

STEM-BASED LEARNING FOR 21ST-CENTURY COMPETENCIES IN INDONESIA: INTEGRATING TECHNOLOGY, PEDAGOGY, AND EDUCATIONAL INNOVATION

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Abstract

This study examines the role of STEM-based learning in developing 21st-century competencies in Indonesia through the integration of technology, pedagogy, and educational innovation. An integrative literature review approach was employed to identify, analyze, and synthesize relevant peer-reviewed literature, primarily indexed in Scopus. The analysis focused on technology integration, STEM pedagogical innovation, authentic and collaborative learning, higher-order thinking skills, and 21st-century competencies. The findings reveal that STEM education in Indonesia has increasingly shifted from content-oriented instruction toward interdisciplinary, student-centered, contextual, and problem-oriented learning. Project-based learning, problem-based learning, inquiry-based learning, and engineering design emerge as prominent pedagogical approaches supporting STEM implementation. These approaches contribute to the development of critical thinking, creativity, problem-solving, communication, collaboration, scientific literacy, and digital literacy. However, STEM implementation remains constrained by disparities in technological infrastructure, teacher readiness, interdisciplinary integration, and unequal implementation across educational contexts and regions. This study proposes an integrated conceptual framework consisting of Technology Integration → STEM Pedagogical Innovation → Authentic and Collaborative Learning → Higher-Order Thinking Skills → 21st-Century Competencies. The framework emphasizes that technology alone does not generate future-ready competencies; rather, its educational value depends on pedagogical transformation and meaningful learning experiences. The study provides conceptual implications for strengthening STEM education and directions for future empirical research in Indonesia.

Keywords: STEM-based learning; 21st-century competencies; technology integration; pedagogical innovation; higher-order thinking skills; Indonesia

INTRODUCTION

Digital transformation, the development of artificial intelligence, automation, and changes in the characteristics of the world of work have encouraged the education system to no longer be oriented solely on knowledge mastery, but also on the development of 21st-century competencies. Critical thinking skills, creativity, problem-solving, communication, collaboration, science literacy, and technological literacy are becoming

increasingly important in preparing students to face complex and multidisciplinary problems. In this context, Science, Technology, Engineering, and Mathematics (STEM) education is developing as a learning approach that integrates various disciplines to connect academic concepts with real-world problem-solving. The development of international research shows that STEM has developed into an increasingly dynamic field of education, with increasing attention to the integration of disciplines, learning practices, technology, and the development of students' competencies (Li, 2025). In Indonesia, STEM is also gaining attention for its potential in building 21st century skills through active, contextual, project-based, and problem-solving-oriented learning (Nugroho et al., 2019; Ilma et al., 2023).

The urgency of this competency development is increasingly evident from the achievements of Indonesian students in the Programme for International Student Assessment (PISA) 2022. Indonesia obtained an average score of 366 in mathematics, 359 in reading, and 383 in science, and all of these achievements are below the OECD average. Only about 18% of Indonesian students achieve at least Level 2 in mathematics, compared to the OECD average of 69%, while in science only about 34% reach Level 2 or higher, compared to 76% in OECD countries. In addition, the creative thinking skills of Indonesian students obtained an average score of 19 out of 60, far below the OECD average of 33 (OECD, 2023, 2024). This condition shows the need to strengthen the learning process that does not just transfer knowledge, but provides opportunities for students to use knowledge integratively in conducting investigations, designing solutions, solving problems, and generating innovations. STEM-based learning is relevant because it connects science and mathematics knowledge with the engineering design process and the use of technology in the context of authentic problems.

Although the implementation of STEM in Indonesia shows considerable progress, its implementation has not been fully evenly distributed and integrated in learning practices. Farwati et al. (2021) found that STEM research and implementation in Indonesia has developed at various levels of education and is used as a learning strategy, approach, assessment, and basis for the development of teaching materials and learning media. However, the spread of STEM research is still concentrated in certain regions, especially West Java and East Java. Problems can also be seen in the aspect of teacher readiness. Studies on integrated STEM show that although Indonesian science teachers are generally familiar with the STEM approach, more than half of the teachers studied have never applied it in their learning (Muchtar et al., 2024). Thus, there is a gap between the increasing academic attention to STEM and its actual implementation capacity in the classroom. Limited facilities, teachers' pedagogical competence, access to technology, curriculum readiness, and infrastructure inequality between regions are also challenges for the sustainable implementation of STEM.

A number of previous studies have shown the contribution of STEM to the competency development of Indonesian students. Farwati et al. (2021), through a *scoping review* of 154 articles, showed that STEM has been applied to improve various 21st-century

competencies, learning motivation, and even entrepreneurial skills. Ardwiyanti et al. (2021) found that STEM research in Indonesia is dominated by the study of learning strategies and the use of experimental research designs. Furthermore, Ilma et al. (2023), through a *systematic literature review* of Indonesia's STEM/STEAM research for the 2016–2021 period, found the dominance of *project-based learning*, *problem-based learning*, and *inquiry learning*, with critical thinking skills, science literacy, and learning outcomes as themes that were widely researched. Other research shows that the integration of STEM with *Education for Sustainable Development* can strengthen sustainability awareness and critical thinking skills through interdisciplinary learning, *project-based learning*, and inquiry (Sihombing et al., 2024). These findings consistently show that STEM has significant potential in driving a learning shift from *teacher-centered learning* to a more active, collaborative, contextual, and problem-solving-oriented learning experience.

However, the developing literature still shows several research gaps. First, most STEM studies in Indonesia focus more on the effectiveness of learning models or strategies on certain variables, while the relationship between technology integration, pedagogical practices, educational innovation, and 21st-century competencies has not been widely synthesized as one integrated conceptual framework. Ilma et al. (2023) show the dominance of research on learning strategies with an experimental approach, while Ardwiyanti et al. (2021) also find the dominance of learning strategy topics. Second, studies on STEM often place technology as a medium or tool to support learning, even though digital transformation requires technology to be placed as an integral part of pedagogical design, exploration, collaboration, modeling, and problem-solving. Third, studies on STEM implementation still show problems with teacher readiness and uneven implementation (Muchtar et al., 2024). Therefore, an integrative study is still needed that explains how the combination of technology, STEM pedagogy, and educational innovation together shapes 21st century competencies in the context of Indonesian education.

This research is important because it is not enough to improve the quality of education only through the provision of technology or the partial application of STEM as a learning method. A more fundamental challenge is how technology can be integrated with pedagogical strategies that allow students to conduct inquiries, collaborate, develop projects, carry out engineering design processes, solve authentic problems, and produce creative solutions. At the same time, the low proportion of Indonesian students who achieve basic proficiency in mathematics and science and the low achievement of creative thinking indicate the need for learning innovations that are able to strengthen high-level thinking skills (OECD, 2023, 2024). The synthesis of literature on the relationship between STEM-based learning, technology integration, pedagogical innovation, and 21st-century competencies is therefore needed to provide a conceptual basis for the development of STEM learning that is more systematic, inclusive, and in accordance with the characteristics of Indonesian education.

Based on the problems and gaps of the research, this study aims to analyze and synthesize the literature on the implementation of STEM-based learning in 21st century

competency development in Indonesia by emphasizing the integration of technology, pedagogy, and educational innovation. In particular, the research is directed to identify the characteristics and development of STEM-based learning implementation in Indonesia; analyze the role of technology in supporting the STEM learning process; identify pedagogical approaches and educational innovations used; and evaluate its contribution to students' critical thinking skills, creativity, collaboration, communication, problem-solving, and literacy. Through this synthesis, the research is expected to produce an integrated conceptual framework that explains the relationship between Technology Integration → STEM Pedagogical Innovation → Authentic/Collaborative Learning → Higher-Order Thinking → 21st-Century Competencies, as well as providing direction for research and development of STEM practices in Indonesia in the future.

LITERATURE REVIEW

STEM-Based Learning

STEM-based learning is an interdisciplinary educational approach that integrates science, technology, engineering, and mathematics to provide an authentic problem-solving learning experience. STEM integration is not only interpreted as the merger of four fields of knowledge, but also as a learning process that allows students to connect cross-disciplinary concepts through investigation, *engineering design*, experimentation, modeling, and solution development. Kelley and Knowles (2016) explained that *integrated STEM education* combines content and practices from various STEM disciplines using authentic contexts so that students are able to build relationships between conceptual knowledge and its application. This approach shifts the learning orientation from mastery of content to the ability to apply knowledge integratively in solving complex problems. In the Indonesian context, the development of STEM also shows a tendency towards learning that is more contextual, multidisciplinary, and oriented to student competencies (Farwati et al., 2021; Ilma et al., 2023).

Technology Integration dalam STEM Education

Technology is a strategic component in STEM learning because it allows students to access information, conduct simulations and modeling, process data, build designs, and collaborate in a digital learning environment. Effective technology integration is not enough just to provide digital tools, but requires alignment between technology, learning materials, and pedagogical strategies. The Technological Pedagogical Content Knowledge (TPACK) framework explains that teachers' ability to effectively integrate technology is determined by the interaction between *technological knowledge*, *pedagogical knowledge*, and *content knowledge* (Mishra & Koehler, 2006). In STEM education, technology thus functions not only as a medium for delivering information, but also as a *cognitive and collaborative tool* that supports inquiry, virtual experimentation, engineering design, programming, modeling, and problem solving. The use of technology that is integrated with STEM pedagogy has the potential to increase student engagement while providing a more flexible and authentic learning environment.

STEM Pedagogy dan Educational Innovation

The success of STEM-based learning is highly dependent on the pedagogical approach used in connecting multidisciplinary knowledge with students' learning experiences. The STEM literature shows that project-based learning, problem-based learning, inquiry-based learning, collaborative learning, and *engineering design-based learning* are widely used approaches because they place students as the main actors in the learning process. In the Indonesian context, Ilma et al. (2023) show that *project-based learning*, *problem-based learning*, and *inquiry learning* are the dominant models in STEM/STEAM implementation. This is in line with the characteristics of STEM which requires students to identify problems, develop alternative solutions, conduct tests, evaluate results, and improve evidence-based designs. Therefore, educational innovation in STEM should not only be understood as the use of new technologies, but as the transformation of learning design towards activities that are more student-centered, interdisciplinary, collaborative, inquiry-driven, and oriented towards real-world problem solving (Kelley & Knowles, 2016; Farwati et al., 2021).

21st century competencies include a set of abilities that enable individuals to adapt, learn, work, and solve problems in an ever-changing social and economic environment. Among these competencies, critical thinking, creativity, communication, collaboration, problem-solving, and information literacy, digital, and science are major concerns in education. van Laar et al. (2017) emphasized the close relationship between digital skills and 21st century skills, especially in the aspects of information management, communication, collaboration, creativity, critical thinking, and problem-solving. STEM-based learning has characteristics that support the development of these skills because learners are not only asked to understand concepts, but also apply them in projects, experiments, designs, and authentic problem-solving. Research in the Indonesian context also shows that the implementation of STEM is largely directed at the development of critical thinking, science literacy, problem-solving skills, creativity, and learning outcomes (Farwati et al., 2021; Ilma et al., 2023).

Integration of Technology, Pedagogy, and Educational Innovation

The effectiveness of STEM in shaping 21st-century competencies can be understood through the synergistic relationship between technology integration, pedagogical innovation, and educational innovation. Technology provides tools and environments for exploration and collaboration, while pedagogy determines how STEM technology and content are used to produce meaningful learning experiences. Educational innovation then becomes a transformation mechanism that connects technology and pedagogy with changes in learning activities. With this perspective, the use of technology without appropriate pedagogical design does not necessarily result in an increase in students' competencies. Conversely, when technology is combined with inquiry, collaborative projects, problem-solving, and *engineering design processes*, students gain opportunities

to develop *higher-order thinking skills* more intensively. The concept is in line with TPACK which emphasizes the interconnectedness of technological knowledge, pedagogy, and content in producing effective learning practices (Mishra & Koehler, 2006).

RESEARCH METHODS

This study uses a library research approach with an *integrative literature review* method to identify, analyze, and synthesize research developments regarding *STEM-based learning* in the development of 21st century competencies in Indonesia, especially in the aspects of integrating technology, pedagogy, and educational innovation. The *integrative review* approach was chosen because it allows the incorporation of findings from various research designs and perspectives to produce a more comprehensive conceptual understanding and identify research gaps (Snyder, 2019; Torraco, 2016). The literature was searched primarily through the Scopus database using a combination of keywords such as "*STEM education*," "*STEM-based learning*," "*technology integration*," "*digital technology*," "*pedagogical innovation*," "*educational innovation*," "*21st-century skills*," "*21st-century competencies*," and "*Indonesia*." The literature considered includes *peer-reviewed journal articles* relevant to the research focus, especially publications that discuss the implementation of STEM in the Indonesian education context, as well as a number of international literature used to strengthen the theoretical and conceptual foundations of research.

Literature analysis is carried out through several stages, namely literature identification, selection based on relevance, organization of findings, thematic analysis, and conceptual synthesis. The collected articles are classified based on the focus of the study, level of education, STEM approach, forms of technology integration, pedagogical strategies, learning innovations, and 21st century competencies developed. Furthermore, findings from various studies are compared to identify patterns, consistency, differences in results, limitations of previous research, and *research gaps* that are still open. Thematic analysis was used to group the findings into main themes, namely technology integration, STEM pedagogical innovation, authentic and collaborative learning, higher-order thinking skills, and 21st-century competencies. The results of the synthesis were then used to build a conceptual framework that described the flow of Technology Integration → STEM Pedagogical Innovation → Authentic & Collaborative Learning → Higher-Order Thinking Skills → 21st-Century Competencies, so that the *literature review* not only produced a description of the development of STEM research in Indonesia, but also offered conceptual integration as a basis for further educational research and practice (Snyder, 2019; Torraco, 2016).

RESULTS AND DISCUSSION

Results

The results of the literature synthesis show that research on STEM-based learning in Indonesia has experienced an increasingly wide development, especially since the mid-

2010s. STEM is no longer only positioned as an approach to integrate science, technology, engineering, and mathematics, but has developed into a learning strategy to build competencies relevant to the needs of the 21st century. Farwati et al. (2021), based on a scoping review of 154 articles, found that the implementation of STEM in Indonesia has been used as a learning strategy and approach, integrated with various learning models, applied in assessments, and developed in the form of teaching materials, modules, and learning media. The research also shows that STEM has been researched at various levels of education, even though secondary school is one of the most studied contexts. Meanwhile, Ardwiyanti et al. (2021) found that around 54% of the Indonesian STEM research analyzed focused on learning strategies and 46% used experimental methods. These findings show that the development of Indonesian STEM research is still strongly oriented towards testing the effectiveness of learning approaches on learning outcomes and students' skills.

The second result shows that pedagogical innovation is a central element in the implementation of STEM-based learning. A synthesis of previous research shows the dominance of *project-based learning* (PjBL), *problem-based learning* (PBL), *inquiry-based learning*, collaborative learning, and activities involving *engineering design*. Ilma et al. (2023) found that the implementation of STEM/STEAM in Indonesia is largely combined with a learning model that places students actively in the process of exploration and problem-solving. These findings are reinforced by Muchtar and Ding (2024), who show that *project-based learning* is the most commonly used method by science teachers in integrated STEM learning. This pattern shows a tendency to shift from content-oriented STEM learning to student-centered learning, where learners identify problems, seek information, design alternative solutions, test solutions, and communicate results. Thus, the pedagogical characteristics of STEM in Indonesia are increasingly leading to authentic, contextual, collaborative, and project-oriented learning.

The third result shows that the application of STEM contributes to the development of various 21st-century competencies. The competencies that appear most in the literature include *critical thinking*, *creativity*, *problem-solving*, *scientific literacy*, and collaborative skills. Farwati et al. (2021) show that the implementation of STEM in Indonesia has been used to improve various 21st-century skills, learning motivation, and even entrepreneurial abilities. The study of Ilma et al. (2023) also identified critical thinking skills and science literacy as some of the important outcomes in Indonesian STEM research. Meanwhile, Muchtar and Ding (2024) found that science teachers use integrated STEM primarily to encourage creativity, critical thinking, problem-solving, and literacy of students. The findings show that STEM's contribution to 21st century competencies does not solely arise from the integration of disciplines, but primarily through learning activities that require learners to apply a wide range of knowledge simultaneously in solving authentic problems. The fourth result identifies an implementation gap in the development of STEM education in Indonesia. Although awareness and knowledge about STEM is growing, its implementation is not evenly distributed. Farwati et al. (2021) found that STEM

implementation research has been conducted in 19 provinces, but is concentrated mainly in West Java and East Java. At the teacher level, Muchtar and Ding (2024) found that Indonesian science teachers in general are familiar with the integrated STEM approach, but more than half of the teachers in the literature they reviewed have never implemented it in learning. Studies on prospective teachers also show rapid development of STEM research, but perceptions of how STEM should be integrated are still diverse (Nugraha et al., 2023). Thus, the results of the synthesis indicate that Indonesia's STEM challenges are no longer only related to the introduction of STEM concepts, but also concern teacher readiness, pedagogical competence, the ability to carry out cross-disciplinary integration, the use of technology, and the transformation of STEM concepts into learning experiences that can be applied consistently.

Discussion

The research findings show that the effectiveness of STEM-based learning in shaping 21st-century competencies cannot be explained only through the existence of four STEM disciplines. The integration of science, technology, engineering, and mathematics must be translated into a learning experience that allows students to use cross-disciplinary knowledge to solve authentic problems. The dominance of research on learning strategies as found by Ardwiyaniti et al. (2021) shows that the pedagogical dimension is an important mechanism in determining the success of STEM. This explains why PjBL, PBL, inquiry, and *engineering design* are widely used in STEM learning: these approaches provide space for students to explore problems, develop hypotheses, produce designs, test alternative solutions, and reflect. Thus, STEM Pedagogical Innovation can be understood as a mechanism that transforms the integration of STEM disciplines into learning activities that are able to produce high-level competencies.

Furthermore, technology integration needs to be placed as a pedagogical *enabler* and not just the use of digital devices. In the STEM framework, technology can expand students' ability to search for information, collect and process data, simulate, model, design, communicate, and collaborate. However, technology only provides educational value when integrated with learning objectives and appropriate pedagogical approaches. This is important because Indonesian STEM research has so far been more dominant in discussing learning strategies rather than developing integrative explanations of the relationship between technology and pedagogical transformation (Ardwiyaniti et al., 2021; Ilma et al., 2023). Therefore, technology integration should be directed to strengthen inquiry, project, engineering design, and problem-solving processes. This perspective shifts attention from technology adoption to technology-enabled STEM pedagogy, which is how technology improves the quality of interaction, exploration, representation, and knowledge creation in STEM learning.

The relationship between STEM and 21st century competencies can then be explained through the formation of authentic and collaborative learning and higher-order thinking skills. When students face real-world problems, they are required to integrate

knowledge from various fields, evaluate information, develop alternative solutions, communicate with group members, and make improvements to the solutions produced. This process allows STEM learning to encourage critical thinking, creativity, problem-solving, and literacy as discovered by Farwati et al. (2021), Ilma et al. (2023), and Muchtar and Ding (2024). Another systematic study of integrated STEM in Indonesia also concludes that there is a relationship between STEM approaches in science learning and 21st-century skills development (Lafifa et al., 2023). Therefore, the relationship between STEM and 21st-century competencies should not be understood as a direct relationship, but as a gradual process in which pedagogical design creates an authentic learning experience that then stimulates higher-level thinking abilities.

Despite its strong potential, the sustainability of STEM education in Indonesia is highly dependent on teacher readiness and equitable distribution of implementation capacity. The finding that more than half of teachers in the study studied by Muchtar and Ding (2024) have never tried to implement integrated STEM shows that there is a gap between conceptual knowledge and learning practice. This condition is important because teachers are the main actors who translate technology, STEM content, and pedagogical strategies into learning activities. In the education of prospective teachers, Nugraha et al. (2023) also found that there is a diversity of perceptions about STEM implementation and proposed elements of disciplinary integration, multiple representations, realistic and relevant problems, *engineering design processes*, collaboration, and *student-centered learning* as important components of integrated STEM. Therefore, strengthening STEM in Indonesia requires the professional development of teachers who not only teach the definition of STEM, but also provide experience in designing, implementing, and evaluating STEM learning directly. Equitable distribution of infrastructure and institutional support is also needed considering that STEM research still shows a certain geographical concentration (Farwati et al., 2021).

Based on the overall synthesis, this study proposes that the development of 21st century competencies through STEM can be explained through the conceptual flow of Technology Integration → STEM Pedagogical Innovation → Authentic & Collaborative Learning → Higher-Order Thinking Skills → 21st-Century Competencies. The framework is a conceptual synthesis of the literature pattern, not a claim that all of its causal relationships have been tested simultaneously in a single study. Technology integration plays a role in providing learning resources and environments; STEM pedagogical innovation transforms these resources into inquiry, project, problem solving, and engineering design activities; authentic and collaborative learning creates a context for learners to apply knowledge; while higher-order thinking is a mechanism that connects these experiences with critical thinking, creativity, problem-solving, communication, collaboration, and literacy. This framework expands the Indonesian STEM literature that has so far focused on testing individual learning strategies to a perspective that sees STEM as an integrated learning ecosystem between technology, pedagogy, innovation, and competency development (Ardwiyanti et al., 2021; Ilma et al., 2023; Nugraha et al., 2023).

CONCLUSIONS AND SUGGESTIONS

Conclusion

Based on the results of the *integrative literature review*, it can be concluded that STEM-based learning has a strategic role in the development of 21st century competencies in the context of Indonesian education. The development of STEM implementation shows a shift from content-mastery-oriented learning to more interdisciplinary, contextual, collaborative, and student-centered learning. The integration of STEM with *project-based learning*, *problem-based learning*, *inquiry-based learning*, and *engineering design* provides space for students to connect science, technology, engineering, and mathematics knowledge in solving authentic problems. This process contributes to the development of *critical thinking*, *creativity*, *problem-solving*, *communication*, *collaboration*, science literacy, and digital literacy as an important part of 21st century competencies. However, the implementation of STEM in Indonesia still faces challenges in the form of teacher readiness and competence, the ability to integrate across disciplines, the use of technology that is not yet optimal, as well as inequality of facilities and the implementation of STEM between regions.

Conceptually, this study shows that STEM's contribution to 21st-century competencies should not be understood as a direct relationship, but rather as a gradual process of learning transformation. The literature synthesis resulted in the framework of Technology Integration → STEM Pedagogical Innovation → Authentic & Collaborative Learning → Higher-Order Thinking Skills → 21st-Century Competencies. Within this framework, technology functions as an *enabler*, while pedagogical innovation becomes a mechanism that transforms the potential of technology into an authentic and collaborative learning experience. The experience further encourages *higher-order thinking skills* that are the foundation for the development of 21st-century competencies. This framework provides the perspective that the success of STEM is not only determined by the use of technology or the application of one particular learning model, but by the ability of the education system to integrate educational technology, pedagogy, and innovation in a sustainable learning ecosystem.

Suggestions

Based on these findings, the implementation of STEM in Indonesia needs to be strengthened through the development of teacher competencies that emphasize the ability to design and implement STEM learning in an integrative manner, including the use of digital technology, *project-based learning*, *inquiry*, *problem-solving*, and *engineering design processes*. Schools and education stakeholders also need to expand access to digital infrastructure and STEM learning resources so that their implementation is not concentrated in certain schools or regions. The development of the STEM curriculum further needs to emphasize authentic problems that are close to students' lives, including

environmental, sustainability, social, and technological issues so that learning can produce competencies that are relevant to future needs.

The next research is recommended to conduct empirical testing of the conceptual framework produced in this study, especially the relationship between Technology Integration, STEM Pedagogical Innovation, Authentic & Collaborative Learning, Higher-Order Thinking Skills, and 21st-Century Competencies. Testing can be carried out through quantitative approaches, longitudinal, *mixed methods*, and *structural equation modeling* to find out the mechanism of the relationship between variables in more depth. In addition, comparative research between education levels and between regions is needed to identify the influence of differences in teacher readiness, technological infrastructure, student characteristics, and the school environment. Thus, STEM research in Indonesia in the future is expected to move from simply testing the effectiveness of learning models to developing an adaptive, inclusive, technology-based, and competency-oriented STEM ecosystem in the future.

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