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Overcoming Challenges in STEM Education: A Literature Review That Leads to Effective Pedagogy in STEM Learning

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Abstract: The current study aims to analyze trends in studies related to challenges of STEM-based learning, analyzing the challenges of STEM education, describing solution approaches to overcome challenges in STEM education, and describing effective STEM pedagogy. To achieve the goals of this study, a literature review related to STEM education and learning was conducted, specifically by performing a bibliometric analysis. The bibliometric analysis is related to a coherent literature review with the theme of "Challenges of STEM-based Learning," analyzed from SCOPUS databases. The results of the study show that to date the existing study trends have addressed a number of challenges related to STEM education, especially those related to STEM pedagogy. The current study proposes a number of approaches to address challenges in STEM education, the focus is on how effective STEM education can be implemented in learning routines. Finally, it was concluded that some effective pedagogical aspects in STEM education and learning include: creating an innovative learning environment that encourages inquiry, experimentation, and critical thinking; utilizing various authentic learning methods and relevant learning resources; facilitating a collaborative learning environment; creating an inclusive learning environment; and reflecting and improving teaching practices.

Keywords: Challenges; Literature Review; Effective Pedagogy; STEM Education and Learning

Introduction

STEM (Science, Technology, Engineering, and Mathematics) education is understood as an interdisciplinary approach to education that aims to connect independent disciplines between sciences to help students solve authentic problems. STEM education provides students with the knowledge and skills they need to succeed in all kinds of challenges in the 21st century. This is why STEM education is used as a benchmark for the success of human resource development in the education system because it is related to a country's global competitiveness (Kayan-Fadlelmula et al., 2022). STEM education is a key driver of human capacity building (Miller-Idriss & Hanauer, 2011) and has the potential to motivate students to continue participating in STEM fields in their future careers (Lee et al., 2019; Margot & Kettler, 2019).

In contemporary education systems, STEM has become a continuously growing trend for the purpose of preparing students who are engaged in it for a brilliant future. For this reason, many education systems have placed STEM as an important part of the curriculum (Al Salami et al., 2017; Bagiati & Evangelou, 2015). Furthermore, STEM education has been integrated in many ways of teaching in the regular curriculum, reflecting the importance of STEM in the education and learning system (Holmlund et al., 2018; Li et al., 2019). STEM integration can occur at different levels, namely: disciplinary (concepts in each discipline are learned separately), multi-disciplinary (concepts in each discipline are learned separately but in the same theme), interdisciplinary (concepts from two or more closely

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related disciplines are learned with the aim of deepening knowledge and skills), and transdisciplinary (knowledge and skills learned from two or more disciplines are applied to real-world problems and projects, thus helping to shape the learning experience) (Leung, 2020).

STEM has been studied as a separate discipline (disciplinary and multi-disciplinary) since the past. However, in its development, STEM is now integrated inter-disciplinarily and trans-disciplinarily as applied in developed countries, so that STEM education is better known as interdisciplinary education. Interdisciplinary STEM education was born to overcome various authentic problems. For example, problems related to environmental pollution or waste processing require solutions from a number of interdisciplinary knowledges in the fields of biological sciences, chemical sciences, and engineering. Problems related to weather forecasting require a number of interdisciplinary knowledges in the fields of biological sciences, chemical sciences, physical sciences, and technology. Matters related to radiation technology require interdisciplinary knowledge in all areas of science (biology, chemistry, physics), engineering, and advanced technology. Even current robotic system automation is an integration of interdisciplinary knowledge from technology, engineering, and mathematics. There are still many contexts that require integrative knowledge in the STEM field.

Until now, the success of STEM education has been reported to have progressed in several developed countries such as the United States, as a supporter of future industrial resource development (Lee et al., 2019). This is due to education reforms in the United States that emphasize the need to develop complex engineering and technology skills among students, as well as encouraging student participation in a knowledge-based modern economy (Börner et al., 2018; van Laar et al., 2017). However, other reports indicate that teachers face many challenges in implementing STEM education (Ryu et al., 2019). This is especially true in developing countries in Asia (Lee et al., 2019). The scarcity of STEM integration models in the existing literature also poses a problem for teachers to successfully implement integrated STEM education in schools (Smith et al., 2022). Lee et al (2019) suggest that more research should be conducted to explore the implementation of STEM education by teachers in Asian countries. This includes Indonesia, which has little knowledge of how STEM education is implemented and how to increase its effectiveness (Verawati et al., 2022).

The study of STEM pedagogy has become important to be further explored in order to provide a more detailed understanding of the effective STEM pedagogical needs to overcome the challenges in STEM learning. Therefore, in the current study, the terminology of STEM education is also specified in the context of STEM learning. The context of the current study aims to analyze several aspects related to STEM education and learning, specifically, the study objectives are: analyzing trends in studies related to challenges of STEM-based learning, analyzing the challenges of STEM education and learning today, describing solution approaches to overcome challenges in STEM education and learning, and describing effective STEM pedagogy.

Method

To achieve the goals of this study, a literature review related to STEM education and learning was conducted, specifically by performing bibliometric analysis. This analysis also serves as a basis for analyzing the current challenges in STEM education and learning, describing approaches to overcome these challenges, and describing effective STEM pedagogy. The bibliometric analysis was adapted from Wirzal et al. (2022) and is related to a coherent literature review with the theme of "Challenges of STEM-based Learning" analyzed from various sources such as studies, documents, and specific databases. In other words, this study is also known as a meta-analysis.

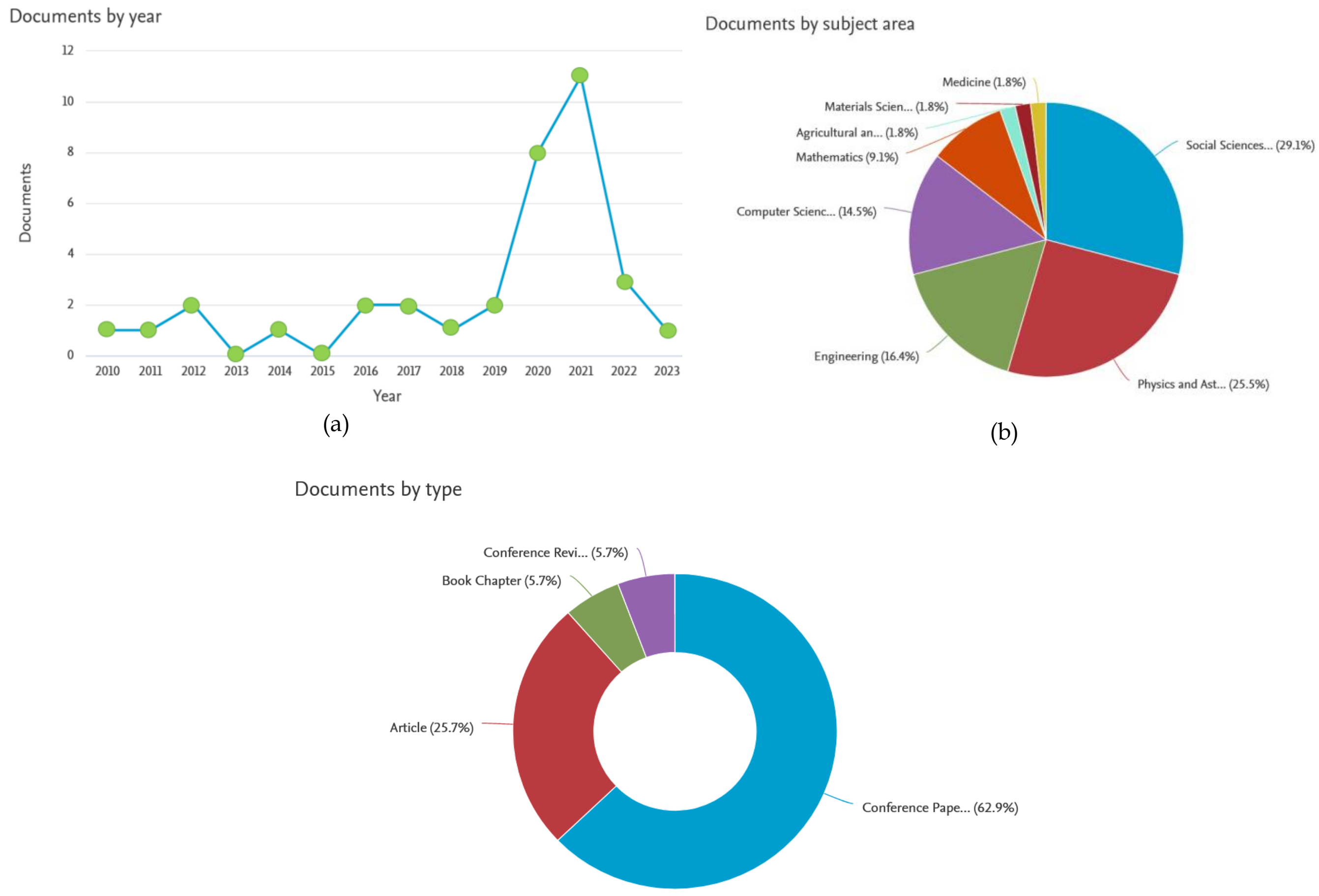
The bibliometric analysis was conducted using the SCOPUS database as a source of information. The SCOPUS database is considered one of the most accurate sources of data in the world, as it evaluates the quality of articles under a publisher umbrella. It has comprehensive features that allow anyone to explore high-quality articles according to the author, title, year, publisher, citations, or other metric data accurately.

The bibliometric analysis was conducted on April 18th, 2023, by exploring the SCOPUS database and entering the keywords or search terms related to the study theme in English. This is done to ensure that SCOPUS can adequately read and explore the study's relevant materials. The keywords used were "Challenges of STEM-based Learning" TITLE-ABS-KEY (Challenges AND of AND Stem AND based AND Learning). This screening process was not limited to any particular year, subject area, document type or source, or other restrictions. Each search result was documented (data curation) in a (.ris)/(.csv) file and visualized. Each data mode was also screen printed (prt-scr) from the SCOPUS database display to facilitate the analysis and discussion process. Finally, the results of this bibliometric analysis served as a starting point for analyzing the current challenges in STEM education and learning, describing approaches to overcome these challenges, and effective STEM pedagogy, compared to other relevant literature.

Result and Discussion

Coherent study trends with the theme 'Challenges of STEM-based Learning'

A coherent literature review on the theme of "Challenges of STEM-based Learning" was analyzed from various study sources, documents, and SCOPUS-based data, indicating that as many as 36 documents were found in the last thirteen years (2010-2023). The distribution of documents is presented in Figure 1a, where no documents discussing STEM learning challenges were found before 2010. Documents sourced from SCOPUS data are classified by subject area and type, as presented in Figures 1b and 1c.



(a) (b) (c)

Figure 1. The results of the SCOPUS data analysis related to the 'Challenges of STEM-based Learning': 1(a) Distribution based on year; 1(b) Distribution based on subject area; 1(c) Distribution based on type.

A total of 36 documents were found in the last thirteen years (2010-2023) that are coherent with the study theme of 'Challenges of STEM-based Learning' (see Figure 1.a). The subject area is not only limited to STEM fields itself but also extends to intersecting fields such as medicine, agriculture, and others (see Figure 1.b).

The distribution based on the document type is mostly comprised of articles and conference documents (see Figure 1.c). The documents related to the theme of 'Challenges of STEM-based Learning' [TITLE-ABS-KEY - Challenges AND of AND Stem AND based AND Learning] that were displayed on the SCOPUS website (https://www.scopus.com/) are presented in Table 1.

Elaborating on the analysis of the articles presented in Table 1, it was found that almost all of the research that is coherent with STEM education and learning considers that the areas that focus on effective STEM pedagogy have had an impact on the development of knowledge and literacy (Annisa et al., 2022), problem-solving skills (English, 2023; Tuong et al., 2023), thinking skills, and mastery of concepts (Zakiyah et al., 2021), as well as other positive impacts in education. However, a review of several other literature sources found some challenges in STEM education and learning. This is further discussed as an important part of the current study, including how to address the solutions to each of the challenges faced.

Table 1. Documents related to the theme 'Challenges of STEM-based Learning'

Title	Author(s)	Source
Utilizing STEM-Based Practices to…	(Tuong et al., 2023)	Journal of Technology and Science Education.
Ways of thinking in STEM-based problem solving	(English, 2023)	ZDM – Mathematics Education.
Effects of STEM-based learning materials on…	(Annisa et al., 2022)	Journal of Physics: Conference Series.
Professional Growth and Identity Development of STEM Teacher Educators in…	(Weinberg et al., 2021)	International Journal of Science and Mathematics Education
…	…	…
…	…	…
…	…	…
From design to prototype - Manufacturing STEM integration in the classroom…	(Flynn, 2011)	Integrated STEM Education Conference
The P3E2 project: The introduction, implementation and evaluation of engineering design integrated …	(Pizziconi et al., 2010)	ASEE Annual Conference and Exposition

Challenges in STEM education and learning

STEM education has been implemented in many countries and is considered an important component. However, the adoption of STEM has brought up several barriers because it differs from the traditional subject paradigm. This has prompted researchers to focus on identifying barriers to effective STEM education.

In the current study, at least six main challenges were identified in STEM education and learning, namely: pedagogical challenges, curriculum challenges, structural challenges, student concerns, assessment concerns, and teacher support. These challenges are in line with other studies by Margot and Kettler (2019) and other research in separate contexts (Aikenhead, 2008; Bagiati & Evangelou, 2015; Dong et al., 2020; Holstein & Keene, 2013; Shernoff et al., 2017). These barriers are then discussed by elaborating on some relevant previous studies. Some recommendations or solutions are also provided to overcome the challenges and barriers in the effective implementation of STEM education.

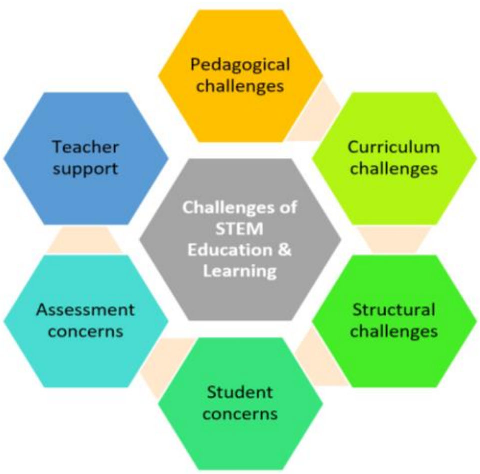


Figure 2. The challenges of STEM education and learning

Pedagogical challenges

The idea of integrating STEM education into the existing pedagogical principles can be intimidating for teachers, causing some of them to believe that they are not prepared to carry out STEM pedagogy (Le et al., 2021). However, STEM requires a type of instruction that emphasizes student leadership in the learning process, thus requiring a new pedagogical system in STEM education (Lesseig et al., 2016; Park et al., 2017). Additionally, Bagiati and Evangelou (2015) and Holstein and Keene (2013) state that teachers are concerned about aligning their pedagogy with the STEM curriculum.

Meeting the diverse needs of students is another concern, as noted by Herro and Quigley (2017) and Park et al. (2017). Finally, Dare et al. (2014) state that teachers may worry that STEM integration could reduce the teaching of essential content concepts in science. Overall, these pedagogical challenges are caused by the typical interdisciplinary nature of STEM, requiring adequate adaptation of teachers' beliefs and knowledge about STEM itself (Dong et al., 2020). Each STEM instructor must also understand and build adequate pedagogical infrastructure in STEM teaching (Verawati et al., 2022), and this is the biggest challenge in STEM pedagogy.

Curriculum challenges

The integrated nature of STEM education presents a challenge in developing its curriculum (Bagiati & Evangelou, 2015), as STEM teaching must follow an interdisciplinary design within the STEM curriculum (Dong et al., 2020). Curriculum is a complex challenge in STEM teaching (Margot & Kettler, 2019), and instructors even perceive STEM curriculum to be rigid and inflexible (Bagiati & Evangelou, 2015; Lesseig et al., 2016).

Other difficulties faced in building a STEM curriculum include integrating multiple specific domains within the STEM field (for example, between Biology and Geometry) (Asghar et al., 2012). Different domains often lead to knowledge miscommunication between teachers who teach and the domains they teach, which impacts instructor anxiety in implementing the STEM curriculum (Asghar et al., 2012; Bell, 2016; EL-Deghaidy et al., 2017). Understanding the interdisciplinary nature of STEM curriculum, knowledge of integrating studies across STEM fields, and understanding the content in STEM areas can provide opportunities for success in building effective STEM curricula (Shernoff et al., 2017).

Structural challenges

The typical institutional structures of educational institutions such as schools and universities can be a barrier to new STEM education practices (Dong et al., 2020; Margot & Kettler, 2019; Shernoff et al., 2017). The organization and policies of schools have an impact on the implementation and progress of STEM education (Shernoff et al., 2017). The time needed for STEM learning practices is usually longer than other fields of study, but if school policies limit scheduling for STEM learning, it can negatively impact the planning and implementation of STEM learning (Asghar et al., 2012; Dare et al., 2014; Lesseig et al., 2016). Policy structures that lead to frequent curriculum changes can also present challenges and consequences that are exhausting for teachers in planning STEM education (Herro & Quigley, 2017). Other obstacles related to structures have been discussed in several studies, such as administrative structure barriers (Asghar et al., 2012; Clark & Andrews, 2010; Park et al., 2016), and the lack of resources and infrastructure support (Wang, Moore et al., 2011).

Student concerns

The integration of STEM education faces other challenges, namely student ability concerns. Active student engagement sometimes becomes a concern for teachers in STEM learning, and this becomes a barrier to the success of STEM education (Margot & Kettler, 2019). The motivation of students to learn STEM has an impact on many aspects of their learning outcomes (Aeschlimann et al., 2016). Based on various studies (Al Salami et al., 2017; Bagiati & Evangelou, 2015; Van Haneghan et al., 2015), teachers often underestimate their students' problem-solving abilities in STEM subjects, according to the experience of teaching STEM. This can cause a decrease in student motivation. This situation is also found to be increasingly challenging, especially for teachers in rural areas where students may have lower performance levels. In addition, adapting STEM lesson plans to meet these student needs is a difficult task (Goodpaster et al., 2012), and these concerns can affect how teachers approach and implement STEM learning (Holstein & Keene, 2013).

Assessment concerns

The implementation of STEM integration by teachers faces significant challenges related to the lack of reliable assessment tools, insufficient planning and implementation time for assessments, and inadequate STEM knowledge (Margot & Kettler, 2019). Teachers argue that there is a scarcity of standard evaluation methods for STEM programs, making it a difficult task to accurately assess student STEM performance (Nadelson & Seifert, 2013). In addition, issues related to individual or group assessments are also a matter of debate (Herro & Quigley, 2017).

Teacher support

The teacher is the main determining factor in implementing all forms of policies in the provision of STEM education and learning. All responsibilities related to the provision of STEM education are entrusted to the teacher. Teacher support is crucial in the framework of STEM education. However, the extra workload that teachers must bear can sometimes be a challenge, including preparing an effective pedagogical framework for STEM, participating in planning and implementing STEM curricula, preparing students to engage and acquire adequate STEM knowledge, preparing STEM evaluation instruments, and others. Finally, teachers must prepare a lot of extra time in STEM education (Margot & Kettler, 2019). The results of a study by Park et al. (2016), state that the biggest challenge for teachers in implementing STEM education and learning is the lack of time, especially if teachers have to meet other administrative demands.

Another challenge in implementing STEM education is that teachers often feel that they have inadequate knowledge of STEM subjects. However, the teacher's knowledge base is a factor in the success of STEM education provision (Dong et al., 2020). According to several studies (Al Salami et al., 2017; Hsu et al., 2011; Nadelson & Seifert, 2013), pre-service teacher training programs are reported to be inadequate in preparing teachers for teaching STEM in the field. In addition, teachers express concern about meeting high expectations from schools and policymakers for student STEM learning outcomes. Although teachers recognize the importance of integrating STEM subjects into learning, they lack confidence in effectively implementing STEM lessons, which can ultimately affect the effectiveness of STEM teaching (Bagiati & Evangelou, 2015; Clark & Andrews, 2010; Holstein & Keene, 2013).

Although teachers are the primary determining factor in implementing all forms of policies in STEM education, not all the responsibility for the challenges lies on their shoulders. Curriculum challenges seem to be the responsibility of all stakeholders in STEM education (policy makers, schools, teachers). Structural challenges are clearly the responsibility of schools and governments to encourage the development of STEM education in schools, including responsibility for assessment concerns (as they relate to the curriculum) and teacher support. The heavy burden on teachers is how to prepare an effective pedagogical infrastructure for STEM education and learning. This will have implications for solving problems related to student concerns.

Table 2. Approaches to address challenges in STEM education and learning

Aspects	Challenges (literature study)	Overcoming challenges
Pedagogical challenges	• Unpreparedness of teachers in implementing STEM pedagogy is due to their lack of understanding of how to effectively implement STEM pedagogy.	• Every STEM instructor must understand and build an adequate effective pedagogical infrastructure for STEM learning.
Curriculum challenges	• Interdisciplinary nature of STEM poses challenges in developing STEM curriculum, especially when connecting multiple specific content or domain within it.	• Understanding the interdisciplinary nature of the STEM curriculum, knowledge of how to integrate different STEM fields of study, and an understanding of the content within the STEM areas can provide opportunities for success in building an effective STEM curriculum.
Structural challenges	• Typical institutional structures (organizations and policies) of educational institutions do not prioritize the development of STEM. This results in a lack of allocation of resources to meet the needs of STEM education.	• The institutional structure is usually autonomously regulated by the school, but interventions aimed at optimizing STEM education should include regulations set by the government. This is an effort to suppress and encourage the development of STEM education in schools.
Student concerns	• The students' motivation to learn STEM is relatively low, which has an impact on their STEM learning outcomes.	• This relates to the arrangement of STEM learning with the intervention of an effective pedagogical system to build motivation in learning STEM.
Assessment concerns	• There is currently no standard evaluation method for STEM programs, which makes it a challenging task for teachers to accurately assess the performance of STEM students.	• A standard evaluation method is needed for STEM programs. This relates to the established curriculum. STEM requires authentic assessment methods.
Teacher support	• The inadequate knowledge of teachers about the STEM domain, coupled with the extra workload on teachers, hinders their support for the implementation of STEM education.	• Programs for teacher training are needed to teach STEM and ensure that every STEM teacher understands the subject matter domain within STEM.

Effective pedagogy in STEM education and learning

In developing STEM pedagogy, one epistemic challenge that arises is when attempting to transition from one discipline to another within the scope of STEM. This is due to the limitations in individuals' pedagogical content knowledge, as each STEM field has unique practices that are not easily modified (Leung, 2020). Therefore, a comprehensive learning framework needs to be built to accommodate the interdisciplinary nature of STEM. An effective pedagogical framework is characterized by the development of students' knowledge, skills, and attitudes, as well as the development of several systemic positive learning outcomes acquired by students.

Effective pedagogy is crucial in STEM education and learning. STEM subjects are an integrated part of several disciplines, therefore developing STEM competencies is crucial. Effective pedagogy can help students understand the concepts, methods, and practices of STEM fields, and make them more prepared to solve real-world problems. Some effective pedagogical aspects in STEM education and learning include: creating an innovative learning environment that encourages inquiry, experimentation, and critical thinking; utilizing various authentic learning methods and relevant learning resources; facilitating a collaborative learning environment; creating an inclusive learning environment; and reflecting and improving teaching practices.

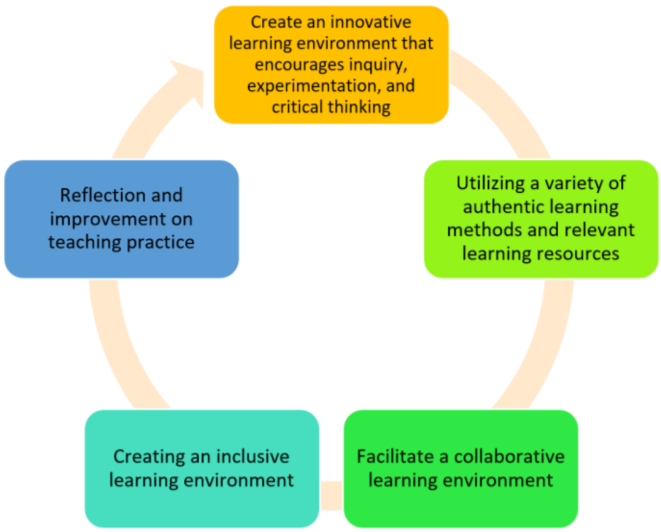


Figure 3. Effective pedagogy in STEM education and learning

Firstly, effective pedagogy in STEM education involves creating an innovative and engaging learning environment that encourages inquiry, experimentation, and critical thinking. Teachers who encourage students to ask questions and provide them with opportunities to explore and experiment, as well as ideas to help develop a deeper understanding of STEM concepts, enable students to become active learners who are responsible for their own learning. This teaching approach allows students to become active learners who are responsible for their own learning. Creating an innovative learning environment provides great opportunities for STEM learning success (Ryoo & Winkelmann, 2021).

Innovative learning is characterized by processes that lead to inquiry and experimentation activities that can foster critical thinking (Prayogi et al., 2018). Scientific literacy through the process of exploration, experimentation, and inquiry has been found to be effective in improving STEM students' critical thinking performance (Bilad, Doyan, et al., 2022). Inquiry-based learning has been found to be effective as a guide in STEM learning in both separate and integrated disciplines. In integrated STEM (interdisciplinary), the presence of technology serves as a bridge in integrating science, engineering, and mathematics teaching and has been found to have a positive impact on students' scientific skills and learning motivation (Wang et al., 2015). Even when inquiry is done in remote learning, the presence of technology can facilitate STEM students to acquire critical thinking skills (Bilad, Anwar, et al., 2022).

Secondly, effective pedagogy demands teachers to utilize various authentic learning methods and relevant learning resources. Effective pedagogy in STEM requires the use of various authentic learning methods. This is addressed in the context of authentic problem-solving, such as problem-based learning (PBL), project-based learning (PjBL), and case-based learning (CBL). PBL is considered the most established learning model in STEM education that can produce effective STEM learning in building students' knowledge and skills, metacognitive reasoning, student motivation, and collaboration (Biazus & Mahtari, 2022; Ekayanti et al., 2022; Fitriani et al., 2022; Hidayat & Evendi, 2022; Smith et al., 2022). PjBL is also used for STEM education and learning in a number of problems in an authentic context that brings together the four STEM disciplines (Oyewo et al., 2022). The application of PjBL in STEM can improve problem-solving competencies (Coufal, 2022), student motivation, and interest in learning (Domenici, 2022).

Consistent with PBL and PjBL, CBL can also be used as a routine pedagogy in STEM learning to develop problem-solving abilities (Sarwi et al., 2021). In addition to learning methods, teachers must also use a variety of learning resources such as multimedia, simulations, and real-world applications to make STEM subjects more accessible to students. However, there are physical limitations for students when dealing with high abstractness STEM content, such as concepts of cells, sound waves, electric current, and others. Technological resources are greatly needed by students to bridge their acquisition of knowledge about STEM content.

Thirdly, effective pedagogy requires teachers to facilitate a collaborative learning environment. STEM professionals typically work in teams, and STEM education should reflect this. Collaborative learning helps students develop teamwork, communication, and problem-solving skills in STEM fields. Effective STEM pedagogy involves teaching students to work together, share ideas, and contribute to group discussions. Opportunities for integrating STEM will be stronger if there is positive collaboration in STEM learning. Previous studies have shown that STEM students who participate in collaborative work demonstrate better cognitive performance (Lange et al., 2021). STEM students who collaborate on a project to produce a product show that teamwork skills are better at producing higher quality products (Kilty & Burrows, 2022).

Fourth, effective pedagogy involves creating a culturally responsive learning environment that is inclusive of diverse learners. STEM education must be accessible and equitable for all students, regardless of their background. Teachers must recognize and respond to the diversity of cultures, perspectives, and student experiences in STEM education. Inclusivity and diversity must be scrutinized as content that has an impact on aspects of STEM pedagogy (Vossen et al., 2023), and teachers must be responsible for creating a STEM learning environment that is responsive to inclusiveness (Edelen & Bush, 2021). Teachers who pay attention to student inclusivity and diversity can increase students' positive perceptions of STEM learning (Clements et al., 2021).

Finally, effective pedagogy in STEM education requires teachers to continually evaluate and reflect on their teaching practices. Teachers must continue to assess student learning, adjust learning methods or models used, and seek professional development opportunities to improve skills in teaching STEM. This teaching approach helps ensure that teachers provide students with the best STEM education and that teachers keep abreast of the latest advances in STEM education. The practice of reflection is absolutely necessary and is carried out by teachers in the STEM learning process in all ways of learning that are conducted (ElSayary, 2021). A recent study by Archer et al. (2022) discussed the reflective practice of teachers in STEM pedagogy aimed at at least three things, namely: deepening knowledge about STEM issues; evaluate the effectiveness of pedagogical practices, including inclusivity; and do better STEM learning planning. Reflection that is done well can help teachers find gaps in STEM learning that is carried out and make efforts to improve learning (Sahin & Top, 2015).

From the five points mentioned above it is concluded that every educator who utilizes effective pedagogy in STEM education can help prepare students for success in the STEM field, and contribute to the development of knowledge in STEM education and learning.

Conclusion

The study of STEM education and learning has been explored in order to provide an adequate understanding of the STEM context, the current challenges of STEM education and learning and addressing these challenges, and effective pedagogy in STEM education and learning. Studies that are coherent with STEM education and learning are currently evolving, and areas that focus on effective STEM pedagogy have had an impact on developing students' knowledge and literacy, problem-solving skills, thinking skills, mastery of concepts, and other positive impacts. The current challenges in STEM education and learning are pedagogical challenges, curriculum challenges, structural challenges, student concerns, assessment concerns, and teacher support. The pedagogical challenge is the most crucial, because it is the teacher's responsibility as a determining factor in STEM education and learning in schools. Several aspects of effective pedagogy in STEM education and learning have been described, namely: creating an innovative learning environment that encourages inquiry, experimentation, and critical thinking; utilizing a variety of authentic learning methods and relevant learning resources; facilitate a collaborative learning environment; creating an inclusive learning environment; reflection and improvement on teaching practice.

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The authors declare no conflict of interest.

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