Pedagogical Models and Applications of STEM Education: A Systematic Literature Review on Approaches, Tools, and Learning Outcomes

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ABSTRACT

This systematic literature review aims to explore and synthesize current research on pedagogical models and applications of STEM (Science, Technology, Engineering, and Mathematics) education. Drawing on over 20 peer-reviewed articles published between 2016 and 2025, this study identifies the dominant instructional approaches, integration of technological and cultural tools, and the resulting impact on student learning outcomes and 21st-century skills. The analysis reveals a strong presence of inquiry-based learning, project-based learning, engineering design processes, and context-specific models such as STEM-EDELCY and ethno-STEM. Media such as virtual reality, IoT-based devices, hybrid laboratories, and indigenous knowledge are increasingly adopted to support experiential and contextual learning. Furthermore, STEM education contributes significantly to developing students' critical thinking, creativity, collaboration, and career interest in STEM fields. However, implementation challenges persist, including curriculum alignment, teacher readiness, and limited resources. This review offers insights for researchers, educators, and policymakers to develop more effective and contextually relevant STEM pedagogies.

Keywords: STEM education, pedagogical models, learning tools, learning outcome, systematic literature review

INTRODUCTION

This Systematic Qualitative Literature Review aims to analyze existing research in peer-reviewed journal articles from 2016-2025 related to the integration of science, technology, engineering, or mathematics (STEM) including a review of approaches, tools and learning outcomes. STEM education in Australia is used as a government step in an effort to make a science country that is not only in the classroom but can be in the meeting room, family room so that it becomes the foundation of prosperity

(Commonwealth of Australia & and Cabinet, 2015). In European and US countries, STEM is positioned as the importance of education as a basis for future economic prosperity.

STEM education in Indonesia continues to increase both in research and practice at all levels of education. In Southeast Asian countries based on bibliometric analysis of STEM between 2000-2019 (Ha et al., 2020), the highest achievements were in Malaysia, Thailand, and Indonesia. The report results explain that the trend of STEM education research in Indonesia continues to increase with the highest number in 2018-2019 (Ha et al., 2020). According to Fatmawati (2021) the implementation of STEM education in 2015-2020 increased and decreased in 2019 due to the pandemic, in addition, STEM education has been implemented at all levels of education from elementary, middle, high school, to undergraduate. The implementation of STEM education in Indonesia is mostly carried out on the island of Java, namely West Java, Central Java, and East Java, although the research conducted rarely involves prospective teachers. The STEM study center at the university is a step to strengthen the implementation of STEM now and in the future in Indonesia, such as at the Indonesian Education University which has a STEM study center and at Semarang State University.

Literature reviews on STEM education in Indonesia are beginning to emerge. Research related to "the urgency of STEM education in Indonesia", aims to investigate how STEM education is implemented by teachers (Nugroho et al., 2021). Meanwhile, Nurwahyuni's research (2021) reviewing the literature on how the STEM approach can improve the quality of science learning in Indonesian schools (Li et al., 2020; Suprapto, 2016; Zulaikha et al., 2021), conducted a literature review on the STEM approach in physics learning, the STEM approach in junior high schools, and the impact of STEM education. STEM education has gained global recognition for its potential to equip learners with the skills and knowledge needed in the 21st century. As education systems adapt to rapid technological changes and complex global challenges, effective pedagogical models that support interdisciplinary STEM learning are essential. In the Indonesian context and beyond, diverse studies have attempted to implement and assess various STEM teaching approaches, media, and contextual applications. However, there remains a gap in systematically synthesizing these approaches and their impact. This review addresses that gap by focusing on the question: What pedagogical models and applications are most prevalent and impactful in STEM education?

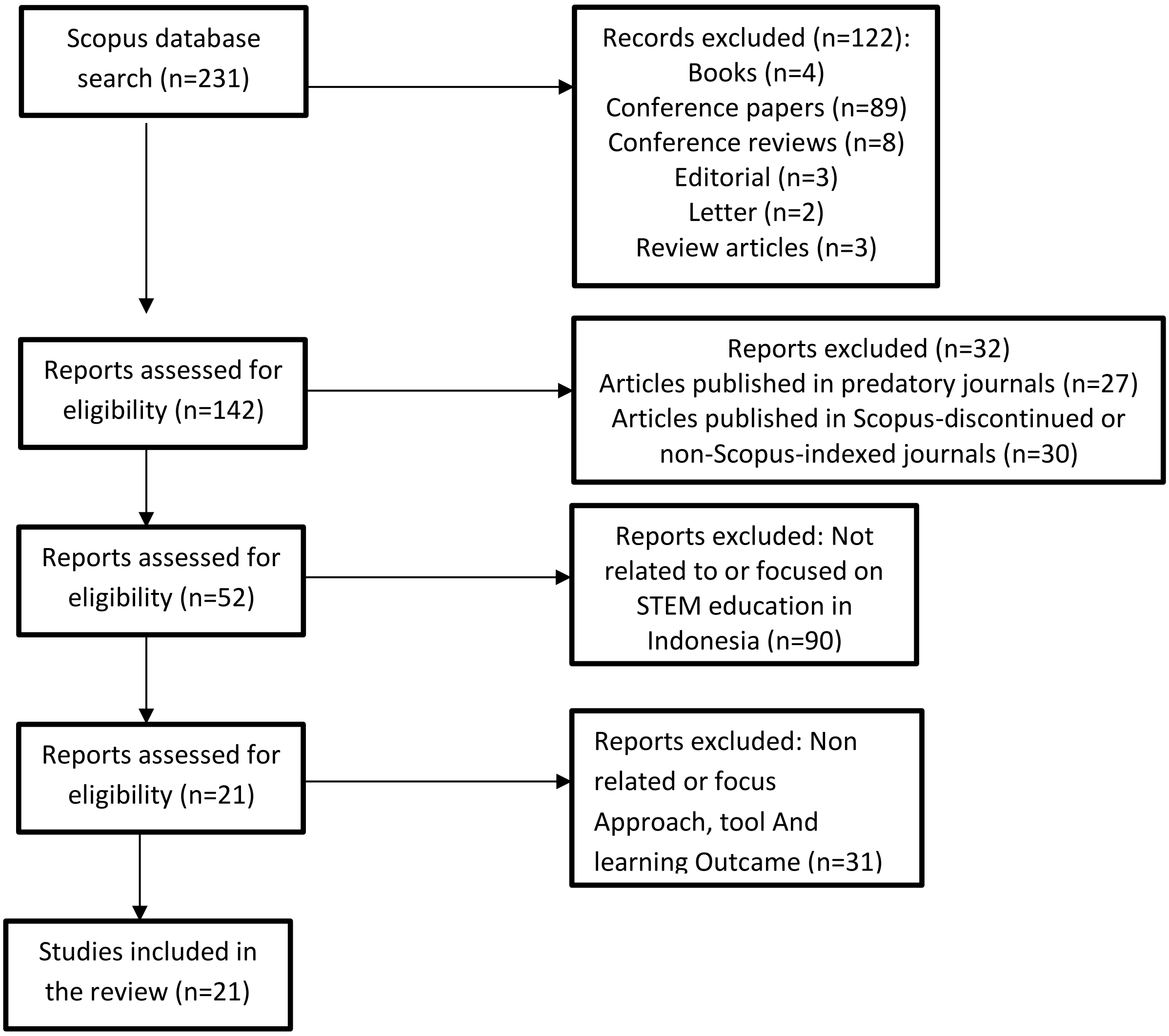
METHOD

This literature review research follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) search protocol in finding published STEM research (Page et al., 2021). A systematic review was conducted to identify, summarize, and evaluate findings from studies relevant to STEM in Indonesia in terms of approaches, tools, and learning outcomes. To prevent bias in selection, this review used a more detailed and comprehensive search strategy by identifying and all studies that fit the topic. We searched data through Scopus, and ERIC with the phrase STEM in Indonesia in 2016-2025.

The literature review process began with a discussion between the authors to clearly define the inclusion and exclusion criteria. The first stage involved screening articles with the stipulation that only peer-reviewed journals or book chapters in English would be considered. This selection process excluded some forms of academic publications, particularly conference papers and dissertation manuscripts. We assume that peer-reviewed journal publications provide a higher level of validity and reliability. Second, the studies had to address the application of STEM in learning. The third criterion required that the articles should include detailed engagement and explanation of the implementation of pedagogical practices in the STEM approach. Finally, to further narrow the scope of the articles, the selected studies focused on STEM education with an examination of the pedagogical model, media/tools used, learning outcomes, and implementation context.

The authors generated a total of 231 articles. After reading the titles and scanning the abstracts of the articles, a total of 89 articles were excluded. These articles were not peer-reviewed journal articles or book chapters and did not focus on STEM education. Regarding the remaining 142 articles, the authors met again and submitted the articles to a second eligibility check as described above. Their abstracts and introductions were scrutinized more closely. At this stage, 90 articles were excluded. After reading all 52 remaining articles, we found that 31 of the studies were not focused on STEM education or were not empirical research (or program evaluations). These studies were then excluded. After using the snowballing exercise, we were able to obtain three eligible articles, giving us a total of 21 articles for this review. Figure 1 below is a diagrammatic representation of the selection and screening process for eligibility.

Figure 1: PRISMA flow diagram



After the articles were collected, the researcher conducted a thematic analysis by grouping the contents of each article based on the main topic. The main focus of the analysis includes: Types of learning models or pedagogical approaches used, integrated media or learning aids, student learning outcomes in terms of knowledge, attitudes, and skills. Information from the articles was then compiled into a synthesis table and explained narratively to make it easier for readers to understand the findings as a whole. In general, the inclusion and exclusion criteria in this study are as in Table 1.

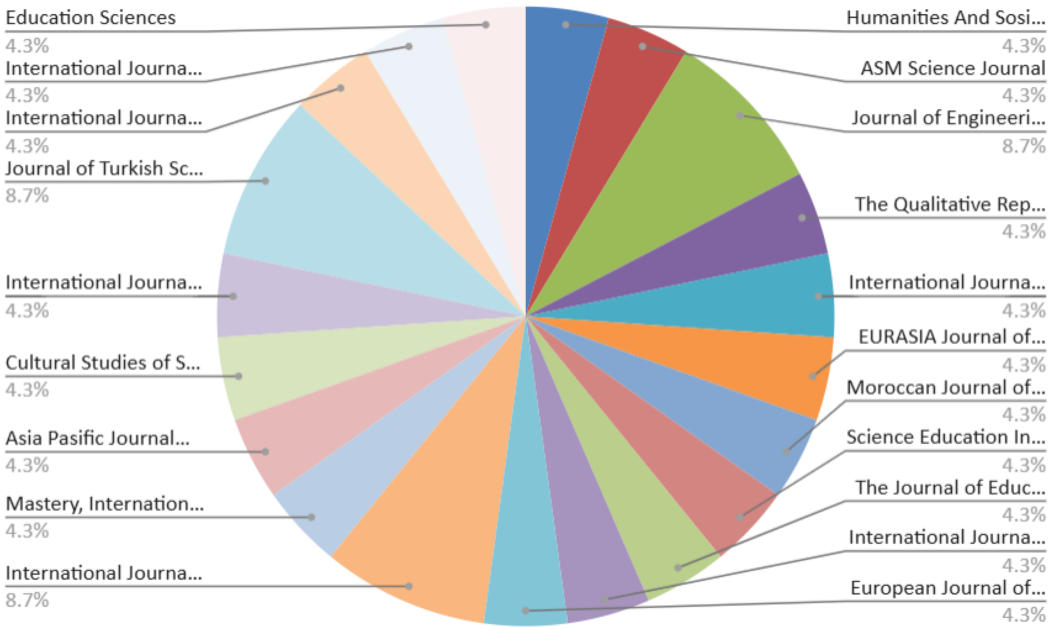
Table 1: Article Inclusion and Exclusion Criteria

Inclusion criteria	Exclusion criteria
Peer-reviewed journal articles, scientific conference proceedings, or research reports	Popular articles, editorials, opinions, or writings without a basis in scientific research
Year of publication between 2016–2024	Published before 2016 or after 2024
Full text is available and accessible	Only abstract or limited access available
Discussing STEM learning from pedagogical, media, learning outcomes, or integration perspectives	Doesn't discuss STEM directly or only discusses STEM as background
Context of primary, secondary or higher education (formal education)	Non-educational contexts or informal education without a pedagogical focus
Empirical or conceptual relevance to the application of STEM education	Does not contain academically relevant data or commentary

FINDINGS AND DISCUSSION

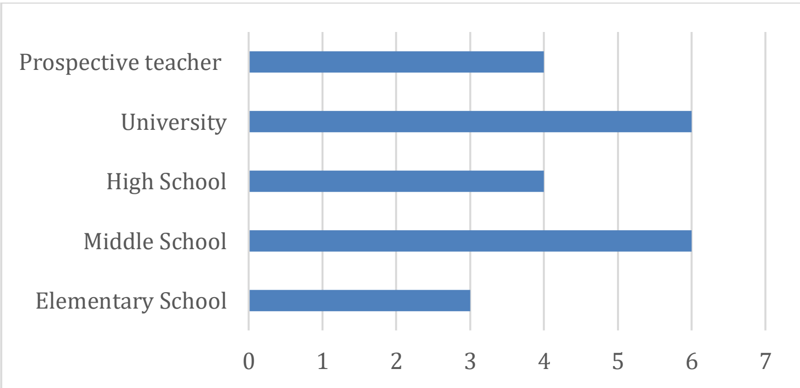
Based on the analysis results, a total of 21 studies passed the selection in this study, all of which were published in 18 different journals. (Figure 2) during the period 2016-2025. Only two articles appeared in the same journal (Journal of Engineering Science and Technology), International Journal of Evaluation and Research in Education (IJERE), and Journal of Turkish Science Education. While the rest are spread across different publications. The diversity of journals with diverse visions and scopes shows the great interest of various academic communities in STEM integration in Education.

Figure 2: Distribution of journal publication articles



Analysis based on the level of education regarding the implementation of STEM shows that the distribution of research shows an even interest but with different approaches at each level, 3 studies were obtained at the Elementary School (SD) level, 6 at the Middle School (SMP), 4 at the High School (SMA), 6 at the University (PT), and 2 studies that focused on teachers or prospective teachers (Figure 3).

Figure 3: STEM implementation based on education level



At the elementary school level, the STEM approach tends to be directed at strengthening students' attitudes and interests in science and technology. The learning model used adopts more simple project-based exploratory activities that are contextual and fun. As explained in the research of Suprapto (2016), elementary school students showed an increased interest in the STEM field after participating in learning activities that were integrated with their daily lives.

At the junior high school level, the pedagogical focus begins to shift towards developing higher-order thinking skills, such as critical thinking, collaboration, and problem solving. Seven studies at this level adopted the STEM-EDELCY, PjBL, and inquiry-based STEM models, which have proven effective in strengthening conceptual understanding and linking learning to real problems. For example, Herianto (2024b) reported that the use of the STEM-EDELCY model can improve students' creativity and systematic thinking skills. Meanwhile, at the high school level, the STEM approach emphasizes strengthening scientific concepts and their technological applications. Five studies at this level show how students are able to complete complex projects such as designing earthquake-resistant buildings (Ardianto et al., 2019) or using IoT-based devices for plant growth experiments (Supahar et al., 2024). The approach used encourages students to think across disciplines and develop innovative solutions. Meanwhile, at the tertiary level, seven articles discuss STEM learning in the context of strengthening academic literacy, professionalism, and research skills. For example, a study by Anggaryani, et.al (2023) used Virtual Reality technology in immersive disaster mitigation learning, while Sayekti (2020) highlighted the importance of the role of librarians in supporting information access and digital literacy for STEM program students.

Finally, two articles focused on teachers and pre-service teachers, suggesting that educator readiness is a crucial element in the successful implementation of STEM. A study by Wahono, et.al (2021) showed that teachers' understanding of STEM approaches and global issues such as low-carbon education can shape more relevant and reflective learning processes. Overall, these findings suggest that STEM learning models are adapted to the cognitive development and needs of learners at each level. This adjustment allows STEM learning to be not only a transfer of knowledge, but also a means to shape more contextual, collaborative, and visionary ways of thinking and acting. Meanwhile, based on the results of the analysis in the context of the research setting for STEM implementation in Indonesia, the results obtained were as in Figure 4.

Figure 3: STEM implementation research setting in Indonesia

Geographically, the majority of research is concentrated in Java Island (15 studies/71%), in Sumatra (2 studies/10%), and in Mataram 1 study (5%). This pattern reflects that Java Island has many universities, adequate human resources, and researchers who live in Java Island. Although the distribution of this area is not evenly distributed, it has shown an awareness of the importance of contextual education in STEM. This can be seen in the study (Suratno et al., 2020) which utilized the coffee plantation area to improve students' problem-solving abilities through the application of STEM with a problem-based approach.

Characteristics of Reviewed Studies

Most studies were conducted in Indonesia, with a mix of research from primary to tertiary education. Common themes included environmental issues, disaster education, local culture, and digital technology integration. The results of the synthesis of the 21 articles reviewed in this study are as shown in Table 2.

Tabel 2: Synthesis Table of Reviewed Articles

No	Article Title	Author	Model used (pedagogical)	Media / tools used (Tools)	Measured learning outcomes (learning outcomes)
1	Factors influencing student interest in	(Amalina et al., 2025)	SEM comparing Model 1	STEM media exposure	Self-confidence,

	STEM careers: motivational, cognitive, and socioeconomic status		(cognitive+motivational+SES) vs Model 2 (cognitive+SES); SCCT as a theoretical framework.	(reading, watching, applying); measured via survey, not class materials.	learning motivation, cognitive ability
2	Virtual Reality as Experiential Learning to Promote STEM-DRR in Tertiary Education	(Anggaryani et al., 2023)	Experiential Learning (Kolb) is delivered through practical training VR modules.	Virtual Reality online training; VR headset, disaster situation simulation.	Learning experience
3	Analyzing higher education students' understanding of earthquake-resistant buildings on stem learning	(Ardianto et al., 2019);	VR-based experiential learning	Virtual Reality (mobile + headset): earthquake-resistant construction simulation.	Understanding the concept of earthquake resistant structures, increasing motivation and efficacy
4	STEM Implementation Issues in Indonesia: Identifying the Problems Source and Its Implications	(Arlinwibowo et al., 2023)	No learning model is used, researchers are more concerned with studying problems in implementing STEM	No media is used	Policy implication
5	Teaching Approaches for STEM Integration in Pre-and Primary School: a	(Larkin & Lowrie, 2023)	Inquiry-based, PBL, PjBL; Play-based emerged	Diverse (robotics, digital games, touchscreen), without a	No quantitative data presented; integration

	Systematic Qualitative Literature Review		but were limited.	single media focus or quantitative evaluation.	trend analysis, not student outcomes.
6	The Effectiveness of STEM Education for Overcoming Students' Misconceptions in High School Physics: Engineering Viewpoint	(Hasanah, 2020)	Engineering design-based STEM and hands-on learning through experimental cycles.	Soundcard oscilloscope: a practical, inexpensive, and interactive device for visualizing AC signals.	Concept understanding, reducing misconceptions
7	Developing student 21st-century skills through STEM engineering design learning cycle (STEM-EDELCY) model	(Herianto et al., 2024a)	EDELCY design cycle: engage, define problem, plan & design, create, test & improve, explain, elaborate, and evaluate	Simple hands-on prototype/activity for junior high school level	Creativity, collaboration, communication, problem-solving
8	STEM-EDELCY learning model: a conceptual and pedagogical framework to facilitate students to develop 21st-century skills	(Herianto et al., 2024b)	STEM-EDELCY	Simple prototype, custom module, LKS	21st century skills
9	How Does Teachers' Perception on STEM Learning for Low Carbon Education?	(Nurramadhani & Riandi, 2024)	Inquiry & design based models in a low carbon context	Simple devices & local materials (energy	Environmental awareness

				experiments, carbon cycle)	
10	The Effectiveness of Science, Technology, Engineering, and Mathematics-Inquiry Learning for 15-16 Years Old Students Based on K-13 Indonesian Curriculum: The Impact on the Critical Thinking Skills	(Pahrudin et al., 2021)	STEM-Inquiry	Momentum and impulse experiment equipment	Critical thinking
11	Elementary students' attitudes towards STEM and 21st-century skills	(Perdana et al., 2021)	Descriptive survey (questionnaire); no practical intervention on learning models	No special media	21st Century Attitudes and Skills
12	Effectiveness of Ethnoecological-STEM Project-Based Learning Model to Improve Critical Thinking Skills, Creativity, and Science Concept Mastery	(Rohman et al., 2024)	Ethnoecological-STEM based on PjBL	Local environment, simple experimental tools, contextual worksheets	Critical thinking skills, creativity, and conceptual mastery
13	Virtual Learning and the Role of Liaison Librarians in STEM Academic Programs	(Sayekti, 2020)	Virtual Learning Model with the help of a librarian	Virtual Learning Environment (VLE) Platform; The role of the	Information literacy skills; Learning independence; Academic

				Liaison Librarian	collaboration
14	Students' interests and attitudes toward science, technology, engineering, and mathematics careers	(Septiyanto et al., 2024)	Not specific but focused on surveying interests and attitudes	Questionnaire, survey	Students' interests and attitudes towards careers in STEM fields.
15	Contemporary Hybrid Laboratory Pedagogy: Construction of a Simple Spectrophotometer with STEM Project-Based Learning to Introduce Systems Thinking Skills	(Shidiq et al., 2022)	STEM Project-Based Learning (PjBL)	Simple spectrophotometer from low-cost materials.	Cognitive, systemic thinking skills, affective
16	Towards Integrating STEM Education into Science Teacher Preparation Programmes in Indonesia: A Challenging Journey	(Sulaeman et al., 2022)	Curriculum development framework and teacher training on STEM integration strategies	Problem/project based module	Improving STEM literacy of prospective teachers, Professional attitudes
17	Indigenous knowledge of Indonesian traditional medicines in science teaching and learning using a science–technology–	(Sumarni et al., 2022)	Ethno-STEM based Project-Based Learning (PjBL).	Traditional Indonesian medicine (herbal medicine, herbal plants), Simple experimental tools to	Understanding of science concepts, Critical and creative thinking skills, Awareness of local

	engineering–mathematics (STEM)			extract/test herbal compounds, Observation of the surrounding environment (gardens, traditional markets).	culture and values, Ability to integrate scientific and traditional knowledge holistically.
18	Implementation of audio biostimulators and IOT in STEM learning to enhance the quantity of herbal medicinal plants in Indonesia	(Supahar et al., 2024)	STEM Project-Based Learning (STEM-PjBL), etno-STEM	Audio Biostimulator; Internet of Things (IoT)	Critical thinking and creative thinking
19	Students' Attitudes towards STEM Education: Voices from Indonesian Junior High Schools	(Suprapto, 2016)	STEM-Project based learning	Science labs, project-based activities, and the use of simple tools in experiments.	Students' attitudes and interests towards STEM,
20	Exploring a Direct Relationship between Students' Problem-Solving Abilities and Academic Achievement: A STEM Education at a Coffee Plantation Area	(Suratno et al., 2020)	Problem-Based Learning	Coffee plantation environment	Problem solving skills and academic achievement
21	Teaching socio-scientific issues through integrated	(Wahono et al., 2021)	STEM-6E, SSI	Worksheets, case studies, science news,	Academic abilities (Social and

	STEM education: an effective practical averment from Indonesian science lessons		simple experiments	environmental awareness, Critical thinking skills, Understanding of science concepts)

Pedagogical Models Used

In this study, various pedagogical models were found to be applied in the context of STEM education. These models not only represent traditional learning frameworks but also demonstrate innovative and contextual approaches that reflect the needs of 21st-century learning. The STEM-EDELCY (STEM Engineering Design Learning Cycle) learning model is one of the most prominent approaches. This model systematically guides learners through the stages of engineering design in solving real problems, while integrating principles of science, technology, and mathematics (Sugianto et al., 2023). In addition to encouraging critical thinking and collaboration skills, this model has also been shown to strengthen design and systematic thinking skills.

Another model is Project-Based Learning (PjBL), which is used in the context of ethnoecology and environmental science learning. This model directs students to complete local problem-based projects, such as the use of biostimulators in herbal farming (Sayekti, 2020). In addition, the Experiential Learning approach based on virtual reality technology is also used in disaster education, such as in the study "Virtual Reality as Experiential Learning to Promote STEM-DRR in Tertiary Education" (Anggaryani et al., 2023)

Several other studies integrate the Inquiry-Based STEM and Socio-Scientific Issues (SSI) models that invite students to explore scientific issues in social and ethical contexts, such as climate change and low-carbon energy (Nurramadhani & Riandi, 2024). Even the Ethno-STEM approach is used to incorporate local community knowledge in science teaching, such as in the use of traditional medicinal plants (Sumarni et al., 2022; Suratno et al., 2020). Interestingly, a number of articles highlight the importance of developing literature-based conceptual models, such as those conducted in developing a STEM conceptual framework for pre-service teachers (Berisha & Vula, 2021; Nugraha et al., 2023). This shows that pedagogical development is not always practical, but also needs to pay attention to theoretical foundations and contextual adaptation.

In general, all identified models have a common thread in terms of constructivist approaches, active student engagement, real-world context-based learning, and interdisciplinary collaboration. These models are not only a means of introducing STEM materials, but also a bridge to character development and 21st century skills.

Media and Technological Tools

In the various studies reviewed, the media and tools used in STEM learning are very diverse, reflecting a paradigm shift towards more contextual, sustainable, and technology-based learning. Several studies have shown the use of immersive technologies such as Virtual Reality (VR) to create immersive learning experiences, especially in the context of disaster education. For example, Ardianto et.al (2019) stated that "The use of VR in earthquake simulation scenarios helps students develop conceptual understanding through multisensory experiences that are difficult to obtain in conventional learning”. Internet of Things (IoT) technology has also become an effective instrument in several STEM projects, such as in a study by Supahar et al. (2024), where students used sensors and actuators to monitor the growth of herbal plants. The study concluded that "the integration of IoT devices in a local context can strengthen the understanding of ecosystem concepts while introducing digital technology skills to students."

In addition, simpler yet innovative tools are also used, such as in the study of Shidiq et al. (2022) which used a project-based hybrid laboratory. In this approach, students are invited to build a simple spectrophotometer independently using recycled materials. This activity not only introduces the basic principles of spectroscopy and the chemical properties of solutions but also encourages systemic and creative thinking skills. Through direct experience in assembling tools and analyzing data, students gain a more meaningful understanding while building values of sustainability and independence in science learning.

Student Learning Outcomes

The learning outcomes achieved in various STEM pedagogical models are not only limited to conceptual mastery, but also include critical thinking skills, problem solving, and students' affective engagement. In the context of physics education, Pahrudin et.al (2021) stated that the application of engineering design-based learning models can significantly reduce students' misconceptions and improve their scientific thinking skills. Meanwhile, research by Rohman et al. (2024) revealed that STEM project-based learning activities that are contextual to the surrounding environment have been shown to improve students' understanding of science concepts, especially in the field of the environment. The study also noted an increase in reflective and communication skills. Affectively, STEM has also been shown to strengthen students' positive attitudes towards science and increase interest in careers in STEM. The application of STEM to elementary school students showed a significant increase in their enthusiasm and scientific attitudes towards science and technology lessons (Atmojo et al., 2023; Perdana et al., 2021). Furthermore, models like STEM-EDELCY have been shown to build 21st-century skills more holistically. "Students showed improvements in collaboration, creativity, and adaptability when faced with design challenges and prototype testing," said Herianto et al. (2024b).

CONCLUSION

Based on the results of a systematic review of 21 articles published between 2016 and 2024, it can be concluded that STEM education in Indonesia has developed with increasingly diverse, contextual, and adaptive pedagogical approaches to the challenges of the 21st century. Learning models such as STEM-EDELCY, Project-Based Learning, Inquiry-Based STEM, and Ethno-STEM have been proven to improve critical thinking skills, creativity, collaboration, and mastery of science and technology concepts at various levels of education. The use of innovative media and learning tools such as Virtual Reality, Internet of Things, hybrid laboratories, and the use of local knowledge, show strong efforts to integrate STEM with meaningful and contextual learning experiences. This shows that the success of STEM education depends not only on the pedagogical model used, but also on the relevance of the local context and the availability of technological resources. However, the implementation of STEM education still faces a number of challenges, such as teacher readiness, limited facilities, and less than optimal curriculum alignment. For this reason, support from various parties—especially in terms of teacher training, integrative curriculum development, and supportive education policies is very crucial.

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