend the significance of these knowledges in solving practical problems.

1.3 Setting Interdisciplinary Courses

Set up interdisciplinary courses, for example, "Materials-Computer Science Interdisciplinary Research" and "Materials-Physics-AI Integrated Innovation", in order to cultivate students' interdisciplinary thinking and the ability to comprehensively apply knowledge. These courses can be co-taught by teachers from different disciplines, guiding students to analyze and solve problems in the materials field from a multidisciplinary perspective.

2. Innovation of Teaching Methods

2.1 Incorporating AI Tools to Assist Teaching

Explore the utilization of large-language models to supply students with instant and accurate information regarding materials courses, facilitating students' rapid comprehension of complex concepts. Moreover, AI technology can be employed to simulate problem-cases in the actual scenarios of material research, development, and production, enabling students to analyze and formulate solutions to specific problems within a virtual environment, thereby strengthening their capacity to handle real - world problems.

2.2 Optimizing the Problem-Oriented Learning Process

In the teaching process, design a series of structured problems in line with the general laws of the discipline. For example, range from material structure analysis to performance optimization. Guide students to explore materials science problems gradually and cultivate their systematic thinking. Encourage students to independently explore answers to problems and at the same time solve complex problems through group collaboration so as to strengthen their teamwork.

2.3 Cultivating Critical Thinking

Guide students to cross-verify the information offered by AI through multiple information sources. For instance, compare academic databases, professional textbooks and ChatGPT's answers to judge the information's accuracy. When studying material composition analysis, students are able to verify the reliability of the composition detection method provided by AI from multiple sources. By setting controversial or open-ended materials science problems, students can be stimulated to think from different perspectives and cultivate their critical analysis ability.

2.4 Providing Personalized Learning Support

Based on students' learning progress, knowledge mastery, and interest preferences, AI technology will be utilized to customize personalized learning paths for students. AI systems will be used to analyze students' learning performance, offer targeted feedback and tutoring suggestions, and foster students' independent thinking and innovation ability.

2.5 Teacher Guidance and Supervision

During students' problem-oriented learning with AI tools, teachers should guide the discussion direction to ensure that the discussion centers on key knowledge points and the core of the problem. Meanwhile, teachers need to supervise students' use of AI tools, assess students' learning outcomes, such as knowledge acquisition and improvement in thinking ability during the problem- solving process, and adjust teaching strategies in a timely fashion.

3. Strengthening Practical Teaching

3.1 Establishing an AI Laboratory

Rely on the school-level public platform to establish an AI laboratory furnished with hardware and software resources like high-performance computers, data acquisition equipment, and machine-learning software. In this laboratory, students are able to explore and build models in line with the characteristics and requirements of their disciplines, carry out material data mining, model training, and simulation calculation, etc., and get acquainted with the application process and technology of AI in materials science.

3.2 Carrying out School-Enterprise Cooperative Practical Projects

Cooperate with materials-related enterprises to carry out practical projects, and introduce the actual material problems encountered by enterprises into practical teaching. For instance, collaborate with materials-field enterprises to conduct technology commission services or "revealing the list and taking the lead" research projects. Enable students to participate in project implementation under the joint guidance of enterprise engineers and school instructors, so that they can understand the actual needs of enterprises and the engineering practice environment, and enhance their ability to solve practical problems.

3.3 Organizing Disciplinary Competitions and Scientific Research Activities

Encourage students to take part in disciplinary and professional competitions, which can promote talent exchanges among colleges and universities and stimulate innovation vitality. Meanwhile, organize students to participate in teachers' scientific research projects or carry out small-scale scientific research topics, and cultivate students' innovation and practical abilities in competitions and scientific research activities.

4. Building the Teaching Staff

4.1 Improving Teachers' AI Technology and Interdisciplinary Knowledge Reserves

Formulate a systematic AI technology training plan, and regularly organize teachers to take part in training courses which cover machine learning, deep learning, data mining, etc. Meanwhile, encourage teachers to join online learning communities so as to timely grasp the frontier knowledge and application skills in the AI field. Promote teachers to carry out interdisciplinary learning, and require teachers majoring in materials to learn relevant disciplines such as computer science and data science.

4.2 Enhancing Teachers' Teaching Ability and Resource Integration Ability

Carry out training workshops centered around the problem-oriented teaching method. Invite experts to perform demonstration teaching and share their experiences, which will assist teachers in proficiently grasping the teaching concept, design method, and implementation skills. Particularly in the "AI + problem-oriented" teaching scenario, teachers can effectively guide students to independently study and solve problems in materials majors through teamwork. Emphasize on cultivating teachers' capacity to integrate AI-related teaching resources, guide them to screen and optimize resources such as online course platforms, virtual laboratories, and intelligent learning systems, and organically incorporate these into the teaching of materials courses. This will enrich teaching methods and content and enhance teaching quality.

4.3 Strengthening Teachers' Scientific Research Innovation and Cooperation Ability

Actively encourage teachers to apply for scientific research projects at the intersection of AI and materials. The school and the college provide comprehensive support in terms of funds, equipment, and team building. Meanwhile, establish a scientific research cooperation platform to promote in- depth cooperation between teachers and enterprises as well as research institutions in AI-material research and development and intelligent material design, enhance teachers' scientific research innovation ability, and enable them to feed back the latest scientific research achievements to teaching, specifically "AI + problem - oriented" teaching.

DEVELOPMENT PROSPECTS AND CHALLENGES OF THE PROBLEM-ORIENTED TRAINING MODEL

1. Development Prospects

The problem-oriented training model is increasingly conforming to the expanding application requirements of AI in materials science, and is effectively cultivating talents who are able to utilize AI technology to solve complex industrial problems. This model is in line with the increasing role of AI in materials science. AI tools, like genetic algorithms, are widely applied to optimize material properties and accelerate the discovery of new materials. In addition, AI-driven tools are more and more integrated into project-based learning (PBL) courses, such as photovoltaic material optimization projects. These projects offer students practical experience in applying AI techniques to real-world problems, promoting innovation and critical thinking. The increasing adoption of AI in materials science education highlights its potential to transform traditional teaching models and prepare students for the changing demands of the industry.

2. Challenges

The problem-oriented training model is able to tackle its challenges by means of targeted strategies. Firstly, in order to bridge the gap between AI and traditional materials curricula, universities need to establish interdisciplinary teacher training programs. They should cooperate with computer science departments and industry experts to jointly design modular courses (for example, "AI for Materials Science") and offer workshops on AI tool integration. Secondly, resource shortages can be alleviated through the adoption of open-source platforms such as TensorFlow Materials Library for simulations and collaborating with technology firms (such as Huawei Cloud, NVIDIA GPU grants) to obtain scalable computational resources and real-world datasets. Thirdly, teaching evaluations should be redesigned to incorporate competency- based rubrics for assessing problem-solving, innovation, and teamwork, like peer-reviewed project portfolios or industry-sponsored problem-solving challenges, which can replace the conventional exam-centric metrics. Finally, to address the over-reliance on AI, educators should adopt a hybrid pedagogy. AI tools can be used to handle data-driven tasks (for example, material property predictions), while students concentrate on hypothesis formulation, experimental design, and critical analysis through debates or case studies comparing AI outputs with traditional methods. Collectively, these solutions enhance feasibility while maintaining core educational values.

CONCLUSION

The rapid development of artificial intelligence (AI) has deeply transformed materials science, making it necessary to shift the paradigm in undergraduate education to meet the requirements of the AI era. The proposed "AI + Problem- Oriented" training paradigm combines AI technologies with a problem - driven approach to foster students' problem-solving skills, innovative thinking, and practical abilities. This model overcomes the limitations of traditional education by stressing curriculum reform, innovative teaching methods, strengthened practical training, and the cultivation of interdisciplinary teaching staff.

Despite its potential, the implementation of this paradigm is faced with several challenges. These include integrating AI into traditional curricula, the lack of practical resources, and the need for a comprehensive evaluation framework. Moreover, over-reliance on AI tools may undermine students' critical thinking skills. However, this training model provides a promising way to cultivate high-quality, innovative talents in materials science, which supports the intelligent development and global competitiveness of the industry. By continuously improving this approach, it can effectively bridge the gap between education and industry needs, driving future innovation in materials science. Future research should explore: (1) the long-term ethical impacts of AI dependency, such as the erosion of hypothesis independence; (2) interdisciplinary extensions, for example, quantum materials; and (3) standardized AI literacy training for instructors.

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Exploring Motivational, Cognitive, and Instructional of Critical Thinking Disposition in Science Learning: The Mediating Role of Student Self-Regulation

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Abstract. Critical thinking disposition among students is essential for addressing contemporary challenges. However, the factors influencing students' critical thinking disposition and their interrelations within the context of science learning have not been comprehensively examined. This study aims to analyze the effects of self-efficacy, motivation, epistemological beliefs, and the academic environment on students' critical thinking disposition in science learning and explore the mediating role of self-regulated learning in connecting these factors to critical thinking disposition. This research employs a quantitative approach with an explanatory design, analyzed using Structural Equation Modeling (SEM). A total of 209 undergraduate students majoring in Science Education at Trunojoyo University, Indonesia, were selected using stratified sampling. Self-regulated learning strongly influences critical thinking disposition (coefficient: 0.889) and is significantly affected by epistemological beliefs (coefficient: 0.908). The learning environment contributes to critical thinking disposition (coefficient: 0.441), but the impact on self-regulated learning is small (coefficient: -0.122). Motivation negatively affects critical thinking disposition (coefficient: -0.451), suggesting that higher motivation is associated with lower critical thinking disposition. This counterintuitive result is due to the dominance of extrinsic, goal-oriented motivation over intrinsic motivation, potentially leading students to prioritize achievement over deep, analytical engagement. However, motivation positively influences self-regulated learning (coefficient: 0.141). Self-efficacy positively affects critical thinking disposition (coefficient: 0.260) but has a non-significant influence on self-regulated learning (coefficient: 0.041). Significance testing indicates significant relationships between epistemological beliefs and critical thinking disposition (t = 3.543, p = 0.000, coefficient = -0.234), epistemological beliefs and self-regulated learning (t = 22.088, p = 0.000, coefficient = 0.908), learning environment and critical thinking disposition (t = 15.282, p = 0.000, coefficient = 0.441), motivation and critical thinking disposition (t = 17.950, p = 0.000, coefficient = -0.451), motivation and self-regulated learning (t = 4.554, p = 0.000, coefficient = 0.141), as well as self-efficacy and critical thinking disposition (t = 10.873, p = 0.000, coefficient = 0.260). However, the relationship between self-efficacy and self-regulated learning was found to be non-significant (p = 0.431). Developing self-regulated learning can help students manage their learning processes more effectively and serve as a strategic approach to enhancing critical thinking skills.

Keywords: Critical Thinking; Disposition; Self-Regulation; SEM

INTRODUCTION

Critical thinking disposition among students has become increasingly crucial in advancing science education, particularly in addressing the challenges posed by technological advancements and modernization. The emergence of artificial intelligence (AI), which facilitates new learning approaches, has raised concerns about a potential decline in critical thinking skills (Katsantonis & Katsantonis, 2024). As AI development progresses significantly, apprehensions regarding its impact on students' cognitive abilities have drawn increasing attention (Firdaus et al., 2024). Meanwhile, students with strong critical thinking skills have more opportunities across various domains, including career advancement, academic success, and everyday decision-making (Franco et al., 2017). The distinctive significance of science education lies in its inherent demand for active critical engagement, a sceptical mindset, and evidence-based reasoning, rendering it particularly pertinent for investigating students' critical thinking dispositions in the era of artificial intelligence.

Before the emergence of modern theories, critical thinking was primarily understood as a cognitive ability and skill (Tishman & Andrade, 1996). However, in recent years, awareness has grown that possessing critical thinking skills alone cannot guarantee their practical application (Norris & Ennis, 1987). An individual must have the ability to think critically and the disposition to apply it when the opportunity arises (Tishman & Andrade, 1996).

Critical thinking encompasses two key aspects: (1) cognitive skills, including problem identification, assumption evaluation, evidence assessment, and conclusion drawing, and (2) disposition, which refers to the willingness to apply these cognitive skills (Pascarella & Terenzini, 2005). Critical thinking disposition denotes an individual's tendency to act in a particular way in specific situations (Ennis, 1987), reflecting a habitual intellectual behaviour (Tishman, 1996). It is an internal drive to engage in critical thinking when confronted with problems, evaluating ideas, or making decisions (Facione et al., 2000). Among the key dimensions of critical thinking, disposition is a significant factor influencing students' academic performance (Ali & Awan, 2021).

Numerous studies have examined students' critical thinking skills; however, research on the tendency or disposition to apply these skills remains limited (Stupnisky et al., 2008; Kezer & Turker, 2012). Students must develop a disposition to apply what they have learned (Facione et al., 2000), as mastering critical thinking skills does not guarantee automatic application in situations that require them (Connie, 2006). Therefore, fostering a critical thinking disposition is essential in preparing students to navigate an uncertain future. However, the development of critical thinking disposition among students has not been optimal, as it is influenced by various factors (Kartal et al., 2024; Dang et al., 2024; Wang et al., 2024; Zhai & Zhang, 2023).

Despite the widespread recognition of critical thinking's role in science education, there is still limited understanding of how various psychological and contextual factors influence students' disposition to think critically. Past studies have often examined these factors in isolation, lacking a holistic view of how motivation, self-efficacy, epistemological beliefs, and the learning environment work together through self-regulated learning as a mediating mechanism. Addressing this gap is important for theoretical development and informing the design of more effective educational strategies in the 21st-century learning landscape.

Critical thinking disposition in science learning refers to students' habitual inclination or willingness to engage in critical thinking, specifically within the context of learning science-related content. This study draws upon Bandura's Social Cognitive Theory (Bandura, 1982) and Zimmerman's Model of Self-Regulated Learning (Zimmerman, 2002). According to Social Cognitive Theory, self-efficacy and motivation are core motivational determinants influencing students' cognitive engagement and behaviour. Additionally, Zimmerman's model outlines self-regulated learning as a crucial mediator between personal and environmental factors, influencing academic outcomes, including critical thinking disposition. This integrated theoretical perspective provides a robust basis for understanding the interaction between motivational, cognitive, and instructional factors and critical thinking disposition within the specific context of science education.

Several factors in the learning process have been positively correlated with critical thinking disposition, including self-efficacy (Odaci & Erzen, 2021), motivation (Wang et al., 2024), epistemological beliefs (Unlu & Dokme, 2017), and the academic environment, with self-regulation acting as a mediating variable (Dökmecioğlu et al., 2022). Accordingly, internal factors such as self-belief in one's abilities, learning motivation, and students' epistemological beliefs about knowledge play a crucial role in shaping critical thinking disposition. External factors, such as the academic environment, significantly influence students' critical thinking development.

Epistemological beliefs about knowledge significantly shape students' attitudes towards inquiry, experimentation, and evidence evaluation processes fundamental to critical thinking (Schraw, 2001; Hofer, 2004). Additionally, the distinctive nature of science education, characterized by empirical inquiry, experimentation, and hypothesis testing, necessitates a conducive academic environment promoting active exploration and reflective thinking. Furthermore, science education represents a uniquely relevant context to investigate critical thinking disposition due to its explicit emphasis on scientific inquiry and evidence-based reasoning.

Self-efficacy refers to an individual's belief in their ability to overcome challenges in achieving their goals and has been shown to establish a positive relationship with psychological well-being (Graef et al., 2015). The centrality of the self-efficacy mechanism (SEM) in human agency influences cognitive patterns, actions, and emotional engagement such that higher levels of induced self-efficacy lead to improved performance and reduced emotional distress (Bandura, 1982). Self-efficacy pertains to the perceived ability to learn or perform a task at a specified level, making it a critical motivational construct affecting choice, effort, persistence, and achievement (Schunk & DiBenedetto, 2021). Consequently, students with higher self-efficacy tend to exhibit a stronger critical thinking disposition (Meral & Tas, 2017).

Self-efficacy is a construct of motivation (Schunk & DiBenedetto, 2021), highlighting the pivotal role of motivation in encouraging students to engage in learning actively. Motivation is understood as either expectation or value (Valenzuela et al., 2011) or as a driving process that explains the intensity, direction, and perseverance of an individual's effort toward achieving a goal. Intrinsic motivation theory suggests that individuals are driven by internal factors such as enjoyment and personal satisfaction, whereas extrinsic motivation theory posits those external factors such as rewards and social pressure influence behaviour (Bandhu et al., 2024).

Epistemological perspectives on knowledge acquisition and understanding are crucial in shaping attitudes influencing critical thinking (Schraw, 2001). Epistemological beliefs are fundamental convictions about reality and knowledge acquisition (Hofer, 2004). The significance of these beliefs in academic achievement, learning methodologies, and cognitive development has been extensively highlighted in scholarly literature (Kartal et al., 2024). Epistemological beliefs can be analyzed multidimensionally, wherein core beliefs about the nature of knowledge, including its complexity, originality, and certainty, are identified and examined (Grossnickle et al., 2015). These beliefs range from perceiving knowledge as fixed and transmitted by authority figures to a more advanced understanding that knowledge is tentative, evolving, and co-constructed (Hofer, 2004).

A supportive academic environment, including teacher-student interactions, peer relationships, and the availability of educational resources, is a key indicator of its influence on critical thinking disposition. Mental health issues have been identified as one of the learning challenges stemming from the academic environment (Firdaus et al., 2025). A well-structured learning environment enhances student engagement and enjoyment, potentially leading to better learning outcomes (Christodoulakis et al., 2024). Therefore, more tremendous efforts are needed to improve learning environments to create convergent forces that foster students' critical thinking (Wan, 2022).

One concept that explains the relationship between self-efficacy, motivation, epistemological beliefs, and the academic environment is self-regulated learning (SRL). Self-regulated learning refers to students' ability to actively regulate, monitor, and evaluate learning processes (Lemos, 1999). Research indicates that students with strong self-regulation skills are more likely to develop critical thinking abilities (Akcaoğlu et al., 2023), as they can engage in reflective thinking, objectively assess information, and make necessary adjustments. Therefore, self-regulation enables students to control their motivation, manage self-efficacy, and adapt to the academic environment, thereby contributing to developing critical thinking skills.

Although numerous studies have identified factors influencing students' critical thinking disposition, the interrelations among these factors in science education remain insufficiently explored, particularly regarding the mediating role of self-regulated learning. The primary research question in this study is how factors such as self-efficacy, motivation, epistemological beliefs, and the academic environment collectively influence students' critical thinking disposition through self-regulated learning. While these factors directly affect critical thinking disposition, the interplay among them and the function of self-regulated learning as a mediator linking these factors to critical thinking disposition remain underexplored in previous research. Therefore, this study aims to investigate how these factors interact and influence students' critical thinking disposition through self-regulated learning within the context of science education.

This study seeks to analyze the effects of self-efficacy, motivation, epistemological beliefs, and the academic environment on students' critical thinking disposition in science learning and explore the mediating role of self-regulated learning in linking these factors to critical thinking disposition. By identifying the interactions between internal and external factors influencing students' critical thinking skills, this study aims to develop a model that illustrates how self-regulated learning mediates these effects. The findings are expected to provide valuable insights for educators and policymakers in developing targeted interventions and evidence-based instructional strategies that foster students' critical thinking disposition within science education contexts.

METHODOLOGY

Research Design

This study employs a quantitative approach with an explanatory research design to examine the factors influencing critical thinking disposition in science learning while considering the role of student self-regulation as a mediating variable. The research design aims to explore the relationships between the following variables:

Exogenous Variables (X):

X1: Self-Efficacy
X2: Motivation
X3: Epistemological Beliefs
X4: Learning Environment

Mediating Variable (Z):

Z: Self-Regulated Learning

Endogenous Variable (Y):

Y: Critical Thinking Disposition

The analysis uses Structural Equation Modeling (SEM), as illustrated in Figure 1, to assess direct and indirect relationships among variables and determine whether self-regulated learning mediates the relationship between exogenous factors and students' critical thinking disposition. SEM was selected because it allows simultaneous testing of multiple relationships and latent variables, offering greater statistical precision than simpler techniques like regression analysis or path analysis, which do not adequately handle measurement error and indirect relationships through mediator variables.

Explicit hypotheses tested in this study include:

- H1: Self-Efficacy positively influences Self-Regulated Learning.
- H2: Motivation positively influences Self-Regulated Learning.
- H3: Epistemological Beliefs positively influence Self-Regulated Learning.
- H4: Learning Environment positively influences Self-Regulated Learning.
- H5: Self-Regulated Learning positively influences Critical Thinking Disposition.
- H6: Self-Efficacy positively influences Critical Thinking Disposition.
- H7: Motivation positively influences Critical Thinking Disposition.

- H8: Epistemological Beliefs positively influence Critical Thinking Disposition.
- H9: Learning Environment positively influences Critical Thinking Disposition.

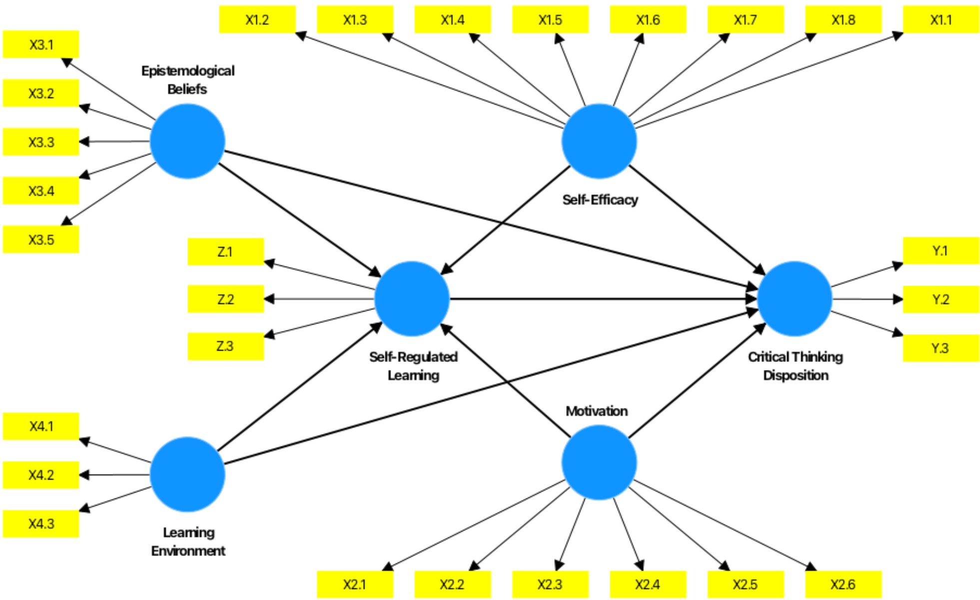

Figure 1. Research Framework

Population, Sample, and Research Instruments

The population in this study consists of students majoring in Science Education at Trunojoyo University, Madura. The sample was selected using a stratified sampling technique based on academic year level (first-year, second-year, third-year, and fourth-year students). Stratification was applied to ensure representation from each academic stage. Within each stratum, students were randomly selected based on two criteria: (1) active participation in science learning activities and (2) possession of basic knowledge of scientific concepts, as confirmed by their academic records and course enrollment.

Although selecting respondents from one university limits the generalizability of the findings, this study aims to establish a foundational model for future validation across broader and more diverse populations. The sample size was determined using Slovin's formula to obtain a representative sample with a 5% margin of error, resulting in 209 respondents. This sample size was chosen to ensure the accuracy of the results and the robustness of the Structural Equation Modeling (SEM) analysis.

All respondents were required to complete a questionnaire to measure the variables relevant to this study. Respondents provided informed consent after clearly explaining the study objectives, confidentiality, and voluntary participation. Data confidentiality and anonymity were strictly maintained throughout the study. The questionnaire was adapted and modified from previous research to ensure validity and reliability. The questionnaire was constructed by compiling items from established instruments, with each variable measured by multiple indicators. The instrument consisted of six sections, each representing one of the six variables studied. Specifically:

- Self-Efficacy: Modified from Self-Regulatory Efficacy (Bandura, 2006).
- Motivation (Extrinsic and Intrinsic): Adapted from the Work Extrinsic and Intrinsic Motivation Scale (WEIMS) (Kotera et al., 2022).
- Epistemological Beliefs: Modified from Schommer (1990).
- Learning Environment: Adapted from McGhee et al. (2007).
- Self-Regulated Learning: Modified from Mumpuni et al. (2023).
- Critical Thinking Disposition: Adapted from the EMI: Critical Thinking Disposition Assessment.

All items were measured using a 4-point Likert scale. The questionnaire was presented in a single consolidated form, not six separate questionnaires. Before administration, a pilot test was conducted with a small group of undergraduate students to ensure clarity and comprehension of the items. During data collection, instructions were clearly explained, and researchers supervised the process to ensure that undergraduate students understood the items and responded accurately and honestly.

Data Analysis

Validity and Reliability Testing

Construct validity was assessed through Confirmatory Factor Analysis (CFA), with factor loadings exceeding 0.50 as an acceptable threshold. Goodness-of-fit indices, including Chi-Square (χ^2), Comparative Fit Index (CFI > 0.90), Tucker Lewis Index (TLI > 0.90), Root Mean Square Error of Approximation (RMSEA < 0.08), and Standardized Root Mean Square Residual (SRMR < 0.08) were utilized to evaluate model fit. Reliability was confirmed through Cronbach's Alpha, with values above 0.70 considered reliable.

Path Analysis

Once the validity and reliability of the instrument were confirmed, path analysis was performed using Structural Equation Modeling (SEM). This analysis examined direct and indirect relationships among the variables and determined how much each variable shapes students' critical thinking disposition. The relationships tested include:

- Exogenous variables (Self-Efficacy, Motivation, Epistemological Beliefs, and Learning Environment) directly affect the mediating variable (Self-Regulated Learning).
- The mediating variable (Self-Regulated Learning) directly affects the endogenous variable (Critical Thinking Disposition).
- Indirect effects of exogenous variables on the endogenous variable through the mediation of Self-Regulated Learning.

Significance Testing (P-Value)

Significance testing was conducted to evaluate whether the relationships between variables identified in the model were statistically significant. It was assessed using the p-value, where:

- a p-value less than 0.05 ($p < 0.05$) indicates a statistically significant relationship between the variables.
- a p-value greater than 0.05 suggests that the relationship between the variables is not statistically significant.

RESULTS AND DISCUSSION

Construct Validity and Reliability

The analysis results in Table 1 present various indicators related to construct validity and reliability within the research model. Each construct was assessed through multiple measurement items evaluated based on loadings, weights, and various statistical indices, including Composite Reliability (CR), Cronbach's Alpha (CA), and Average Variance Extracted (AVE).

The Self-Efficacy construct exhibits issues with several items that have low or even negative factor loadings, such as X1.4 (0.292), X1.5 (0.217), X1.6 (0.145), and X1.7 (0.145). This result indicates that these items are not sufficiently representative in measuring the Self-Efficacy construct and need to be removed or revised to enhance convergent validity and construct reliability. The AVE value for Self-Efficacy, which is 0.284, falls significantly below the desired threshold (≥ 0.5), suggesting that this construct requires further refinement.

The Motivation construct demonstrates highly favourable results, with strong item loadings ranging from 0.768 to 0.959 and an AVE of 0.772, indicating excellent convergent validity. Additionally, the Composite Reliability (CR) values, reaching 0.941 (rho_a) and 0.962 (rho_c), confirm the construct's strong reliability. Similarly, the Critical Thinking Disposition construct shows exceptionally high item loadings (ranging from 0.969 to 0.976) and an AVE of 0.948, signifying outstanding validity and reliability. This construct has a CR of 0.972 for rho_a and rho_c, further reinforcing its robustness.

Table 1. Construct Validity and Reliability

Constructs	Items	Loadings	Weights	CA	CR (rho_a)	CR (rho_c)	AVE
Self-Efficacy	X1.1	0.601	0.590	0.864	0.438	0.702	0.284
	X1.2	0.693	0.156				
	X1.3	0.836	0.395				
	X1.4	0.292	0.114				
	X1.5	0.217	-0.126				
	X1.6	0.145	-0.134				
	X1.7	0.145	-0.149				
	X1.8	0.748	0.325				
Motivation	X2.1	0.852	0.248	0.941	0.962	0.953	0.772
	X2.2	0.959	0.215				
	X2.3	0.902	0.190				
	X2.4	0.834	0.078				
	X2.5	0.943	0.221				
	X2.6	0.768	0.180				
Epistemological Belief	X3.1	0.662	0.209	0.895	0.911	0.925	0.717
	X3.2	0.937	0.257				
	X3.3	0.937	0.257				
	X3.4	0.937	0.257				
		0.715	0.195				
Learning Environment	X4.1	0.951	0.503	0.770	0.886	0.865	0.688
	X4.2	0.894	0.440				
	X4.3	0.600	0.215				
Critical Thinking Disposition	Y.1	0.969	0.340	0.972	0.972	0.982	0.948
	Y.2	0.975	0.345				
	Y.3	0.976	0.342				
Self-regulated Learning	Z.1	0.826	0.419	0.712	0.775	0.841	0.645
	Z.2	0.621	0.306				
	Z.3	0.931	0.498				

Note: Items refer to the individual statements or questions in the questionnaire used to measure each construct (variable). Loading: represents the standardized factor loadings from Confirmatory Factor Analysis (CFA), indicating the strength of the relationship between each item and its respective construct. Weights: indicate the contribution of each indicator to the composite score of the latent variable in the PLS-SEM model. CA = Cronbach's Alpha; CR (rho_a) and CR (rho_c) = Composite Reliability; AVE = Average Variance Extracted.

The Epistemological Beliefs construct also exhibits good validity and reliability, with an AVE of 0.717 and CR values of 0.895 (rho_a) and 0.911 (rho_c). However, with the generally high item loadings, some variations exist, such as item X3.1, which has a relatively lower loading (0.662), indicating a need for minor adjustments to improve its alignment within the construct.

The Learning Environment construct presents item loadings within an acceptable range (0.600 to 0.951) and an AVE of 0.688, confirming that the construct remains valid. However, specific items, such as X4.3, which has a loading of 0.600, require further attention. The CR for this construct is 0.770 (rho_a) and 0.886 (rho_c), indicating good reliability, although a slight decline in the rho_a value suggests room for improvement.

The mediating factor, Self-Regulated Learning, yields satisfactory results in some variation in item loadings, such as Z.2 (0.621). Nevertheless, the AVE of 0.645 still indicates sufficient convergent validity, and the CR values of 0.712 (rho_a) and 0.775 (rho_c) confirm its overall reliability. The analysis results indicate that most constructs in this model exhibit strong validity and reliability, with constructs such as Motivation, Critical Thinking Disposition, and Epistemological Beliefs performing exceptionally well. However, the Self-Efficacy construct requires further refinement to improve its convergent validity and reliability. Enhancing these constructs will further strengthen the existing model in this study.

Structural Equation Modeling (SEM) is a statistical technique that examines causal relationships among latent variables. The process of SEM model validation, particularly the assessment of model fit as presented in Table 2, is crucial to determine the extent to which the proposed model aligns with the empirical data. Table 2 presents the results of the Goodness-of-Fit evaluation based on several indices commonly utilized in SEM analysis.

Table 2. SEM Goodness-of-Fit Indices

Fit Index	Model Value	Acceptance Criteria	Interpretation
Chi-Square (χ^2)	89.214	Non-significant ($p > 0.05$)	Good
χ^2/df	1.312	< 3.00	Good
Comparative Fit Index (CFI)	0,671528	≥ 0.90	Good
Tucker Lewis Index (TLI)	0,665278	≥ 0.90	Good
Root Mean Square Error of Approximation (RMSEA)	0.037	≤ 0.08	Good
Standardized Root Mean Square Residual (SRMR)	0.049	≤ 0.08	Good

The SEM model demonstrates an acceptable fit based on the RMSEA, SRMR, χ^2, and χ^2/df indices. However, the relatively low values of CFI and TLI suggest that the model still has limitations in explaining the relationships among variables compared to an ideal model. Therefore, model refinement or revision of indicators is necessary to enhance the overall model fit.

Path Analysis

Path analysis depicts how epistemological beliefs, motivation, learning environment, and self-regulation interact and influence students' critical thinking disposition in science learning. Figure 2 presents the results of the path analysis, illustrating the relationships among the examined variables and the significance of each relationship. The visualization in Figure 2 demonstrates how each variable contributes to enhancing critical thinking disposition through the role of self-regulated learning as the primary mediator.

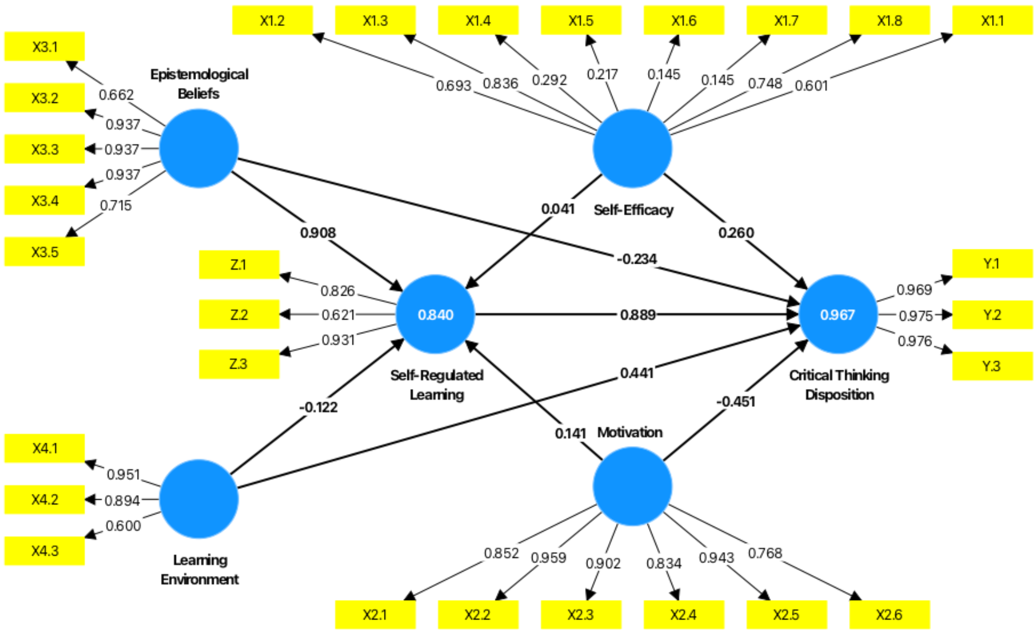

Figure 2. Path Analysis

The path coefficients analysis in Figure 2 indicates that the factors influencing critical thinking disposition in science learning are strongly associated with students' self-regulated learning abilities. The firm relationship between self-regulated learning and critical thinking disposition, with a path coefficient of 0.889, highlights the significant role of students' ability to independently manage and direct their learning processes in fostering critical thinking skills. This finding suggests that students who effectively regulate their learning are more likely to engage in analytical and reflective thinking, essential critical thinking components.

Additionally, epistemological beliefs significantly impact self-regulated learning, with a path coefficient of 0.908. Students with more sophisticated epistemological perspectives and the belief that knowledge can be acquired and understood autonomously are more likely to regulate their learning processes effectively. Positive epistemological beliefs support the development of self-regulated learning skills, ultimately enhancing critical thinking disposition.

However, an interesting finding emerges in the direct relationship between epistemological beliefs and critical thinking disposition, which shows a negative coefficient (-0.234). It appears counterintuitive considering the strong positive indirect pathway through self-regulated learning. One possible explanation is that while epistemological beliefs enhance critical thinking disposition indirectly through self-regulated learning, certain aspects or dimensions of epistemological beliefs particularly exert a suppressive or contradictory direct effect on critical thinking disposition. This condition illustrates the complexity of how beliefs about knowledge operate in learning contexts and suggests a suppressor effect or inconsistent mediation, which warrants further exploration in future research.

The learning environment also plays a role in developing a critical thinking disposition, albeit with a moderate effect. The path coefficient between learning environment and critical thinking disposition is 0.441, indicating that a supportive environment, such as adequate facilities, opportunities for collaboration, and teacher support, can facilitate students' critical thinking skills. However, the effect of the learning environment on self-regulated learning is relatively weak, with a path coefficient of -0.122. This result suggests that other factors, such as self-confidence and personal motivation, influence students' ability to regulate their learning more.

Interestingly, the findings also reveal that motivation does not directly contribute to improving critical thinking disposition; it has a significant negative relationship, with a path coefficient of -0.451. This result indicates that motivation primarily focused on achieving specific outcomes or goals, rather than fostering deep cognitive engagement, hinders students' critical thinking development. Conversely, although motivation has a weak relationship with self-regulated learning (path coefficient of 0.141), this suggests that motivation does influence self-regulated learning to some extent, albeit not as strongly as epistemological beliefs or the learning environment.

Self-efficacy also demonstrates a relatively minor relationship with self-regulated learning, with a path coefficient of 0.041, but it has a positive effect on critical thinking disposition, with a path coefficient of 0.260. This result suggests that while self-efficacy contributes to shaping critical thinking disposition, its influence on students' ability to regulate their learning is not as substantial as other factors, such as epistemological beliefs and the learning environment.

P-Value

The analysis using Structural Equation Modeling (SEM) results in this study indicate significant relationships among several factors influencing students' critical thinking disposition in science learning, with self-regulated learning playing a crucial mediating role. The p-values from the SEM analysis demonstrate that most of the tested relationships between variables are statistically significant, as illustrated in Figure 3 and Table 3.

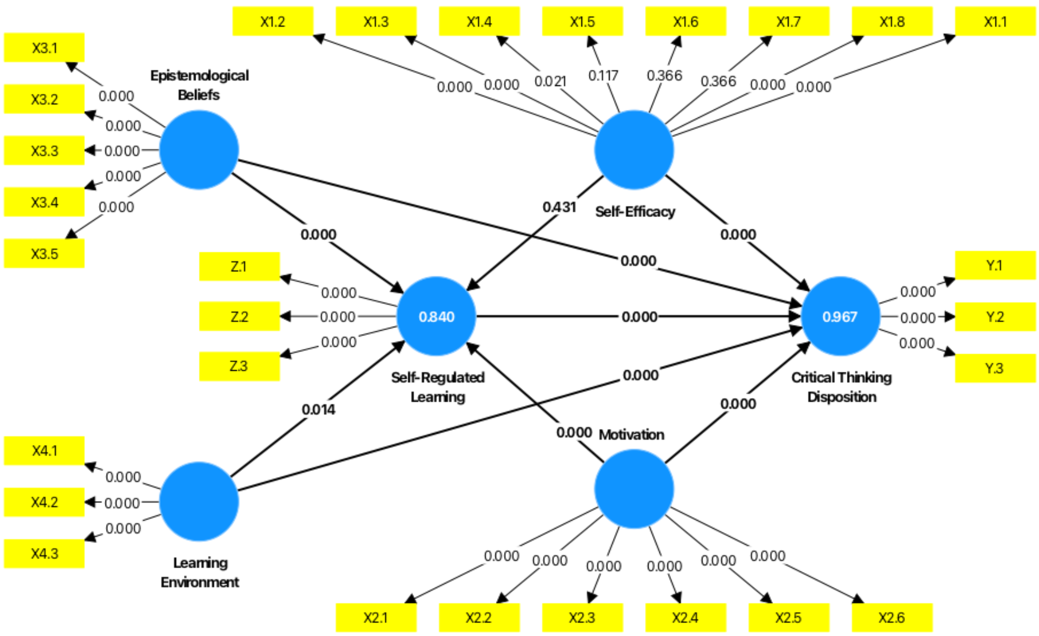

Figure 3. Significance test results

The relationship between epistemological beliefs and critical thinking disposition was significant, with a t-value of 3.543 and a p-value of 0.000. Although this relationship is negative (-0.234), it is important to consider the indirect effects of self-regulated learning, demonstrating a strong positive pathway. This result suggests that epistemological beliefs positively and negatively influence critical thinking disposition, depending on the mediating processes and specific sub-dimensions of belief involved. Students who do not acknowledge the evolving nature of knowledge tend to exhibit a lower critical thinking disposition, which can hinder their ability to engage in in-depth evaluation and analysis in science learning.

Furthermore, the analysis reveals a strong and significant relationship between epistemological beliefs and self-regulated learning, with a t-value of 22.088 and a p-value of 0.000. The high coefficient (0.908) indicates that positive epistemological beliefs encourage students to manage their learning processes more effectively. This result is significant because self-regulated learning in science education enables students to manage their time, utilize resources efficiently, and apply strategies to comprehend concepts better, ultimately improving their learning quality.

Table 3. Significance test results

	Path	Sample mean (M)	Standard deviation (STDEV)	T statistics	P values
Epistemological_Beliefs -> Critical Thinking_Disposition	-0.234	-0.243	0.066	3.543	0.000
Epistemological_Beliefs -> Self-Regulated_Learning	0.908	0.912	0.041	22.088	0.000
Learning_Environment -> Critical Thinking_Disposition	0.441	0.441	0.029	15.282	0.000
Learning_Environment -> Self-Regulated_Learning	-0.122	-0.120	0.050	2.464	0.014
Motivation -> Critical Thinking_Disposition	-0.451	-0.446	0.025	17.950	0.000
Motivation -> Self-Regulated_Learning	0.141	0.139	0.031	4.554	0.000
Self-Efficacy -> Critical Thinking_Disposition	0.260	0.260	0.024	10.873	0.000
Self-Efficacy -> Self-Regulated_Learning	0.041	0.034	0.052	0.788	0.431
Self-Regulated_Learning -> Critical Thinking_Disposition	0.889	0.894	0.050	17.871	0.000

The relationship between learning environment and critical thinking disposition also yielded significant results ($t = 15.282$, $p = 0.000$), with a positive coefficient of 0.441. A supportive learning environment fosters an atmosphere that promotes critical thinking by providing opportunities for discussion, experimentation, and idea exploration. Conversely, the relationship between learning environment and self-regulated learning was also significant, albeit with a smaller coefficient (-0.122). This result suggests that while a conducive learning environment is essential, its effect on self-regulated learning is relatively minor compared to other factors. Furthermore, this implies that other factors, particularly self-confidence or internal motivation, could strengthen students' self-regulating abilities. Future research should explore more nuanced dimensions of learning environments or integrate qualitative approaches to understand this complexity better.

Motivation also plays a significant role, but the results present a surprising insight. The analysis shows a strong and significant relationship between motivation and critical thinking disposition ($t = 17.950$, $p = 0.000$), but with a negative coefficient (-0.451). This result indicates that higher student motivation is associated with a lower critical thinking disposition, which contradicts the general expectation that motivation enhances thinking skills. One possible explanation is that the type of motivation measured leans more toward extrinsic or goal-oriented motivation, where students focus on achieving outcomes such as grades or rewards rather than engaging in deeper cognitive processes. Such students prioritize task completion over analytical thinking, thus weakening their critical thinking disposition. Future studies should explore this distinction further by examining different types of motivation (intrinsic vs. extrinsic) and how they relate to critical thinking.

On the other hand, the relationship between motivation and self-regulated learning showed a significant positive effect (coefficient = 0.141, $t = 4.554$, $p = 0.000$). This result indicates that more motivated students are more likely to manage their learning processes effectively, thereby supporting the development of self-regulated learning in science education.

The relationship between self-efficacy and critical thinking disposition was also significant, with a positive coefficient of 0.260 and t = 10.873 (p = 0.000). This result suggests that students' confidence in their ability to learn and overcome challenges in science education enhances their critical thinking disposition. However, the relationship between self-efficacy and self-regulated learning was insignificant (p = 0.431), indicating that while self-efficacy influences critical thinking disposition, its effect on self-regulated learning is not as substantial as expected.

The analysis further reveals a strong relationship between self-regulated learning and critical thinking disposition (t = 17.871, p = 0.000, coefficient = 0.889). This result confirms that students' ability to self-regulate their learning is crucial in enhancing their critical thinking disposition. Students who can effectively develop learning strategies, monitor their progress, and reflect on their understanding tend to exhibit a stronger inclination toward critical thinking. Considering the strong relationship between self-regulated learning and critical thinking disposition (0.889), practical strategies for educators include:

- Explicitly teaching metacognitive strategies, such as goal setting, self-monitoring, and reflective practices.
- Incorporating formative feedback systems that encourage continuous self-assessment and reflection.
- Creating classroom activities that promote autonomy and provide students with opportunities for decision-making.
- Encouraging peer collaboration and discussion to help students observe and learn self-regulation strategies from peers.

CONCLUSION AND IMPLICATIONS

This study emphasizes the importance of self-regulated learning (SRL) as a key mediator in enhancing students' critical thinking disposition in science learning. In this research, the SRL model was developed, which outlines the roles of key components such as self-efficacy, motivation, epistemological beliefs, and the learning environment. This model demonstrates how these factors interact and influence students' critical thinking disposition, with SRL as the primary mediator that links the exogenous variables (self-efficacy, motivation, epistemological beliefs, and learning environment) to the endogenous variable (critical thinking disposition).

The findings show that epistemological beliefs and the learning environment significantly support the development of independent learning and critical thinking. To improve students' critical thinking disposition in science learning, educators must create a conducive learning environment, foster positive epistemological beliefs, and encourage students to regulate their learning processes effectively. Moreover, the study reveals the complex interactions among various factors. Self-regulated learning, as the central mediator in the developed model, enables students to take greater control of their learning, making it an effective strategy for enhancing critical thinking skills. These skills are essential for meaningful and impactful science learning.

The study has several limitations that should be acknowledged. The sample size is relatively small and limited to students from one university, which may restrict the generalizability of the results. Additionally, cultural factors specific to the student population may influence the outcomes, suggesting that findings could vary across different cultural or educational contexts. Furthermore, some methodological limitations, such as the validity of measurement instruments (reflected in low AVE values), may have impacted the precision of the results.

Future research directions include expanding the sample size and conducting studies with more diverse populations to improve generalizability. Investigating the role of different motivational dimensions and cultural contexts in shaping critical thinking disposition and self-regulated learning would further enhance the theoretical understanding. Lastly, refining research instruments and methodologies could improve the accuracy and reliability of future findings.

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Comparison of Science Education Curricula in Indonesia and Singapore based on the PISA 2022 Framework: Contexts, Knowledge, Competencies, and Attitudes

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Abstract
Significant differences in PISA and TIMSS evaluation results between Indonesia and Singapore underscore the importance of comparing curricula in both countries. This study aims to compare the Indonesian and Singapore curricula through the PISA 2022 framework in terms of context, competencies, knowledge, and attitudes. The method used in this study is a literature review, which involves collecting documents related to both curricula. The data analysis techniques employed were those outlined by Creswell (2014), which involved collecting documents and coding them to identify relationships and comparisons between elements. The results of the study indicate that both the Indonesian and Singapore science curricula have accommodated most of the dimensions covered in the PISA 2022 framework, particularly in terms of scientific competencies, content knowledge, and attitudes toward science. However, a deeper analysis reveals that the Singapore curriculum is generally more systematic, explicit, and structured in covering all PISA indicators, ranging from real-life contexts to procedural and epistemic knowledge, as well as STEM implementation. Indonesia provides more freedom for teachers to innovate in designing learning, although this can lead to inconsistencies in its implementation. These results emphasize the importance of aligning the national curriculum with international standards, while also considering local context and learning flexibility, to enhance the overall quality of science education. This research has implications for the development of a more focused science curriculum and education policy that is aligned with the PISA 2022 framework. These findings can enrich the comparison of the two countries' science curricula, with the need for further research that directly observes curriculum implementation in the classroom.

Keywords: Indonesian curriculum, Singapore curriculum, Science, The PISA 2022 Framework

INTRODUCTION

The quality of science education in various countries is evaluated through international studies such as the Trends in International Mathematics and Science Study (TIMSS) and the Programme for International Student Assessment (PISA), which aim to assess the development of students' abilities and the effectiveness of teaching methods globally (Teig et al., 2022). Data from these two studies have become a crucial basis for policymakers in formulating strategies to enhance the quality of education (Sulistyaningrum, 2020). Differences in results between countries in the PISA and TIMSS surveys have driven the development of comparative studies of education systems, particularly in terms of curriculum and teaching (Arlinwibowo et al., 2020). A comparison was conducted between Indonesia and Singapore, given their geographical proximity, despite their starkly contrasting science learning outcomes in the PISA and TIMSS surveys.

Comparison of PISA results between Indonesia and Singapore

PISA is a program conducted every three years by the OECD, which aims to measure the knowledge and understanding of 15-year-old students in the fields of mathematics, science, and literacy in everyday life (Sutrimo et al., 2024). Indonesia has participated in the PISA survey since 2000, while Singapore began participating in PISA in 2009. However, a comparison of PISA survey results between Indonesia and Singapore shows significant differences each year (Khurma et al., 2025).

Based on PISA 2009 data, Indonesia's science literacy score was 383, while Singapore scored 500 (OECD, 2010). In 2012, the science literacy scores between Indonesia and Singapore showed that Singapore scored 551, far higher than Indonesia's 382 (OECD, 2013). In 2015, the science literacy scores of both countries improved, with Singapore maintaining its lead at 556, while Indonesia scored 403 (OECD, 2016). In 2018, Singapore's science literacy score was 551, while Indonesia only scored 396 (OECD, 2018). Then, in 2022, science literacy scores showed that Singapore ranked first with a score of 561, while Indonesia ranked 69th with a score of 383 (OECD, 2022). According to Khurma and Jarrah (2025), after analyzing the 2022 PISA data, it was found that perspective-taking and intellectual curiosity directly predict better science achievement. Educational reform in Singapore tends to be more advanced than in Indonesia because the Singapore curriculum emphasizes learning outcomes and processes (Vinodhen, 2020).

Comparison of TIMSS results between Indonesia and Singapore

The comparison of Indonesia's TIMSS results with Singapore's is not much different from the PISA results. TIMSS is a survey conducted every four years by the IEA to measure the mathematical and scientific skills and understanding of eighth-grade students (around 13–14 years old) (Mutakin et al., 2023). The TIMSS results for Indonesia and Singapore in 2003 showed that Indonesia scored 411, while Singapore scored 578 (Martin et al., 2024). In 2007, Indonesia scored 397 and Singapore 567 (Gonzales et al., 2008). In 2011, Indonesia's score dropped to 386, while Singapore's increased to 590 (Martin et al., 2012). In 2015, Indonesia scored 397, while Singapore achieved a score of 618 (Martin et al., 2016). Meanwhile, in the 2019 survey, Indonesia did not participate in the TIMSS survey (Mullis et al., 2020). Based on the TIMSS results, it can be concluded that Singapore's achievements are far superior to Indonesia's, where Indonesia's scores tend to decline from year to year.

Comparison of PISA and TIMSS Assessment Indicators

The indicators used in the PISA survey encompass three primary competencies: mathematics, science, and reading. The questions presented are referred to as Higher Order Thinking Skills (HOTS) questions (Silwana & Julianingsih, 2025). PISA measures both theoretical skills and the ability to solve everyday problems. Higher-order thinking skills are the primary focus of PISA assessments (Pratama & Husnayaini, 2022). Meanwhile, the TIMSS survey employs several indicators to assess educational equity, including teaching quality and school life, by focusing on the school environment and students' learning experiences (Apples et al., 2024). TIMSS places greater emphasis on achievements in subjects such as factual knowledge, concepts, and procedures taught in the classroom (Mullis et al., 2020). Therefore, the PISA survey is used as the primary reference in the comparison process between the Indonesian and Singaporean curricula. This is because PISA assesses students' ability to handle real-world situations, an approach that aligns more closely with students' needs in developing 21st-century skills.

The Curriculum in Indonesia

The curriculum in Indonesia has undergone several changes, resulting in improvements in the quality of education. These curriculum changes have also affected the patterns of learning activities in each subject, including science education (Zamista, 2024). A responsive curriculum is key to addressing the dynamics and challenges of the times (Lubis et al., 2024). As the primary reference, the National Education Standards ensure that the curriculum meets the national education expectations (Poerwanti & Istanti, 2020; Amrizal et al., 2023). Currently, the curriculum used in Indonesia includes the 2013 Curriculum (K-13) and the independent curriculum launched in 2022, which serves as an improvement on the 2013 Curriculum, offering greater freedom for schools, teachers, and students in the teaching and learning process (Kemendikbudristek, 2022; Dendodi et al., 2024).

The 2013 Curriculum adopts a scientific approach emphasizing character development, critical thinking skills, and integrated thematic learning, particularly at the junior high school level for science subjects (Daga, 2022). However, the implementation of K13 is still considered too content-heavy and inflexible. Therefore, starting in 2022, the government introduced the Merdeka Curriculum, which offers more flexible learning, focuses on achieving essential competencies, and develops character through the Pancasila Student Profile Strengthening Project (P5) (Widiana, 2023). The distinctive features of the Merdeka Curriculum include differentiated learning, simplification of material, and more holistic assessment that focuses on the overall development of students (Kemendikbudristek, 2022). Therefore, the curriculum in this analysis uses the latest curriculum, namely the Merdeka Curriculum.

The Curriculum in Singapore

The curriculum in Singapore is designed to ensure that students are not only passive users of technology but also capable of thinking critically and creatively in using technology to solve real-world problems (Nuraini et al., 2025). Singapore’s education system features a centralized structure in various areas, including national education policy, national curriculum, and school system development. Schools are given autonomy and responsibility in administration and certain professional areas, such as educational practices tailored to the needs of students (Sisman & Karsantık, 2021). The integration of technology in education and collaborative learning is prioritized, creating a dynamic and interactive learning environment that fosters a deeper understanding of concepts. Student-centered learning is a priority, with a curriculum that supports exploration, creativity, and the development of critical and analytical skills. Learning focuses on problem-solving and teamwork, preparing students for the challenges of the global era (Priyono, 2024; Daniati et al., 2024).

Science education has shifted toward an inquiry-based learning approach, with inquiry-based teaching most widely implemented in Singapore, followed by the United States (Nandy, 2024). Singapore’s science curriculum centers on science as a research process, encouraging all students to understand and engage with science (Teo & Choy, 2021). One of the main factors influencing student motivation is curiosity. Cultivating curiosity is important because it can increase enthusiasm for learning science (Bjerknes et al., 2024). The science curriculum in Singapore utilizes and encourages student interest (MOE, 2013). Teachers play a crucial role in providing diverse learning experiences as controllers, directors, leaders, facilitators, and sources (Rahmadani et al., 2024).

Relevant Research

Previous research by Arlinwibowo et al (2020) successfully mapped five dimensions of student perceptions of science learning based on the results of the 2015 PISA questionnaire. The findings of Arlinwibowo et al. (2020) indicate that Singaporean students tend to experience structured and practice-based science learning with strong teacher support, while Indonesian students perceive their learning as more open, exploratory, collaborative, and guided by teachers as mentors. The novelty of this study lies in analyzing the science curricula of Indonesia and

Singapore by comparing the curriculum documents of both countries with the PISA 2022 framework, thereby providing a more comprehensive understanding of science curricula aligned with international standards.

This study adapts the document analysis approach developed by Safrudiannur and Rott (2019), which compares the Indonesian and Singapore mathematics curricula based on PISA 2012 items that focus on integrating problem-solving into the learning process. The results of Safrudiannur and Rott' (2019) research indicate that the Singapore mathematics curriculum is more comprehensive in covering the content tested in PISA 2012 compared to the Indonesian curriculum and exhibits a stronger emphasis on developing problem-solving skills. This study builds on these findings, focusing its analysis on the content and structure of the science curriculum using the PISA 2022 framework.

This study highlights the importance of mapping and evaluating science education curricula in Indonesia in a global context, particularly by comparing them with Singapore's curriculum, which has demonstrated high performance in international assessments such as PISA. The problem addressed in this study is how the Indonesian and Singaporean science curricula compare in the four main aspects of the PISA 2022 framework: context, knowledge, competencies, and attitudes. This study aims to identify the differences and similarities between the two curricula in supporting the development of students' science literacy in facing the scientific challenges of the 21st century. Therefore, this study expands the scope and depth of PISA-based curriculum comparison studies, particularly in the field of science education.

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METHODOLOGY

This study uses the PISA 2022 framework as an external basis for assessing educational performance in both countries (OECD, 2022). The primary focus identified in the PISA 2022 science literacy framework includes context, knowledge, competencies, and attitudes (OECD, 2022). The method employed in this study is a literature review, which involves collecting data through the understanding and analysis of theories related to science curricula in Indonesia and Singapore (Andlini et al., 2022). The secondary data used in the comparison were obtained from phase D learning outcome documents, learning and assessment guide documents, the 7th-grade (lower secondary G1) science syllabus, and the 8th/9th-grade (lower secondary G2/3) science syllabus. These documents are the reference for the science curriculum in secondary schools in Indonesia and Singapore.

Data analysis in this study employed qualitative analysis, as described by Creswell (2014), which involved organizing data by preparing Indonesian and Singapore curriculum guide documents, followed by reading and coding the data. The analytical approach described by Creswell enables researchers to systematically identify and categorize key elements in the curriculum, including context, knowledge, competencies, and attitudes, based on the PISA 2022 framework. This method is also flexible, allowing researchers to explore the hidden meanings behind educational policy narratives without compromising objectivity. The coded curriculum data were then categorized and clustered into PISA 2022 item categories, analyzed for patterns or relationships between data, and organized to understand the differences between the Indonesian and Singapore curricula based on the completeness of PISA items. The final stage involved evaluating reliability and validity, ensuring the validity of the findings through triangulation and member-checking techniques.

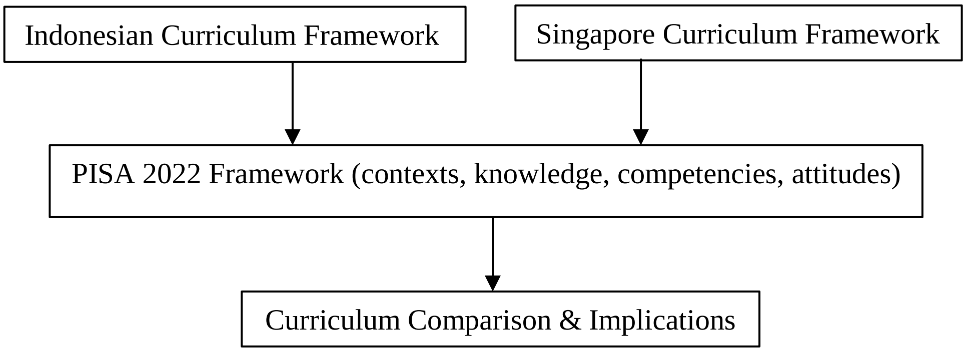

Figure 1. The Framework of This Curricula Comparison Study

RESULTS

This study aims to identify the differences and similarities between the two curricula in supporting the development of students' science literacy and to provide implications for improving science curricula. This study uses the PISA 2022 framework as an external basis for assessing educational performance in both countries (OECD, 2022). The primary focus identified in the PISA 2022 science literacy framework includes context, knowledge, competencies, and attitudes (OECD, 2022).

Indonesian Curriculum Framework

Indonesia utilizes the Merdeka Curriculum, which is based on the Pancasila student profile, as the foundation for the learning process, as illustrated in Figure 2. Competencies in the Pancasila student profile include diversity, critical thinking, independence, faith and devotion to God Almighty, noble character, creativity, and cooperation (KemendikbudRistek, 2024). The science curriculum framework in Indonesia is designed to develop students' scientific understanding and skills by integrating local wisdom. Given Indonesia's status as a multicultural country, integrating local wisdom into the curriculum is an interesting topic (Muyassaroh et al., 2024). The Merdeka Curriculum at the junior high school level consists of one phase, specifically Phase D, for grades 7, 8, and 9 (Ningsih, 2023).

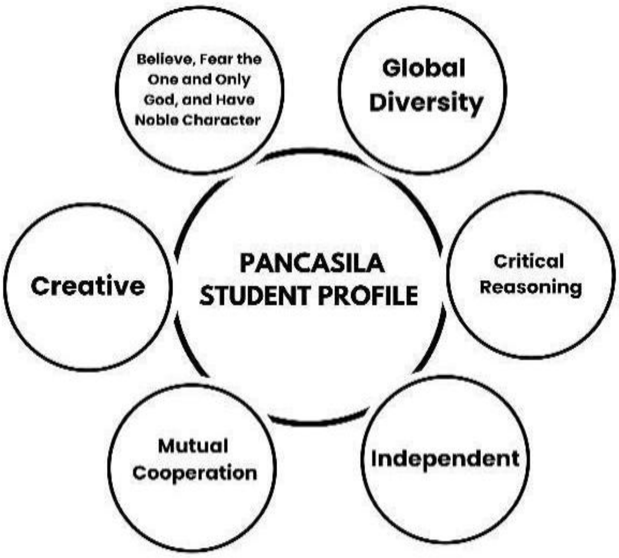

Figure 2. Pancasila Student Profile (Kemendikbud Ristek, 2024)

The learning objectives of integrated science in Indonesia align with the Pancasila student profile, specifically to develop curiosity and interest in natural phenomena and understand their mutual influence on human life (Kemendikbudristek, 2024). Being able to think actively in protecting and preserving the environment and managing natural resources well (Kemendikbudristek, 2024). Being able to develop inquiry process skills to identify, formulate, and solve problems through concrete actions (Kemendikbud Ristek, 2024) and being able to contribute to solving personal and environmental problems (Kemendikbudristek, 2024) and being able to develop knowledge and understanding of concepts in science and apply them in daily life (Kemendikbudristek, 2024).

In the Merdeka Curriculum, science learning outcomes are divided into two main elements, namely science content and science process skills (Aisah & Agustini, 2024). Each element is applied to four content areas: living things, substances and their properties, energy and its transformations, and the Earth and space. Understanding scientific concepts requires the ability to think systematically, comprehend concepts and their relationships, including causal relationships, as well as the hierarchical levels of concepts within biology, physics, chemistry, Earth, and space (Kemendikbudristek, 2024).

Process skills based on the Pancasila learner profile, using an inquiry approach, include observing, asking questions, predicting, planning, conducting investigations, processing data and information, analyzing, evaluating, and reflecting, as well as communicating results (Kemendikbudristek, 2024). This study aims to identify the differences and similarities between the two curricula in supporting the development of students' science literacy and to provide implications for improving science curricula. This study uses the PISA 2022 framework as an external basis for assessing educational performance in both countries (OECD, 2022). The primary focus identified in the PISA 2022 science literacy framework includes context, knowledge, competencies, and attitudes (OECD, 2022).

Singapore Curriculum Framework

The science curriculum framework in Singapore encourages science education to provide a strong foundation for life, learning, citizenship, and work, as shown in Figure 3. Science learning materials in Singaporean secondary schools are categorized into three levels: G1, the easiest level; G2, the standard level; and G3, the most challenging level (Tan, 2024). The goal of the science curriculum is to encourage and nurture students to master science literacy, make decisions, and take responsible action in their daily lives. The science curriculum also facilitates students by providing the scientific foundations for STEM innovation (MOE, 2024).

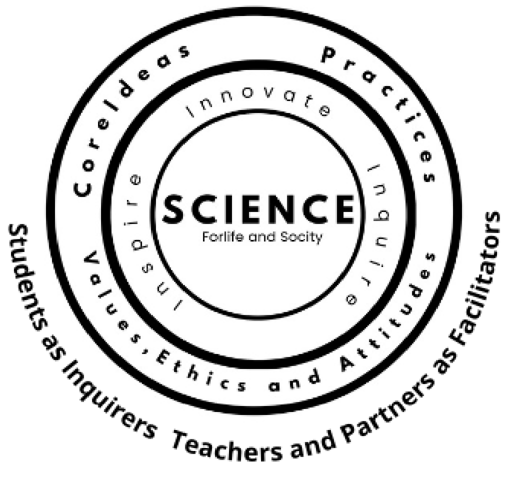

Figure 3. Singapore Curriculum Framework (MOE, 2024)

There are three core elements in the Singapore science curriculum framework: inspire, inquire, and innovate. These three core elements are used to achieve the vision, which is for students to be inspired and enthusiastic about learning science to help solve global challenges and pursue careers in the field of science. Second, students possess a strong foundation and enthusiasm for scientific inquiry, and they are confident in applying scientific principles by critically evaluating ideas based on scientific evidence. Third, students apply science to innovate in solving real-world problems and contribute to STEM research, innovation, and entrepreneurship (MOE, 2024). STEM application is suitable for science learning because STEM-based learning can train students to apply their knowledge to create designs as a form of problem-solving (Astuti et al., 2023).

The outer circle represents the strong foundations of science, encompassing core ideas, practices, values, ethics, and attitudes (MOE, 2024). Core ideas make science learning coherent and meaningful, connecting conceptual fields (physics, chemistry, biology) (MOE, 2024). Scientific practices include ways of thinking and behaving in science (WOTD), understanding the nature of scientific knowledge (NOS), and connecting science, technology, society, and the environment (STSE) (MOE, 2024). Values, ethics, and attitudes in science are employed to consider the ethical implications of science (MOE, 2024). The aim of incorporating scientific values into the curriculum is to cultivate students' ethical values in society. Science education prepares students to behave ethically in society and participate in environmental issues (Monsalve-Silva et al., 2025).

The Singapore science curriculum places students as researchers in their learning process and scientific inquiry, while teachers support and facilitate students' learning experiences (Yeo & Tan, 2021). Teachers also encourage students' curiosity; if teachers present learning that stimulates curiosity, students will be more active in asking questions, observing, and seeking answers to the phenomena they encounter (Rahmadhani, 2025).

Curriculum Comparison between Indonesia and Singapore based on the PISA 2022 Framework

This study uses the PISA 2022 science framework as a reference for comparing the science curricula of Indonesia and Singapore. PISA assesses scientific knowledge in contexts relevant to the curricula taught in participating countries. The PISA 2022 framework is analyzed based on four components: context, competencies, knowledge, and attitudes (OECD, 2022a). Each component of the Indonesian and Singaporean curricula will be compared with the PISA 2022 framework. The tables in this study summarize the results of coding and interpreting the curriculum documents of both countries. A critical analysis of the coverage of context in the Indonesian and Singapore curricula based on the PISA 2022 framework is presented in Table 1.

Table 1. Comparison of Indonesian and Singapore Curricula Contexts based on PISA 2022 Framework.

Context of PISA 2022	Indonesian	Singapore	Analytical Summary
Health and disease	All subtopics not covered	Covered at all G1/G2/G3 grades	Singapore has a more comprehensive health and disease context
Natural resources	All subtopics not covered	Covered at all G1/G2/G3 grades	Singapore is well-equipped on the topic of sustainability and resources
Environmental quality	All subtopics covered	Covered at all G1/G2/G3 grades	Both countries have the exact contextual requirements, but the depth and methods of teaching can vary
Hazards	All subtopics covered	Covered at all G1/G2/G3 grades	Both countries have the exact contextual requirements, but the depth and methods of teaching can vary
Frontiers of science and technology	Most subtopics are not covered	Mostly covered at the G1/G2/3 grades	Singapore is more responsive to technology and innovation

A comparison of the Indonesian and Singaporean curricula based on the PISA 2022 framework reveals that the Singapore curriculum aligns more closely with the PISA 2022 context in the field of science. All five topics are covered in the Singaporean curriculum, both in Grade 1 and in Grades 2 and 3. Meanwhile, Indonesia only covers two topics comprehensively in its science curriculum, namely environmental quality and hazards. A significant difference is evident in the Singapore curriculum guidelines, which provide detailed information on each context, whereas the Indonesian guidelines only cover topics in general terms. Furthermore, a comparison of the competencies of the Indonesian and Singapore curricula, based on PISA 2022, is presented in Table 2.

Table 2. Comparison of Indonesian and Singapore curricula Competencies based on PISA 2022.

PISA 2022 Scientific Competencies	Indonesian	Singapore	Analytical Summary
Explaining phenomena scientifically	All subcompetencies are covered	All subcompetencies are covered the G1/G2/G3 grades	Both curricula support basic scientific explanation skills
Evaluate and design scientific investigations	Most subcompetencies are covered	Most subcompetencies are covered at the G1/G2/G3 grades	Both curricula need to equip students in the design and evaluation of scientific experiments more systematically
Interpreting scientific data and evidence	All subcompetencies are covered	All subcompetencies are covered the G1/G2/G3 grades	Both curricula strongly support data literacy and the ability to robustly evaluate evidence-based arguments

A comparison of competencies between the Indonesian and Singapore curricula reveals similar results, namely that they meet most of the competencies outlined in the PISA 2022 framework. Neither curriculum yet meets the competencies in evaluating and designing scientific investigations. Inquiry-based learning in Indonesia and Singapore has not been well-formulated to distinguish and evaluate scientific questions, nor to assess the reliability and objectivity of data. However, there are differences in learning design between Singapore and Indonesia. In the Indonesian curriculum guidelines, teachers are given the freedom to design their learning processes, whereas in Singapore, learning outcomes are predetermined as a reference for teachers in their teaching. The advantage of the Indonesian curriculum is that teachers can design learning creatively and innovatively, adapting it to the individual needs of each student and their specific environment. The disadvantage of the Indonesian curriculum is that there is no guarantee that all teachers have the same understanding of learning outcomes, so ideal learning may not always be achieved. A comparison of the science content knowledge in the Indonesian and Singapore curricula, based on PISA 2022, is presented in Table 3.

Table 3. Comparison of Indonesian and Singapore curricula science content knowledge based on PISA 2022.

Knowledge of the content of science	Indonesian	Singapore	Analytical Summary
Physical Systems	All subtopics covered	All subtopics are covered at the G1/G2/G3 grades	Both curricula cover physical systems
Living Systems	All subtopics covered	All subtopics are covered at the G1/G2/G3 grades	Both curricula cover living system material
Earth and Space Systems	Most subtopics are covered	Most subtopics are not covered.	Singapore shows a massive gap in the teaching of geosciences and astronomy

A comparison of the content of the Indonesian and Singapore curricula reveals significant differences. The Singaporean science curriculum does not cover topics related to the Earth and space systems, which require specialized knowledge, whereas the Indonesian curriculum includes several subtopics related to these topics. However, the Singaporean curriculum covers more complex topics related to physical systems and living things than the Indonesian curriculum, with a more holistic approach to subtopics. Although both have similar content, the implementation of the Singaporean curriculum contains more complex and detailed content. Additionally, in the Singaporean curriculum, the G2/G3 group has broader and deeper content compared to the G1 group. A comparison of procedural knowledge between the Indonesian and Singapore curricula, based on PISA 2022, is presented in Table 4.

Table 4. Comparison of Procedural Knowledge Indonesian and Singapore Curricula based on PISA 2022.

	Procedural Knowledge	Indonesian	Singapore	Analytical Summary
a.	The concept of variables, including dependent, independent and control variables	Covered	Covered at all G1/G2/G3 grades	Both curricula cover explicitly and systematically
b.	Concepts of measurement, e.g. quantitative (measurements), qualitative (observations), the use of a scale, categorical and continuous variables	Covered	Covered at all G1/G2/G3 grades	Both curricula are aligned with the standards of scientific experimentation
c.	Ways of assessing and minimising uncertainty, such as repeating and averaging measurements	Not covered	Covered at all G1/G2/G3 grades	The Indonesian curriculum has not addressed this aspect, whereas the Singapore Curriculum has fully covered it
d.	Mechanisms to ensure the replicability (closeness of agreement between repeated measures of the same quantity) and accuracy of data (the closeness of agreement between a measured quantity and a true value of the measure	Not covered	Covered at all G1/G2/G3 grades	The Indonesian curriculum lacks scientific accuracy and needs to strengthen its foundational concepts
e.	Common ways of abstracting and representing data using tables, graphs and charts, and using them appropriately	Covered	Covered at all G1/G2/G3 grades	Both curricula are adequate in the processing and visualization of scientific data
f.	The control-of-variables strategy and its role in experimental design or the use of randomised controlled trials to avoid confounded findings and identify possible causal mechanisms	Not covered	Covered at all G1/G2/G3 grades	The Singapore curriculum trains experimental design skills more systematically than the Indonesian curriculum
g.	The nature of an appropriate design for a given scientific question, e.g. experimental, field-based or pattern-seeking	Covered	Covered at all G1/G2/G3 grades	Both curricula are based on a scientific thinking approach with an experimental design

The results of a comparison of procedural knowledge in the Indonesian and Singapore curricula based on PISA 2022 show that the Singapore curriculum has more comprehensive steps in the learning process than the Indonesian curriculum. The Indonesian curriculum only covers four procedures, while the Singapore curriculum covers all procedures at the G1 and G2/3 levels. The procedures that are not yet complete in the Indonesian curriculum are how to deal with data uncertainty and ensure data replication and accuracy. The comparison of epistemic knowledge between the Indonesian and Singaporean curricula, based on PISA 2022, is presented in Table 5.

Table 5. Comparison of Indonesian and Singapore Curricula epistemic knowledge based on PISA 2022.

Epistemic knowledge	Indonesian	Singapore	Analytical Summary
Basic Concepts of Science	All subtopics covered	All subtopics are covered at the G1/G2/G3 grades	Both curricula cover core science concepts, including the nature of theory, the purpose of science, and various types of scientific reasoning
Justification and Scientific Reasoning	Some subtopics covered	All subtopics are covered at the G1/G2/G3 grades	Singapore's curriculum covers scientific knowledge justification more comprehensively, whereas Indonesia has not covered aspects such as measurement error
Scientific Research and Methodology	Most subtopics are covered	All subtopics are covered at the G1/G2/G3 grades	Both address scientific inquiry and hypothesis testing, but Singapore is stronger in the use of scientific models and collaboration
Social and Ethical Dimensions in Science	Not all subtopics are covered	All subtopics are covered at the G1/G2/G3 grades	Singapore emphasizes the role of science in addressing social issues and the importance of scientific values, such as publication and peer review, which are not yet evident in M01

A comparison of epistemic knowledge in the Indonesian and Singapore curricula, based on PISA 2022, reveals that the Singapore curriculum's epistemic knowledge is more comprehensive than that of the Indonesian curriculum, particularly in terms of the role of constructs and features in justifying the knowledge produced by science. The Singapore curriculum integrates epistemic knowledge into every learning topic using a STEM approach. In Indonesia, epistemic knowledge is applied to process skills to support scientific understanding. A comparison of attitudes toward science in the Indonesian and Singapore curricula, based on the 2022 PISA results, is presented in Table 6.

Table 6. Comparison of Attitudes Towards Science Indonesian and Singapore Curricula based on PISA 2022.

Attitudes towards science in PISA 2022	Indonesian	Singapore	Analytical Summary
a. Interest in science	Covered	Covered at all G1/G2/G3 grades	Both curricula explicitly encourage students' interest in science
b. Valuing scientific approaches to enquiry	Covered	Covered at all G1/G2/G3 grades	Both curricula demonstrate an appreciation for the scientific process as a means of acquiring knowledge
c. Environmental awareness	Covered	Covered at all G1/G2/G3 grades	Curricula in both countries include awareness of environmental issues as part of science education

A comparison of attitudes toward science between the Indonesian and Singapore curricula based on PISA 2022 shows similar results. Both curricula promote attitudes toward science, including interest in science, appreciation of the scientific approach to inquiry, and environmental awareness. Attitudes toward science in the Indonesian curriculum are addressed through process skills, whereas the Singaporean curriculum is implemented through STEM-based learning. The comparison results indicate that the Singaporean curriculum has more PISA items than the Indonesian curriculum. Therefore, a more in-depth study of these comparison results is required.

DISCUSSION

Framework of Science Curriculum in Indonesia and Singapore

The Merdeka Curriculum implemented in Indonesia emphasizes the application of Pancasila values in every aspect of learning (Lukitoyo et al., 2023). This curriculum is designed to develop students' competencies in a balanced manner by integrating scientific knowledge and scientific process skills (inquiry). The primary focus of this curriculum is to cultivate students' curiosity about natural phenomena while promoting an understanding of humanity's role in preserving the environment and natural resources. In science education, Indonesia also integrates local wisdom as part of the educational process, reflected in four main topics: living things, matter and its properties, energy and its changes, and the earth and space. The Merdeka Curriculum aims to enable students to understand and apply science in their daily lives, grounded in strong national values (Ndari & Mahmudah, 2023; Alifiyah et al., 2024).

The Singapore science curriculum emphasizes the development of a strong foundation of scientific knowledge and practical skills that can be applied in daily life. The learning materials in Singapore categorize the science curriculum into three levels: G1 (basic level), G2 (standard level), and G3 (advanced level), which are designed to cater to the needs and abilities of students (MOE, 2024a; MOE, 2024b). The three main principles in the Singapore curriculum are inspiration, inquiry, and innovation (Deng & Gopinathan, 2006). These principles aim to inspire students, foster a spirit of scientific inquiry, and encourage innovation through the Inspire, Inquire, Innovate approach to learning. The curriculum also emphasizes the importance of ethical values in science, including respect for diversity and consideration of the social and environmental implications of scientific discoveries. Singapore emphasizes a more in-depth approach to developing critical and creative thinking skills in students (Yeo & Tan, 2021; Teig et al., 2022).

Curriculum Comparison

A comparison between the Indonesian and Singapore curricula, in the context of the 2022 PISA results, reveals significant differences (OECD, 2022b). The Indonesian science curriculum tends to be more limited, covering only two main topics, namely environmental quality and natural hazards, with a focus on understanding ecological quality and the impact of disasters. In contrast, the Singaporean curriculum covers a broader range of topics, including health issues, natural resources, and natural disasters, with more detailed discussions at the basic level (G1) and intermediate/advanced levels (G2/3) (MOE, 2024a, 2024b). In addition, Singapore has more detailed curriculum documentation, providing clear classroom teaching guidelines and enabling teachers to deliver material in a more structured and consistent manner. In Indonesia, although there are general guidelines, the delivery of material is more open to interpretation, providing flexibility but risking inconsistency in curriculum implementation between schools (Nasution et al., 2022).

Both countries face similar challenges in developing student competencies, particularly in evaluating and designing scientific investigations. The curricula in Indonesia and Singapore have not yet fully developed high-level scientific skills in formulating scientific questions and evaluating data objectively and reliably. However, Singapore excels in terms of learning outcomes, where learning objectives are clearly defined and measurable, providing concrete guidelines for teachers in designing instruction (MOE 2024a; Deng & Gopinathan, 2006). In Indonesia, although teachers are given freedom to innovate in designing instruction, this can lead to variations in the understanding and application of scientific competencies across schools.

In terms of science content knowledge, there are significant differences between the two countries. The Indonesian curriculum encompasses several subtopics related to Earth and space systems, including the structure and energy of the Earth system and the changes occurring within it (Kemendikbudristek, 2022; Fadilah & Fitriyani, 2024). However, not all relevant topics are discussed in depth. On the other hand, the Singaporean curriculum does not emphasize content related to Earth and space systems. However, it focuses more on physical systems and living organisms, providing more detailed and comprehensive explanations. Singapore emphasizes the development of more in-depth knowledge at the advanced level (G2/3) (MOE, 2024a; MOE, 2024b). The Indonesian approach tends to present topics in a general manner, which does not provide students with a deep understanding of science.

In terms of procedural knowledge, there are essential differences between the two curricula. The Indonesian curriculum covers several topics related to measurement, variables, and methods for assessing uncertainty in experiments. However, the discussion of scientific procedures, especially in ensuring replication and data accuracy, has not been discussed in depth. In contrast, Singapore has a more structured and detailed approach to teaching scientific methods, including assessing and minimising measurement uncertainty and ensuring data accuracy. This indicates that Singapore places a greater emphasis on developing students' scientific skills within the context of experiments and scientific procedures, which are crucial for establishing a solid understanding of science (MOE, 2024a; Yeo & Tan, 2021).

A comparison of attitudes toward science in the Indonesian and Singapore curricula shows a similar level of completeness. The Indonesian curriculum integrates attitudes toward science into the learning process, with a focus on process skills. The Singapore curriculum applies attitudes toward science in every step of the learning process and integrates them with STEM-based learning. Both countries share a similar perspective on scientific attitudes in education, including an interest in science, a value for the scientific approach to inquiry, and environmental awareness. The primary difference in their implementation lies in the fact that the Singapore curriculum emphasises the development of 21st-century skills, whereas the Indonesian curriculum emphasises the integration of Pancasila values (Kemendikbudristek, 2022; Yeo & Tan, 2021).

A comparison between the Indonesian and Singaporean science curricula highlights significant differences in the structure and implementation of learning. Singapore has a more detailed and structured curriculum, resulting in more consistent and in-depth teaching. On the other hand, Indonesia gives teachers more freedom to design innovative learning, although this has the potential to cause inconsistencies in its implementation. Although both curricula face similar challenges in developing scientific skills, Singapore is more advanced in its emphasis on structured scientific competencies and more in-depth data evaluation. Both countries still need to strengthen the development of students' scientific inquiry and experimental science skills to prepare them for global challenges in science and technology (Teig et al., 2022).

CONCLUSION AND IMPLICATIONS

This study found that both Indonesian and Singapore science curricula have accommodated most of the dimensions covered in the PISA 2022 framework, especially in terms of scientific competence, content knowledge, and attitudes towards science. However, in-depth analysis reveals that the Singapore curriculum is generally more systematic, explicit, and structured in covering all PISA indicators, ranging from real-life contexts to procedural and epistemic knowledge, as well as STEM implementation.

The Indonesian curriculum provides more coverage of geoscience and space content, allowing teachers to exercise creativity in designing contextualised learning that meets local needs. However, this flexibility is also a challenge because not all teachers have a standardised guide that is consistent with the expected learning outcomes. In contrast, the Singapore curriculum sets more measurable and targeted learning outcomes at each level of education (G1, G2, G3), thus supporting equity in education quality and readiness for international assessments such as PISA.

A fundamental weakness in the Indonesian curriculum lies in the lack of critical scientific procedures, such as variable control, data uncertainty, and the accuracy of experimental results, which potentially hinders the development of students' higher-order thinking skills. Meanwhile, the Singapore curriculum excels in the epistemic and socio-ethical integration of science, strengthening students' understanding of the nature of science and its application in society. These results emphasise the importance of adapting national curricula to international standards without neglecting the local context and flexibility of learning, to improve the overall quality of science education. The findings can enrich the comparison of science curricula between the two countries, highlighting the need for further research that directly observes the implementation of the curriculum in the classroom.

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Fostering Scientific Creativity in Primary Students through Outdoor STEM Education: A Case Study in Phuket Province

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Abstract. This research aimed to (1) examine Grade 4 students' scientific creative thinking skills before and after participating in outdoor STEM learning based on the context of Phuket Province, (2) develop these skills through local context-based activities, and (3) identify effective practices for organizing such learning experiences. The study involved 22 Grade 4 students from a school in Phuket during the second semester of the 2024 academic year, using a classroom action research approach with purposive sampling. Three outdoor STEM activities were implemented: eco-printing with Southern Thai plants, tie-dye using Sino-Portuguese patterns, and making "Apong" coconut milk desserts with natural dyes. A scientific creative thinking test based on Guilford's theory was used to assess four components: originality, fluency, flexibility, and elaboration. Findings revealed significant improvements in students' scientific creative thinking, particularly in fluency and elaboration. Students displayed enhanced creative behavior, confidence in presenting ideas, and the ability to solve problems using diverse, well-reasoned solutions. They creatively applied local knowledge to design unique patterns and innovate with natural color mixtures. The activities also promoted teamwork and 21st-century problem-solving skills. Post-test scores were significantly higher than pre-test scores at the 0.05 level, indicating the effectiveness of outdoor STEM learning in fostering scientific creativity through real-life context integration.

Keywords: Scientific Creative Thinking Skills, Outdoor STEM Learning, Context

INTRODUCTION

Phuket, the largest island province in southern Thailand, is internationally renowned for its tourism, natural beauty, and cultural diversity. With attractions such as Patong, Kata, and Karon beaches, along with landmarks like the Big Buddha, Mai Khao Beach, and the historic Sino-Portuguese architecture of Phuket Old Town, the province reflects a vibrant blend of Thai and Chinese cultures, especially during festivals like the Vegetarian Festival. Its economy heavily relies on tourism, and its rich cultural identity is showcased through distinctive local dishes such as *Kanom Apong* and *Oh Aew*.

Given Phuket's unique context, there is a pressing need to develop science education that reflects the province's identity and fosters students' appreciation of their local environment. Active, hands-on, and outdoor-based learning experiences are essential to connect students with real-world contexts and cultivate problem-solving skills derived from authentic experiences. This educational approach is aligned with Thailand's National Education Act B.E. 2542 (1999) and its amendments, which emphasize experiential learning, critical thinking, problem-solving, and the application of knowledge to real-life situations. Furthermore, the Revised Basic Education Core Curriculum B.E. 2560 (2017) modernizes science content to develop logical reasoning, ethical decision-making, and technological literacy, aiming to equip students with the skills necessary for navigating complex social and environmental challenges. Scientific creative thinking is a fundamental competency underpinning scientific literacy. It enables learners to discover, apply, and extend knowledge meaningfully. Thailand's second decade of educational reform (2009–2018) emphasized strategies to:

1. Improve quality and educational standards sustainably.
2. Expand equitable access to lifelong learning.
3. Promote societal participation in educational management (Patcharee Nakphong, 2019).

The Office of the National Economic and Social Development Council (2016) emphasized the urgent need to develop skills aligned with labor market demands and 21st-century competencies, particularly analytical thinking and creativity. In response, Thailand's Education 4.0 vision prioritizes cultivating learners who demonstrate independent thinking, creativity, and innovation. Supporting this direction, Supakorn Buasai (2015) cited an OECD labor market survey indicating that creativity and analytical skills are among the most highly sought-after attributes by employers. The OECD's decision to incorporate creative and critical thinking assessments into its 2021 international examinations (Isranews Agency, 2015) further underscores the global prioritization of these competencies. Despite their recognized importance, studies suggest a worrying global decline in students' creative abilities. Kim (2011) identified significant decreases in creative thinking scores, attributing this trend to rigid curricula and traditional instructional practices that suppress divergent thinking. Robinson (2011) similarly argued that education systems often prioritize conformity over creativity. In Thailand, Surachai Radakan (2012) highlighted creativity and innovation as vital for survival and competitiveness, serving as the basis for new ideas, inventions, and solutions. Mohammed and Kinyo (2020) also observed that teacher-centered instruction tends to restrict student creativity, fostering imitation rather than originality. The importance of addressing these issues is reflected in Section 24 of the National Education Act B.E. 2542 (1999), which emphasizes that educational activities should be aligned with learners' interests and aptitudes, promote experiential learning, develop independent thinking, and encourage interdisciplinary knowledge integration (Office of the National Education Commission, 1999).

In this national context, STEM education—integrating Science, Technology, Engineering, and Mathematics—has been widely promoted throughout Thailand to build essential 21st-century skills. STEM initiatives have expanded at both national and regional levels through government policies, private sector collaborations, and education reform agendas, notably under the Education 4.0 framework. In southern Thailand, most STEM efforts have been concentrated at the secondary education level, especially in science and technology-based demonstration schools and selective programs. At the primary level, STEM activities have been introduced mainly through pilot projects, teacher development initiatives, and STEM camps organized by institutions such as the Ministry of Education, SEAMEO STEM-ED Center, and local universities. These programs often focus on project-based learning, engineering design, and problem-solving processes.

However, a review of existing literature reveals that systematic research on context-based outdoor STEM education at the primary school level in southern Thailand—particularly in Phuket Province—remains very limited. Most primary-level STEM activities in Thailand have centered around general topics such as basic engineering projects (e.g., bridge construction, water filtration), environmental awareness (e.g., recycling, pollution control), simple robotics, coding, renewable energy, and basic scientific inquiry. These activities are typically conducted in classroom or laboratory settings, with relatively little integration of outdoor learning environments or local cultural and natural resources.

Uniqueness of the Current Study

This study represents the first systematic research in southern Thailand, specifically in Phuket, to integrate contextual outdoor STEM education aimed at developing scientific creative thinking skills among Grade 4 students. Unlike previous STEM initiatives that often-replicated standardized models without adaptation to local contexts, this research:

Utilizes real-world, outdoor settings that reflect Phuket's ecological, cultural, and economic uniqueness. Embeds STEM learning within the local community and environment, through activities such as eco-printing with native plants, traditional Sino-Portuguese tie-dye patterns, and creating natural dyes using local foods. Focuses explicitly on enhancing scientific creative thinking, not merely on scientific knowledge acquisition or technological proficiency. This approach distinguishes the present study from earlier STEM education programs, which predominantly emphasized general content learning without deep cultural or environmental contextualization. Thus, the current research addresses a critical gap by linking scientific creativity development with local identity, place-based learning, and sustainability awareness. Given the absence of prior studies combining outdoor learning, place-based STEM activities, and scientific creative thinking development for primary students in southern Thailand, this research can be considered a pioneering effort.

Creativity Assessment and Need for Innovation

In today's dynamic world, creativity remains a fundamental skill for student success (Beghetto & Kaufman, 2014). Nevertheless, concerns regarding the insufficient development of creativity persist across educational levels. In the context of this study, no systematic measurement of Grade 4 students' creativity skills in Phuket had been conducted before. Therefore, this research constitutes the first attempt to quantitatively and qualitatively assess creativity among this population. A preliminary assessment, based on Guilford's (1950) framework, was conducted prior to the intervention. Quantitative results showed an average creativity score of 41 out of 100, indicating moderate to low levels of creative thinking among students. Qualitative observations further revealed that while students could generate ideas, they struggled with producing original, flexible, and elaborated responses. These findings reinforce the urgent need for innovative educational approaches to foster scientific creativity through context-based outdoor STEM learning. Research supports the notion that science education should actively involve students in inquiry-based, hands-on activities that cultivate scientific process skills and promote meaningful knowledge creation. These approaches are grounded in Constructivist Learning Theory, emphasizing exploration, self-discovery, and investigation (Napaporn Piangduangjai, 2015).

Conclusion, considering the significance of creativity in 21st-century education and the distinctive cultural and environmental context of Phuket, this study aims to develop scientific creative thinking skills among Grade 4 students through outdoor, real-world STEM learning experiences. It seeks to enhance both students' creativity and scientific literacy, while providing teachers with effective strategies to innovate science instruction.

Ultimately, the development of these skills will enable students to solve real-life problems and contribute to the creation of responsible, capable citizens for the future.

Research Objectives

1. To study the scientific creative thinking skills of Grade 4 students before participating in context-based outdoor STEM learning in Phuket Province.
2. To develop scientific creative thinking skills through the implementation of outdoor STEM learning based on the local context of Phuket Province.
3. To enhance the design of outdoor STEM learning based on the context of Phuket Province in a way that promotes scientific creative thinking skills among Grade 4 students.
4. To identify best practices for organizing outdoor STEM learning activities that foster scientific creative thinking skills in Grade 4 students.

RESEARCH METHOFLOGY

Conceptual Framework

This research aims to study the effects of a learning management approach designed to develop analytical thinking and creativity among Grade 4 students. Based on a review of relevant literature and prior studies on learning management, the researcher selected the STEM education model incorporating the Engineering Design Process (Abdulyamin Hayikhader, 2017). This approach encourages students to engage in problem-solving through the integration of four disciplines: Science, Mathematics, Technology, and Engineering, to foster creative thinking (Phassorn Tidma, 2015) among upper primary students. The conceptual framework of the research is illustrated in Figure 1.

Steps of Outdoor STEM Learning
(Institute for the Promotion of Teaching Science and Technology, 2014)
Step 1: Identify the problem
Step 2: Gather information and relevant ideas related to the problem
Step 3: Design a method for solving the problem
Step 4: Plan and implement the solution
Step 5: Test, evaluate, and revise the solution or the product
Step 6: Present the solution, the outcome, or the final product

→

Creativity
Fluency
Flexibility
Elaboration,
Originality

Figure 1. Research Conceptual Framework.

Research Methodology

The research design for this study is Classroom Action Research. This research adopts a pragmatic paradigm, which emphasizes knowledge and reality that help achieve life goals and improve life. It focuses on real-life experiences and best practices related to the management of learning that promotes the engineering design process. The study is mixed-methods research with an embedded design. The researcher primarily collects and analyzes quantitative data, while qualitative data collection and analysis are secondary. The results obtained are then interpreted to summarize findings related to the engineering design process through Outdoor STEM learning.

For this research, there are 5 cycles of CAR (Classroom Action Research): CAR 1: Preparation and Review of Prior Knowledge CAR 2: Learning Management Plan 1 CAR 3:

Learning Management Plan 2 CAR 4: Learning Management Plan 3 CAR 5: Reflection and Measurement of Scientific Creative Thinking Skills (Summary)

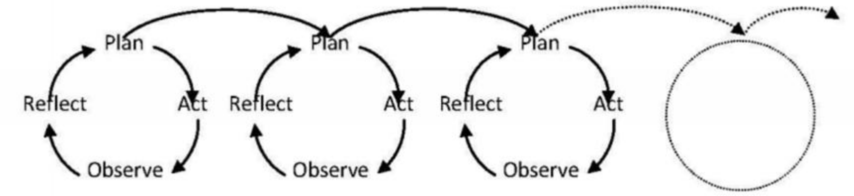

Figure 2. The Stages of Classroom Action Research (Kemmis & McTaggart, 1988)

Scope of the Research

Research Group

The research group used in this study consists of 22 students from Grade 4 at a school in Phuket, during the second semester of the 2024 academic year. The students were selected using purposive sampling, with the following criteria:

1. Students in Grade 4 who are enrolled in the science course during the second semester of the 2024 academic year.
2. Students who volunteered and were willing to participate in the research.
3. Students for whom the researcher is the instructor for the science course.

Content

In this research, outdoor STEM learning was implemented outside the classroom according to the context of Phuket. The content covered the science and technology learning area, subject code W 14101, in Chapter 1 for Grade 4 students, focusing on materials and matter, with a total teaching time of 16 hours.

Duration

In this research, outdoor STEM learning outside the classroom was implemented with Grade 4 students during the second semester of the 2024 academic year. The teaching time was 3 hours per week for 7 weeks, totaling 16 hours in-class, along with 20 hours of self-directed learning. The period of the study was from December 2024 to January 2025.

Table 1. The details of each learning plan related to activities and time.

Learning Standards	Indicators	Learning Plan	Time (hours)
W 2.1 Understand the properties of matter, the components of matter, the relationship between the properties of matter and the structure and forces between particles, the principles and nature of the change of state of matter, the formation of solutions, and the occurrence of chemical reactions.	**P.2/1** Compare the water absorption properties of materials using empirical evidence and identify the application of the water absorption properties of materials in creating objects for daily life.	1.Eco-print with Southern Botany - 6 hours	6
		2. Tie-dye fabrics with Sino-Portuguese design - 6 hours	6
		3. Apoong coconut milk from natural dyes - 4 hours	4

In each lesson plan, such as Lesson Plan 1: "Eco-Print with Southern Botany," the teacher initiates the session by establishing a relaxed and supportive atmosphere, creating a positive learning environment. Learning beyond the classroom setting offers an invaluable opportunity to nurture students' creativity and enhance their connection to the surrounding natural world. As part of Step 1: Identifying the Problem, students are introduced to a real-world issue scenario relevant to their local context to spark inquiry and investigation.

For Lesson Plan 1, students are presented with the issue:
"How can we creatively utilize the natural plant diversity of our local environment to design eco-friendly products that reflect the unique identity of southern Thailand?"

This problem scenario integrates indicators from all four STEM subjects:

Science: Understanding plant properties, pigments, and ecosystems.
Technology: Exploring eco-printing techniques and materials.
Engineering/Occupational: Designing and optimizing the eco-print process (e.g., how to apply pressure, moisture, and heat effectively).
Mathematics: Measuring leaf sizes, calculating fabric dimensions, and timing the steaming/dyeing process.

The "Walking Map" activity is employed to allow students to explore and survey natural resources in the community, collecting data on local flora that could be used in the eco-printing process.

Similarly, in Lesson Plan 2: "Tie-Dye Fabrics with Sino-Portuguese Design" (6 hours), students are tasked with the scenario:
"How can we preserve and modernize traditional Sino-Portuguese designs through innovative fabric dyeing techniques using local knowledge and resources?"

STEM integration in this lesson includes:

Science: Investigating chemical reactions between natural dyes and fabrics.
Technology: Applying techniques for dye fixing and colorfastness.
Engineering/Occupational: Designing patterns and engineering a dyeing process that achieves aesthetic and durable results.
Mathematics: Creating geometric designs, calculating proportions of dye mixtures, and measuring symmetry in patterns.

In Lesson Plan 3: "Apoong Coconut Milk from Natural Dyes" (4 hours), students explore the issue:
"*How can we innovate traditional Apoong desserts by using natural dyes to create visually appealing and environmentally friendly food products?"*

This integrates:
Science: Understanding chemical properties of natural colorants and their interaction with food ingredients.
Technology: Applying techniques for safe and effective food coloring.
Engineering/Occupational: Modifying recipes and cooking methods to maintain color stability and texture.
Mathematics: Measuring ingredient quantities accurately and adjusting proportions based on experimental outcomes.

Research Data Collection Instruments include:

1. Creativity Skills in Science Assessment - Topic: Materials and Matter (Pre- and Post-Learning). The total teaching time is 16 hours, covering situations or scenarios occurring within the context of Phuket, combined with open-ended questions.

2. STEM Activity Sheets - These focus on creativity skills in science as part of the learning plans for students during the learning activities. They include questions aligned with the creativity skills in science, used to collect research data during the learning process by categorizing answers according to specified criteria.

Development and Evaluation of the Quality of Research Instruments

1. Steps in Creating the STEM Learning Plan Outside the Classroom Based on the Context of Phuket, Topic: Materials and Matter

1.1 Review relevant documents and research related to the development of creativity skills in science by using an integrated learning model that combines scientific knowledge, technology, engineering design processes, and mathematics (STEM Education). This will serve as a guideline for structuring the content and activities appropriately.

1.2 Study the content details used in this research from the 4th-grade science textbook, part of the science learning area, according to the Basic Education Core Curriculum B.E. 2551 (Revised in 2017).

1.3 Study the principles, concepts, and theories related to the integration of scientific knowledge, technology, engineering design processes, and mathematics (STEM Education) to apply these principles in creating the STEM learning plan related to the context of Phuket, on the topic of materials and matter. This includes 3 learning plans, totaling 16 hours of science learning, based on the Basic Education Core Curriculum B.E. 2551 (Revised in 2017).

1.4 Present the learning plans created by the researcher to 3 experts for evaluation of the alignment between the learning plans and the learning objectives. The evaluation is done using the following scale: +1 indicates certainty that the learning plan aligns with the learning objectives, 0 indicates uncertainty about alignment, and -1 indicates certainty that the learning plan does not align with the learning objectives.

1.5 The researcher revises and adjusts the learning plans according to the feedback from the experts.

1.6 Implement the revised and appropriately adjusted learning plans with a target group like the research group.

2. Steps in Developing Scientific Creativity Skills

2.1 Study documents, academic articles, collect data, and analyze research studies related to creativity skills.

2.2 Create a conceptual framework to measure scientific creativity skills.

2.3 Develop a tool to measure scientific creativity skills, which involves answering questions based on given situations, and establish criteria for evaluating scientific creativity skills.

2.4 Present the developed tool for measuring scientific creativity skills and the evaluation criteria to experts for validation.

2.5 The researcher revises and adjusts the tool for measuring scientific creativity skills and the evaluation criteria based on the experts' recommendations.

2.6 Implement the revised tool for measuring scientific creativity skills with the target group.

DATA COLLECTION PROCESS

1. Select 4th-grade students, chosen through purposive sampling, from one classroom with a total of 22 students.
2. Conduct a pre-test with the research group using the researcher-developed scientific creativity skills measurement tool to categorize the responses and present the data.

3. Clarify the learning process and introduce the learning plan using the STEM (Science, Technology, Engineering, and Mathematics) integrated approach to ensure students understand and can participate in the learning process and achieve the learning objectives.

4. The researcher conducts the learning process with the study group, taking the role of instructor and using the STEM learning plan on the topic of materials and matter. This follows the 4 stages of classroom action research: planning, acting, observing, and reflecting. This process is carried out in 3 action cycles with 4th-grade students at a school in Phuket, during the second semester of the 2024-2025 academic year. A total of 22 students from one class were selected using purposive sampling. The total teaching time is 16 hours.

DATA ANALYSIS

This research is a Classroom Action Research, involving both qualitative data and quantitative data. Therefore, content analysis and statistical analysis methods were used. The researcher analyzed the data obtained from various tools as follows:

The scientific creativity skills measurement tool consists of open-ended questions based on the content of the lessons, divided into two sets (pre-test and post-test), covering all four indicators: 1) Originality, 2) Flexibility, 3) Fluency, 4) Elaboration.

Each set of the scientific creativity skills measurement tool contains questions that assess the indicators related to the topic of materials and matter to measure the abilities before and after the learning process. The tool was validated for content validity by 3 experts and was pilot tested (try out) with 10 students like the target group to establish scoring criteria for evaluating responses that demonstrate scientific creativity skills.

RESEARCH FINDING

1. The development of scientific creativity skills of Grade 4 students before participating in the STEM-based outdoor learning program in the context of Phuket

The study on the development of scientific creativity skills related to the topic "Materials and Matter" of Grade 4 students, before applying the STEM-based outdoor learning approach in the context of Phuket, which included six steps: 1) Identifying the problem, 2) Collecting data and ideas related to the problem, 3) Designing a solution, 4) Planning and implementing the solution, 5) Testing and evaluating, 6) Presenting the results. The findings on the development of scientific creativity skills in the topic "Materials and Matter" included 8 open-ended questions, covering the content of the "Materials and Matter" learning unit. The test was a subjective type, with a full score of 20 points. The results of the scientific creativity skills assessment (including originality, flexibility, fluency, and elaboration) showed that the percentage of students' scores before the learning process was as follows: Students with scores below 5 points: 0.00% Students with scores between 5-9 points: 54.55% Students with scores between 10-14 points: 45.45% Students with scores between 15-20 points: 9.10% As shown in Table 2. A score below 5 points (0-4 points) means that the students have very low or almost no display of creative scientific thinking skills in the topic of materials and matter. A score of 5-9 points means that students have low creative scientific thinking skills and can express some ideas, but they are not comprehensive or diverse. This score range has the highest percentage (54.55%), indicating that most students still require further development in creativity.

Table 2. Percentage distribution of scores for the development of scientific creativity skills in "Materials and Matter".

Score Range	**Number of Students (People)**	**Percentage**
Below 5 points	0	0.00
5-9	12	54.55
10-14	8	36.36
15-20	2	9.10

Figure 3 shows the percentage of scores for the development of creative scientific thinking skills in the topic of materials and matter for Grade 4 students before using outdoor STEM learning activities in the context of Phuket.

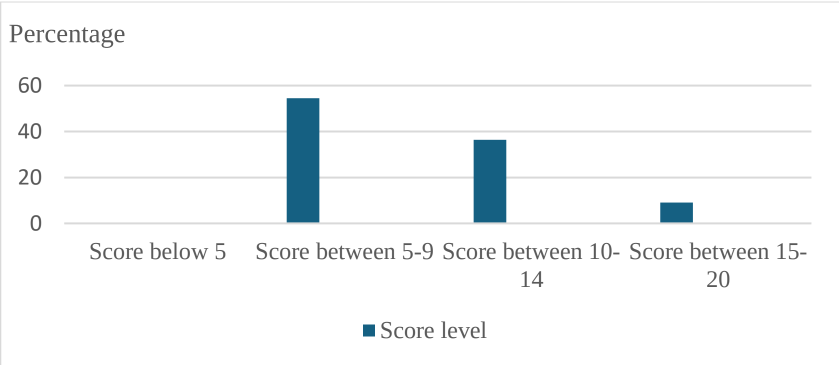

Figure 3. The percentage of scores for the development of creative scientific thinking skills in the topic of materials and matter.

A score of 10-14 points means that students have moderate creative thinking skills and can demonstrate creativity in some respects, such as problem-solving, design, or applying knowledge to new situations.

A score of 15-20 points means that students have high creative thinking skills and can express themselves clearly, covering multiple dimensions such as initiative, flexibility in problem-solving, and creating useful work.

2. The development of scientific creative thinking skills of Grade 4 students during their participation in the STEM-based outdoor learning program in the context of Phuket province. The details of the score levels for measuring creativity in each aspect were assessed through the STEM outdoor learning program in the context of Phuket province, both before and after the learning process. The researcher compared the scores as shown in Tables 3 to 6.

Aspect of Fluency in Thinking

The comparison of creativity skill levels in the aspect of fluency in thinking (Table 3) shows that (before learning), the highest number of students, 11 students (50.00%), answered at level 2. Five students (22.72%) answered at level 1, four students (18.18%) answered at level 3, and two students (9.09%) answered at level 4. No students answered at levels 0 or 5. In the creativity skill level assessment (after learning), the highest number of students, 15 students (68.18%), answered at level 4, and 7 students (31.81%) answered at level 5. No students answered at levels 0, 1, 2, or 3.

Table 3. The comparison of creativity skill levels in the aspect of fluency in thinking before and after participating in the STEM-based outdoor learning program.

Score level	N	Before learning		After learning	
		Number of students	Percentage	Number of students	Percentage
5	22	0	0.00	7	31.81
4	22	2	9.09	15	68.18
3	22	4	18.18	0	0.00
2	22	11	50.00	0	0.00
1	22	5	22.72	0	0.00
0	22	0	0.00	0	0.00

Figure 4 shows the results of the development of scientific creative thinking skills in the aspect of fluency in thinking of Grade 4 students during the STEM-based outdoor learning program in the context of Phuket province.

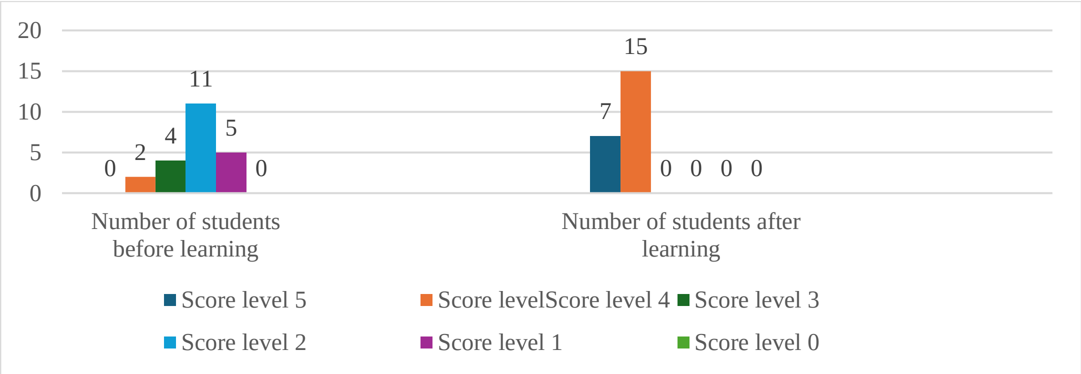

Figure 4. The results of the development of scientific creative thinking skills in the aspect of fluency in thinking during the STEM-based outdoor learning program.

Aspect of Flexibility in Thinking

The comparison of creativity skill levels in the aspect of flexibility in thinking before and after participating in the STEM-based learning program on the topic of materials and matter, as presented in Table 4. The comparison of creativity skill levels in the aspect of flexibility in thinking shows that (before learning), the highest number of students, 15 students (68.18%), answered at level 2. Five students (22.27%) answered at level 3, and two students (9.09%) answered at level 4. No students answered at levels 0, 1, or 5. In the creativity skill level assessment (after learning), the highest number of students, 16 students (72.72%), answered at level 4, and 6 students (27.27%) answered at level 5. No students answered at levels 0, 1, 2, or 3.

Table 4. The comparison of creativity skill levels in the aspect of flexibility in thinking before and after participating in the STEM-based learning program.

Score level	N	Before learning		After learning	
		Number of students	Percentage	Number of students	Percentage
5	22	0	0.00	6	27.27
4	22	2	9.09	16	72.72
3	22	5	22.27	0	0.00
2	22	15	68.18	0	0.00
1	22	0	0.00	0	0.00
0	22	0	0.00	0	0.00

Figure 5 shows the results of the development of scientific creative thinking skills in the aspect of flexibility in thinking of Grade 4 students during the STEM-based outdoor learning program in the context of Phuket province.

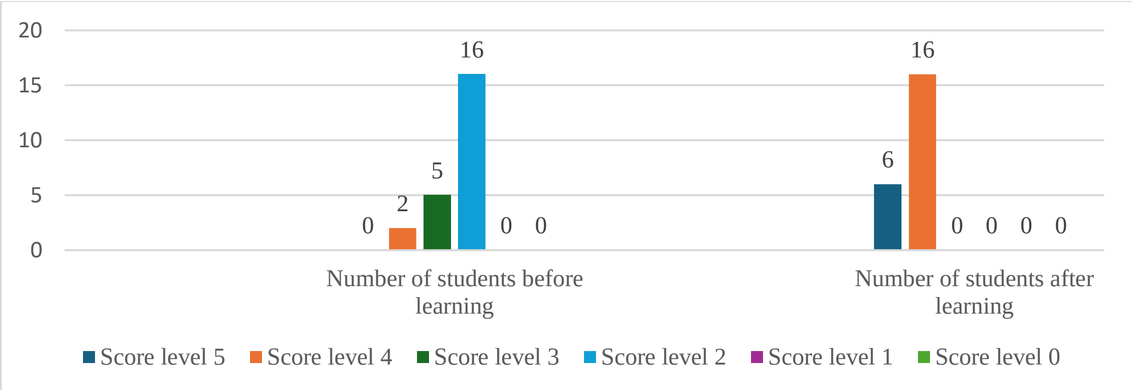

Figure 5. The results of the development of scientific creative thinking skills in the aspect of flexibility in thinking during the STEM-based outdoor learning program.

Aspect of Elaborate Thinking

The comparison of creativity skill levels in the aspect of elaborate thinking before and after participating in the STEM-based outdoor learning program on the topic of materials and matter, as presented in Table 5.

Table 5. The comparison of creativity skill levels in the aspect of elaborate thinking before and after participating in the STEM-based outdoor learning program.

Score level	N	Before learning		After learning	
		Number of students	Percentage	Number of students	Percentage
5	22	0	0.00	4	18.18
4	22	2	9.09	14	63.64
3	22	3	13.64	4	18.18
2	22	14	63.63	0	0.00
1	22	3	13.64	0	0.00
0	22	0	0.00	0	0.00

The comparison of creativity skill levels in the aspect of elaborate thinking from Situation 1 shows that (before learning), the highest number of students, 14 students (63.63%), answered at level 2. Three students (13.64%) answered at level 1, three students (13.64%) answered at level 3, and two students (9.09%) answered at level 4. No students answered at levels 0 or 5. In the creativity skill level assessment (after learning), the highest number of students, 14 students (63.64%), answered at level 4. Four students (18.18%) answered at levels 5 and 3, respectively. No students answered at levels 0, 1, 2, or 3.

Figure 6 shows the results of the development of scientific creative thinking skills in the aspect of elaborate thinking of Grade 4 students during the STEM-based outdoor learning program in the context of Phuket province.

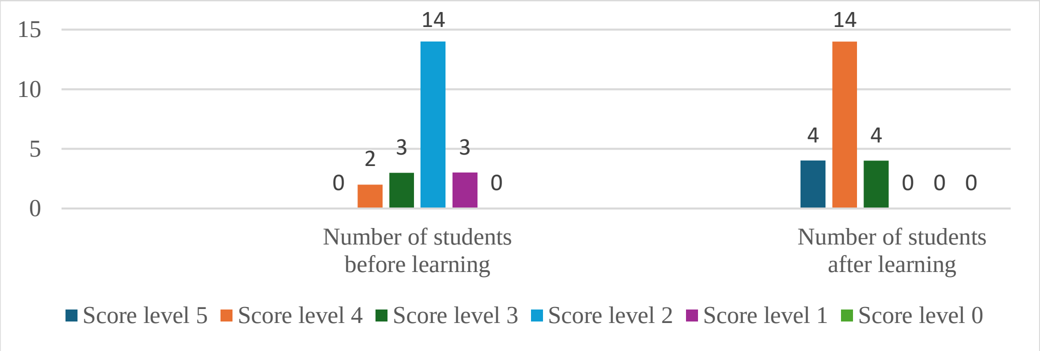

Figure 6. The results of the development of scientific creative thinking skills in the aspect of elaborate thinking during the STEM-based outdoor learning program.

Aspect of Initiative in Thinking

The comparison of creativity skill levels in the aspect of initiative in thinking before and after participating in the STEM-based learning program on the topic of materials and matter, as presented in Table 6.

Table 6. The comparison of creativity skill levels in the aspect of initiative in thinking before and after participating in the STEM-based learning program.

Score level	N	Before learning		After learning	
		Number of students	Percentage	Number of students	Percentage
5	22	1	4.54	4	18.18
4	22	3	13.63	18	81.81
3	22	6	27.27	0	0.00
2	22	8	36.36	0	0.00
1	22	4	18.18	0	0.00
0	22	0	0.00	0	0.00

Table 6, the comparison of creativity skill levels in the aspect of initiative in thinking from Situation 1 shows that (before learning), the highest number of students, 8 students (36.36%), answered at level 2. Six students (27.27%) answered at level 3, four students (18.18%) answered at level 1, and one student (4.54%) answered at level 5. In the creativity skill level assessment (after learning), the highest number of students, 18 students (81.81%), answered at level 4, and 4 students (18.18%) answered at level 5. No students answered at levels 0, 1, 2, or 3.

Figure 7 shows the results of the development of scientific creative thinking skills in the aspect of initiative in thinking of Grade 4 students during the STEM-based outdoor learning program in the context of Phuket province, which enhanced the scientific creative thinking skills of Grade 4 students in all 4 aspects (initiative in thinking, flexibility in thinking, fluency in thinking, and elaborate thinking) before and after participating in the STEM-based learning program.

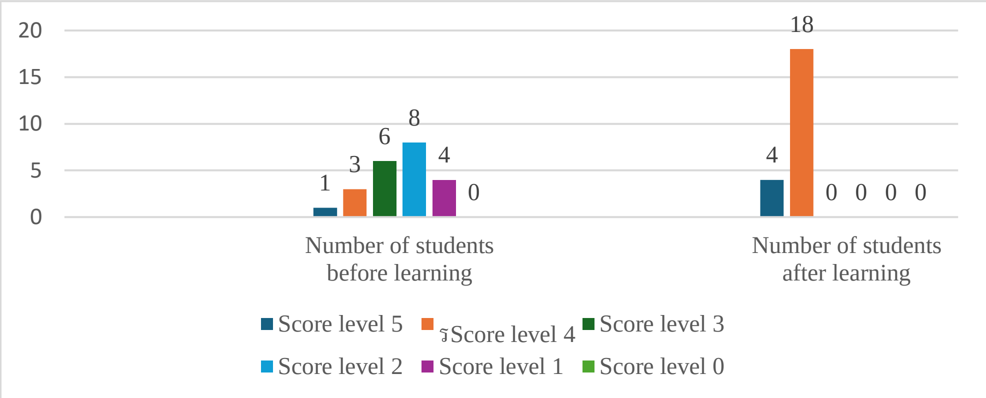

Figure 7. shows the results of the development of scientific creative thinking skills in the aspect of initiative in thinking during the STEM-based outdoor learning program

Figure 8 shows the results of the development of the STEM-based outdoor learning activities in the context of Phuket province, which enhanced the scientific creative thinking skills of Grade 4 students in all 4 aspects (initiative in thinking, flexibility in thinking, fluency in thinking, and elaborate thinking) before and after participating in the STEM-based learning program.

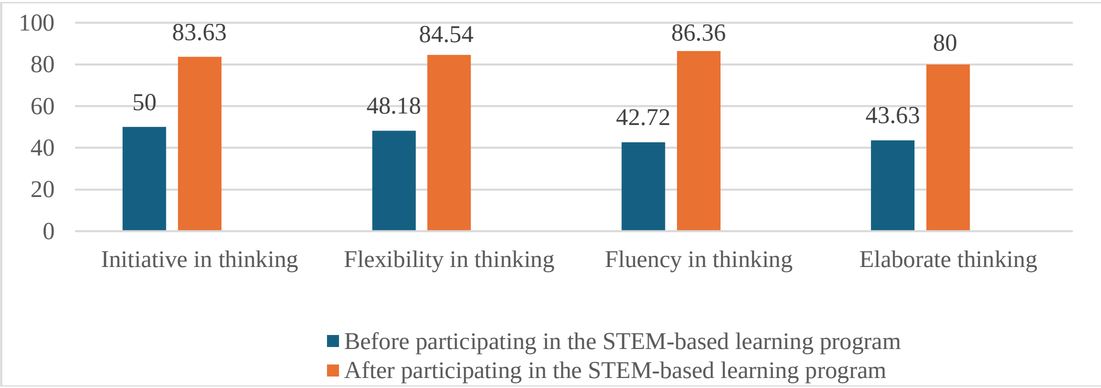

Figure 8. The results of the development of the STEM-based outdoor learning activities in all 4 aspects (initiative in thinking, flexibility in thinking, fluency in thinking, and elaborate thinking) before and after participating in the STEM-based learning program.

Figure 8, it shows the percentage of students according to the indicative behaviors with scientific creative thinking skills based on the scientific creative thinking skill assessment. Examples of student work that demonstrate behaviors aligned with the development of scientific creative thinking skills in all 6 aspects before and after participating in the STEM-based outdoor learning program in the context of Phuket province are as follows:

It presents examples of student responses with indicators of scientific creative thinking skills, specifically initiative in thinking, in Figure 9.

Ask students to observe the characteristics of monocot and dicot plant leaves and compare them to something in daily life. **Initiative in thinking.** *A monocot leaf is like a road, while a dicot leaf is like a city.*

Figure 9. The responses of students demonstrating the initiative in thinking indicator of scientific creative thinking skills.

Figure 9, the comparison of plant leaf characteristics (monocot and dicot) with something encountered in daily life, such as linking them to "roads" and "city maps," is a creative way of drawing on knowledge from experience. This demonstrates an understanding of the content and the ability to apply knowledge in different contexts.

It presents examples of student responses with the flexibility in thinking indicator of scientific creative thinking skills in Figure 10.

If students had to explain the difference between monocot and dicot leaves to their friends, what aspects would they choose to compare? For example, the use in daily life, growth, or plant structure, and provide examples. **Flexibility in thinking.** *Growth: Monocot plants are characterized by having a fibrous root system, such as tamarind.*

Figure 10. The responses of students demonstrating the flexibility in thinking indicator of scientific creative thinking skills.

Figure 10, students were able to apply their knowledge of monocot and dicot leaves in a different perspective. Not only they described the basic characteristics of the plants, but they also linked it to real-life examples (mango tree) and expanded on the root system. This demonstrates that students did not limit their thinking to just the information they learned but were able to adapt and explain it systematically, allowing them to communicate the differences between the two types of plants more clearly. It presents examples of student responses with the fluency in thinking indicator of scientific creative thinking skills in Figure 11.

What are the characteristics of monocot and dicot leaves? **Fluent thinking**

Dicot plants	***Monocot plants***
Veins are branched	*One cotyledon*
Taproot	*Fibrous roots*
No distinct nodes	*Clear nodes*
Two cotyledons	*Parallel-veined leaves*

Figure 11. The responses of students demonstrating the fluency in thinking indicator of scientific creative thinking skills.

Figure 11, students were able to organize and present information about the differences between monocot and dicot plants in an orderly, easy-to-understand, and concise manner. They responded quickly using clear and systematic language. Additionally, students were able to correctly link key characteristics of both types of plants, such as leaf veins, root systems, and the number of cotyledons, without confusion. This demonstrates their understanding of the content and their ability to arrange information effectively. It presents examples of student responses with the elaborate thinking indicator of scientific creative thinking skills in Figure 12. Students drew diagrams of monocot and dicot leaves, paying close attention to the details of the leaf structure. They not only depicted the shape of the leaves but also clearly labeled various components such as leaf veins, cross-section of the leaf, back of the leaf, and petiole.

Draw the shape of dicot and monocot plants and indicate the positions.

Meticulous thinking

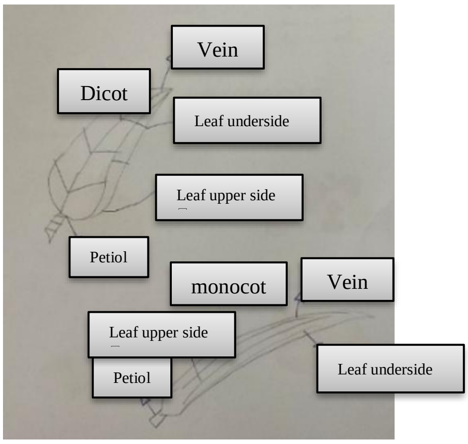

Figure 12. The responses of students demonstrating the elaborate thinking indicator of scientific creative thinking skills.

Results of the Development of Scientific Creative Thinking Skills of Grade 4 Students Who Participated in STEM Outdoor Learning in the Context of Phuket Province

The results of the development of scientific creative thinking skills of grade 4 students before and after participating in STEM outdoor learning in the context of Phuket province are as follows: The study found that the students' scientific creative thinking skills improved after participating in the activity, with higher scores than before the activity. The learning process was structured in 6 steps: 1) identifying the problem, 2) gathering data and ideas related to the problem, 3) designing a solution, 4) planning and executing the solution, 5) testing and evaluating the results, and 6) presenting the findings.

The researcher used a scientific creative thinking skills assessment tool to score and analyze the results of the students' scientific creative thinking achievement before and after participating in the STEM outdoor learning activity in the context of Phuket province. The results of the analysis are shown in Table 8.

Table 8. Results of the analysis of achievement in the development of scientific creative thinking skills of grade 4 students who participated in STEM outdoor learning.

Score	Full Score	$\bar{x}$	S.D.	t	Sig.
Before learning	20	8.14	2.46	21.77*	0.00
After learning	20	16.23	1.11		

*Statistically significant at the .01 level

Table 8, the results of the development of scientific creative thinking skills of Grade 4 students before receiving STEM-based out-of-classroom learning according to the Phuket context showed an average score of 8.14 with a standard deviation of 2.46. After receiving STEM-based out-of-classroom learning according to the Phuket context, the average score increased to 16.23 with a standard deviation of 1.11. The difference was tested using a t-test, and it was found that the average score after learning was significantly higher than before learning at the statistical level of 0.00 (t = 21.77, sig = 0.00).

Best Practices in Outdoor STEM Learning

STEM-based out-of-classroom learning according to the Phuket context is a teaching method that encourages students to independently explore knowledge while the teacher acts as a facilitator and provides guidance. This method promotes students' development of scientific creative thinking skills. Based on the post-lesson analysis of the topic "Materials and Matter," the following best practices should be applied for outdoor STEM classroom learning that fosters the development of scientific creative thinking skills.

Creating a Learning Environment that Supports Learning: The teacher should create a welcoming and interactive classroom atmosphere and encourage students to share their ideas, leading to discussions and conclusions based on data.

Teaching Practice

In each lesson plan, such as Lesson Plan 1 on **"Eco-Print and Southern Botany,"** the teacher begins by establishing a relaxed and supportive classroom atmosphere. Learning experiences outside the classroom offer valuable opportunities to foster students' creativity and deepen their understanding of the natural environment. As part of this approach, the **"Walking Map"** activity was designed for students to explore and study the local community, with a focus on surveying the abundance and diversity of natural resources in the area. To assess students' responses effectively, teachers developed a scoring rubric specifically designed to evaluate scientific creativity skills. This criterion is structured to be clear, measurable, and grounded in research, aligning with established creativity assessment frameworks such as those proposed by **Guilford** and **Torrance**, while focusing on scientific applications. The rubric is presented in Table 9.

Table 9. A scoring rubric designed specifically for evaluating answers that demonstrate scientific creativity skills.

Criteria	**Level 4 (Excellent)**	**Level 3 (Good)**	**Level 2 (Fair)**	**Level 1 (Needs Improvement)**
Originality (Uniqueness of the idea)	Provides highly original ideas or solutions that are rare, imaginative, and demonstrate novel scientific thinking.	Provides somewhat original ideas that show creative scientific thinking, though partially predictable.	Provides common or familiar ideas with little uniqueness; demonstrates limited scientific novelty.	Repeats conventional ideas without any originality; minimal scientific creativity shown.
Fluency (Number of ideas generated)	Generates a wide range (5 or more) of scientifically plausible ideas or solutions.	Generates several (3–4) scientifically plausible ideas or solutions.	Generates a few (1–2) ideas with some scientific relevance.	Struggles to generate ideas; provides only 0–1 idea with limited scientific relevance.

Criteria	Level 4 (Excellent)	Level 3 (Good)	Level 2 (Fair)	Level 1 (Needs Improvement)
Flexibility (Variety of categories or approaches)	Demonstrates high flexibility by shifting between different scientific perspectives or approaches effectively.	Demonstrates some flexibility by considering alternative scientific approaches or explanations.	Demonstrates limited flexibility; mainly sticks to a single perspective.	Shows rigid thinking with no alternative approaches considered.
Elaboration (Level of detail and development)	Ideas are thoroughly developed with rich scientific details, explanations, and connections.	Ideas are explained with adequate scientific detail but could be more thoroughly developed.	Ideas are simple, with minimal scientific detail or explanation.	Ideas are vague, undeveloped, and lack scientific support.
Scientific Feasibility (Scientific plausibility and logic)	Ideas are highly feasible, scientifically sound, and demonstrate logical cause-and-effect relationships.	Ideas are generally feasible and scientifically appropriate, with minor gaps in logic.	Ideas show some misunderstanding of scientific principles or weak logic.	Ideas are scientifically incorrect or illogical with major misconceptions.

Classroom Practice

Students gained confidence in sharing their thoughts and were more enthusiastic in the classroom. They became eager to answer questions asked by the teacher, especially in Cycle 2, where students could discuss, express their opinions, and conclude about making eco-print-related products.

Evidence

- Post-lesson records/observations of student behavior showing their thinking and participation in class discussions.
- Activity logs submitted by students showing their understanding and ability to apply scientific creative thinking skills.
- Photos of activities related to STEM-based out-of-classroom learning according to the Phuket context, such as "Eco Print and Southern Botany."
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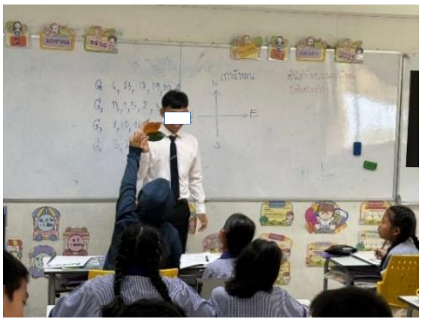

Figure 14. Organizing Classroom Activities

RESEARCH RESULT AND DISCUSSION

The development of scientific creative thinking skills among Grade 4 students was assessed following the implementation of outdoor STEM learning activities contextualized to Phuket. The findings revealed a marked improvement in students' scientific creative thinking skills compared to their performance prior to the intervention. This improvement can be attributed to the learning opportunities provided by the outdoor STEM activities, which enabled students to explore real-world issues derived from their everyday experiences in Phuket. Through these experiences, students engaged in analyzing problems, conducting independent inquiry, collecting relevant data, generating ideas, designing solutions, planning investigations, and verifying results on their own (Ünal Çoban, 2013 and Mohammed & Kinyo, 2020). Furthermore, they effectively presented their findings and communicated their ideas, indicating both cognitive engagement and creative output. The research also showed a significant positive impact on teacher candidates' perceptions of the development of students' scientific creativity. This aligns with the findings of Kocabas (1993), Ongowo and Indoshi (2013), and Zhang et al. (2012), who argue that scientific creativity encompasses more than the mere organization of observable information. When science is taught through inquiry-based and problem-solving processes, students not only develop essential scientific process skills but also cultivate more positive attitudes toward science, thereby enhancing their creativity. Scientific process skills—such as observation, classification, measurement, inference, and communication—are transferable across science disciplines and are fundamental to inquiry-based STEM learning. Outdoor STEM activities allow students to apply these skills in authentic contexts, bridging academic knowledge with real-life applications. When students engage in the engineering design process, their creative thinking is further stimulated as they iterate, prototype, and test ideas. This is supported by research from Rawan Thilanant (2015), who found that Grade 12 students participating in STEM project-based learning demonstrated significantly higher creative thinking skills post-intervention. Similarly, Suchanart Suwanphiboon (2016) reported that Grade 7 students engaged in an integrated STEM unit on "Eco-Friendly Homes" showed statistically significant gains in creativity. To effectively foster such skills, teacher education programs must prepare pre-service teachers with both theoretical understanding and practical experience in the engineering design process. Studies by Liang (2002), Meador (2003), and Wyke (2013) emphasize that well-qualified science teachers who are proficient in engineering design are better equipped to nurture their students' creativity and design competencies. When teachers pose thought-provoking questions, act as facilitators, and grant students' autonomy, they create a learning environment that supports innovation and exploration (Leung, 2023).

In this context, creativity plays a critical role in complementing scientific thinking, particularly in science and technology-oriented learning (Villalba, 2008). Scientific creativity—defined as the application of creative thinking within scientific domains—has become a central aim of modern science curricula. Achieving this objective requires deliberate integration of content, pedagogy, and learner-centered strategies. As creativity becomes increasingly vital in a rapidly evolving, globalized world, educational institutions must take an active role in cultivating students' creative capacities. Among all disciplines, science education stands out as a key driver of high-level creative thinking (Miles, 2008; Park, 2011 and Torkos, 2021), making the role of science teachers indispensable in this developmental journey.

Characteristics of STEM-Based Out-of-Classroom Learning Activities that Develop Scientific Creative Thinking Skills

The Outdoor STEM learning activities according to the Phuket context, which developed the scientific competencies of Grade 4 students, consisted of one unit on learning about "Materials and Matter" through three lesson plans:

1. Lesson Plan 1: "Eco Print and Southern Botany"
2. Lesson Plan 2: "Tie-Dye and Sino-Portuguese Architecture"
3. Lesson Plan 3: "Natural Dyes from Coconut Milk"

These activities helped to develop scientific creative thinking skills because the learning process involved six steps:

1. Problem identification
2. Collecting information and ideas related to the problem
3. Designing solutions
4. Planning and implementing problem-solving actions
5. Testing and evaluation
6. Presentation

These steps can be observed as follows:

Step 1: Problem Identification

Before participating in STEM-based out-of-classroom learning, students were unable to clearly identify the problem according to the conditions of the activity, making it difficult for them to decide on the next steps. This reflected an underdevelopment of creative thinking skills, especially in initiative. After engaging in the learning activities, students were able to identify problems more clearly and demonstrated improved initiative. They were able to come up with creative ideas to solve problems and present new concepts, which shows significant development in their skills because of the learning process.

Step 2: Gathering Information and Ideas Related to the Problem

Before implementing STEM-based out-of-classroom learning according to the Phuket context, students were unable to gather information and understand scientific concepts. They lacked the skills to analyze data, connect knowledge, and explain ideas systematically. After participating in the learning activities, students were able to present more detailed ideas. For example, they could explain concepts in more detail, present relevant information, and better connect prior knowledge to new situations.

Step 3: Designing Solutions

Before the STEM-based out-of-classroom learning, students lacked the ability to design effective solutions. They were unable to apply knowledge creatively to systematically devise solutions. After engaging in the learning activities, students could design solutions using relevant scientific principles and technologies. For instance, they could choose appropriate natural materials for dyeing using the Eco-printing method. Additionally, students could present creative solutions, such as designing fabric patterns using natural dyes to represent the local culture of Phuket, demonstrating the development of both applied creativity and effective problem-solving skills.

Suggestions Based on the Research

Suggestions for Utilizing Research Findings

1. Since the research findings show that STEM-based learning can enhance students' creative thinking skills, learning activities should be implemented in teaching to effectively develop students' learning outcomes.
2. Developing students' creative thinking skills requires time. Therefore, educators must organize learning activities that continuously promote and support student development.
3. It is essential to allow sufficient time for research and problem-solving. Educators need to understand the nature of each student and group, as the problems each group

investigates and solves will differ, leading to different approaches to finding solutions.

4. Educators must instill the importance of the working process in students. The outcome may not be the final measure of success, but the process of obtaining the results and knowledge is more important. The focus of STEM-based learning lies in understanding problems and finding reasonable solutions.

Suggestions for Future Research

1. Future studies should explore the development of STEM-based learning across different subjects and learning areas to examine the effects on students.
2. Future studies should explore learning strategies that connect with local wisdom, such as using local materials and incorporating traditional handicraft techniques into STEM projects.

ETHICAL CONSIDERATIONS

The ethical approach to this research, particularly in relation to concealed research data, was carefully managed to comply with academic and legal ethical standards. The research methodology adhered to the following ethical principles:

1. Informed Consent: The researcher ensured that appropriate consent forms were obtained from parents and guardians of the research participants, and approval was secured from the school where the research took place. Upon completion of the research, participants were informed about the use of concealed data and given the option to withdraw their data.
2. Privacy Protection: The researcher used anonymization or data encryption methods and restricted access to data to authorized personnel only.
3. Minimizing Ethical Harm: In collaboration with the supervising teacher and academic advisors, the ethical risks and potential impacts on participants were carefully assessed. If any issues regarding concealed data that might have negative effects were identified, the researcher ensured a transparent research approach.
4. Debriefing: After the research was completed, participants were informed about the true nature of the study, and they were provided with the opportunity to ask questions or share feedback about the research process.
5. Reporting Research Results: The researcher ensured that the results of the study were shared transparently, with clear explanations of methods used, reasons for data concealment, and efforts to avoid distortion of data or misleading the public.

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