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Effects of STEM Practices on Students' Problem-Solving Skills: A Meta-Analysis

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Abstract

This meta-analysis study aimed to comprehensively examine the effect size of STEM practices on the development of students' problem-solving skills. By combining the results of 25 individual studies, the researchers can gain a holistic understanding of the overall impact of STEM approaches. Consequently, these studies were categorized according to four key characteristics: education levels, teaching methods and techniques, topics, and durations. The analysis revealed that the number of studies with a very high effect size is exactly 11 out of 25, and the average effect size across all studies was also very high. When examining the effect sizes by educational levels, the largest impacts were found for preschool (2.195) and high school (1.673) students, compared to lower effect sizes for middle school (0.645), higher education (0.623), and elementary school (0.506) students. In terms of teaching methods and techniques, the highest average effect sizes were associated with experiential learning (5.2), the design thinking model (3.033), and approaches focused on the earth's layers and disaster-related topics (2.949). In contrast, lower effect sizes were found for the 5E learning model (-0.346) and content related to electrical conduction (-0.762). The durations of STEM interventions also appeared to influence their effectiveness. Studies with the longest durations of 6-7 weeks (2.960) and 14-16 weeks (1.010) demonstrated greater impacts on problem-solving skills compared to shorter 4-5 week (-.210) and 8-10 week (0.743) interventions. These findings suggest that STEM practices can have a substantial positive impact on the development of students' problem-solving skills, with certain approaches, educational levels, and durations demonstrating particularly strong effects. The results offer valuable insights for educators and researchers seeking to optimize STEM-based learning experiences.

Introduction

People are always trying to find solutions to the problems they encounter in their lives and making efforts to elevate their lives to the best possible state (Aydınlı & Avan, 2017). For this reason, countries place importance on cultivating qualified and productive individuals who can solve global and everyday problems, think creatively, work in teams, and possess strong communication skills and so on (Carnevale, 1990). To reach this goal, many countries place a strong emphasis on training individuals in these skills starting from the early stages of their educational lives within school settings (Hilton & Pellegrino, 2012). In this direction, changes are being made in curricula, and educational environments that foster the development of 21st century skills are being designed (Gut, 2011). According to Allen and Van der Velden (2012), these 21st century skills include collaboration, communication, technological proficiency, cultural competence, problem-solving, creativity, and critical thinking. Meanwhile, Kennedy and Odell (2014) defined 21st century skills more broadly, encompassing life and career skills such as problem-solving, creativity, leadership, critical thinking, global awareness, productivity, communication, information literacy, collaboration, media literacy, technological literacy, and a sense of responsibility.

In recent years, STEM (Science, Technology, Engineering, Mathematics) education has gained prominence globally as an approach that enables students to acquire a wide range of 21st century skills (Amelia & Santoso, 2021; Baran et al., 2021; Tytler, 2020). At its core, STEM education provides a framework for the integration of different disciplinary areas, allowing for a more holistic and interconnected approach to learning and problem-solving (Bybee, 2010; Marrero et al., 2014). By engaging with STEM curricula, individuals are able to tackle complex problems that require the application of knowledge and skills from various disciplines, going beyond the traditional boundaries of subjects like mathematics and science (Bybee, 2013; National Research Council, 2012; Xie et al., 2015). This interdisciplinary approach inherent to STEM education is particularly valuable in the development of individuals' 21st century skills (critical thinking, creativity, and adaptability), with a strong emphasis on problem-solving skills - all of which are essential for navigating the dynamic and rapidly changing world (Batdi et al., 2019; Ichsan et al., 2023; Sen et al., 2018; Zulkifli et al., 2022). By seamlessly integrating multiple disciplines, STEM education empowers learners to approach problems from diverse angles, fostering the kind of multifaceted problem-solving skills that are highly sought after in the 21st century job market and beyond (Kanadli, 2019; Yildirim, 2016).

Problem-Solving Skills

Problem-solving is considered a complex skill that involves the cognitive or affective processes an individual uses to identify problems and discover effective or adaptive solutions to a problem (Jonassen, 2000; McGuire, 2005). In this process, there are three interrelated components: a daily life problem, the process of solving this problem, and the solution reached at the end of the process. First, in examining the term "problem" more closely, the basic definition of a problem is that a gap between where we are or what we have, and a desired location or outcome (Treffinger et al., 2008). Secondly, the process of problem solving is the thinking and behavior we engage in to obtain the desired outcome we seek (Jonassen, 2000).

At this point, it is evident that the process of problem-solving has been categorized and labeled in various ways by different researchers (Gelbal, 1991; Polya, 2004; Schoenfeld, 1992). There are no strictly defined, universal steps related to the problem-solving process. For example, as given in Table 1, Polya (2004) outlined the steps as understanding the problem, devising a plan, carrying out the plan, and looking backward. In contrast, Schoenfeld

(1992) listed the steps as reading or rereading the problem, analyzing the problem (in a coherent and structured way), exploring aspects of the problem, planning all or part of a solution, implementing a plan and verifying a solution. Similarly, Gelbal (1991) defined the steps as noticing the problem, defining the problem, producing alternative solutions, and applying the selected solutions. Beyond simply outlining the steps, some studies have also focused on developing competencies related to the problem-solving process and constructing rubrics for assessing these competencies.

Table 1. The Steps of Polya's (2004) Problem-solving Process

Steps	Process	Explanations
Step-1	Understanding the problem	Identifying the problem's knowns (givens) and unknowns and, if appropriate, using suitable notation, such as mathematical symbols, to represent the problem.
Step-2	Devising a plan	Determining appropriate actions to take to solve the problem.
Step-3	Carrying out the plan	Executing the actions that have been determined to solve the problem and checking their effectiveness.
Step-4	Looking backward	Evaluating the overall effectiveness of the approach to the problem, with the intention of learning something about how similar problems may be solved on future occasions.

Ultimately, the final component is a solution. The solutions can take various forms - they may be numbers, equations, or graphs in mathematics (Gelbal, 1991; Polya, 2004; Schoenfeld, 1992), while in STEM activities the solutions are often hands-on products designed with concrete materials or digital forms (Bilgin et al., 2022; Bybee, 2010; Marrero et al., 2014). Whether it's a mathematical proof, an engineering prototype, or a computational model, the solution represents a tangible outcome (Szymanski, 2018; Zhou et al., 2023).

To effectively transition from identifying a problem to reaching a solution, problem-solving skills can be significantly enhanced by improving the competencies associated with each step—understanding the problem, devising a plan, executing that plan, and reflecting on the process. Also, problem solving is emphasized as an individual learning and development process (Malçok & Ceylan, 2020). Therefore, researchers continue exploring ways to best support learners in improving their problem-solving skills through various models and frameworks (Antonenko et al., 2014; González-Pérez & Ramírez-Montoya, 2022; Monsen & Woolfson, 2012; Proença, 2022; Zelazo et al., 1997). By developing strong problem-solving skills, individuals equip themselves with a powerful toolkit for navigating daily life and achieving their goals-making it a critical 21st century competency for preparing the next generation of problem-solvers (Allen & Van der Velden, 2012; Antonenko et al., 2014; Zelazo et al., 1997).

STEM Practices and Problem-Solving Skills

STEM education is a stepping stone in building 21st century skills in learners (Amelia & Santoso, 2021; Baran et al., 2021; Koyunlu-Ünlü & Dökme, 2022; Tytler, 2020). Within the framework of STEM education, STEM practices—specific activities, methodologies, and techniques used to teach STEM concepts—are employed (Bybee, 2010; Marrero et al., 2014). In literature, a variety of studies have focused on the impact of STEM practices on problem-solving skills, despite differences in the implementation of STEM activities, time periods, sample groups, teaching methods, and covered STEM topics practices (Akcay-Malcok, 2022; Hebebci & Usta, 2022; İnce & Ekmekçi, 2023; İnce et al., 2018; Kavak, 2019; Köngül, 2019; Martaningsih et al., 2022; Özkızılcık & Cebesoy, 2020; Şimşek, 2020; Taşçı, 2019). Based on existing research, we have identified several key characteristics as potential moderators of these effects: (1) education levels, (2) teaching methods, (3) STEM topic areas, and (4) durations of STEM implementations.

Education Levels

Educational level is a key element in designing learning environments because it ensures that the content, teaching methods, and assessment strategies are developmentally appropriate and aligned with students' cognitive and emotional needs (Fouad et. al., 2010; Tikka et. al., 2000). Also, the educational level of students plays a significant role in the effectiveness of STEM activities on problem-solving skills. Numerous studies have highlighted positive outcomes across various grades, including pre-service science teachers (Özkızılcık & Cebesoy, 2020), 8th graders (Hebebci & Usta, 2022; Taşçı, 2019), 7th graders (İnce & Ekmekçi, 2023; Şimşek, 2020), 6th graders (Köngül, 2019; Martaningsih et al., 2022), 5th graders (İnce et al., 2018), and even 4th graders (Kavak, 2019), as well as 6-year-old children (Akcay-Malcok, 2022). By examining education levels, we can better understand how developmental factors influence learning outcomes and how these effects vary, as this is crucial for designing and implementing STEM interventions.

Teaching Methods

STEM education encompasses a variety of instructional methods such as the 5E learning model, gamified STEM approaches, the Montessori method, inquiry-based learning, design thinking, experiential learning, problem-based learning, and project-based learning. The 5E learning model guides students through phases of engagement, exploration, explanation, elaboration, and evaluation, fostering a deeper understanding of concepts (Bybee, 2010). Gamified STEM incorporates game elements into the learning process, enhancing motivation and making complex topics enjoyable (Deterding et al., 2011). The Montessori method promotes hands-on learning and self-directed exploration, encouraging independence and a passion for discovery (Lillard, 2017).

Inquiry-based learning allows students to pose questions and investigate real-world issues, nurturing curiosity and developing problem-solving skills (Bruner, 2009). Design thinking focuses on empathy and innovation, guiding students through defining problems, ideating, prototyping, and testing solutions collaboratively (Carlgren et al., 2016). Experiential learning emphasizes direct experience, enabling students to apply theoretical knowledge in practical contexts while reflecting on their learning (Kolb, 2014). Problem-based learning engages students in collaborative efforts to solve complex, real-world problems, enhancing critical thinking and practical application (Savery, 2015). Project-based learning involves students in extended projects that require research and creative solutions to authentic challenges, fostering deeper engagement and learning (Kokotsaki et al., 2016).

The teaching methods and techniques employed in STEM education can significantly influence the development of problem-solving skills. Since different pedagogical approaches may yield varying results (Garside, 1996; Grossman, 2009), it is essential to examine the choice of teaching strategies used during STEM activities. For example, project-based learning and problem-based learning are commonly utilized in STEM practices, and their effects are still under discussion (Noordin et. al., 2011; Noviyani et. al., 2021). Therefore, selecting the most effective teaching methods and techniques is crucial for educators aiming to enhance problem-solving skills through STEM practices.

STEM Topic Areas

STEM encompasses a wide range of subject areas, each with unique characteristics that may differentially affect problem-solving skills. By investigating how the effects of STEM activities are distributed across various topic areas—such as mathematics, engineering, and life sciences—we can gain insights into which subjects are most effective in fostering these skills.

Durations of STEM Implementations

The length of time that STEM activities are implemented can also moderate their effectiveness. Short-term versus long-term engagements may produce different outcomes in terms of skill development (Gul, 2014). Analyzing how the durations of STEM initiatives influences problem-solving skills is necessary for understanding the optimal conditions for effective learning.

Purpose of the Study

It can be seen that there exist many studies using meta-analysis in the literature. For example, meta-analysis was used to show the effect of STEM education on academic success (Ayverdi & Aydın, 2020; Wang et al., 2022), 21st century skills (Azriyanti, 2023; Gümüş & Eroğlu, 2024), interest in STEM careers (Gümüş & Eroğlu, 2024), interest in STEM (Young et al., 2017), critical thinking skills (Zulyusri et al., 2023), higher-order thinking and cognitive ability (Zeng et al., 2018), creative-thinking skills (Suganda et al., 2021), and students' attitudes (Ulum, 2022). Additionally, there exist studies focused on the effectiveness of computer-based scaffolding in STEM education (Belland et al., 2017; Kim et al., 2018). Therefore, understanding the size of the effect can help to evaluate how worthwhile and impactful STEM-focused implementations are, which can guide the improvements of such programs' designs (Azriyanti, 2023; Belland et al., 2017; Kim et al., 2018; Zulyusri et al., 2023).

Similarly, there is a mass of individual studies on the same problem, with different samples or various methods showing that STEM activities have a positive effect on problem-solving skills. Thus, the need may arise to illustrate the big picture of the effects of STEM activities on problem-solving skills. The meta-analysis method can be used to show the overall effect size of the individual studies demonstrating that STEM practices have an effect on problem-solving skills. Thus, the aim of the study is to analyze the average effect size of STEM practices on problem-solving skills. The research question and sub-questions are as follows:

To what extent do STEM practices affect students' problem-solving skills?

- How are the effect sizes of existing studies focused on STEM practices and their impact on problem-solving skills distributed across different education levels?
- How are the effect sizes of existing studies focused on STEM practices and their impact on problem-solving skills distributed across different teaching methods or techniques?
- How are the effect sizes of existing studies focused on STEM practices and their impact on problem-solving skills distributed across different STEM topic areas?
- How are the effect sizes of existing studies focused on STEM practices and their impact on problem-solving skills distributed across different durations of STEM implementations?

By focusing on these moderators, the research aims to provide a comprehensive understanding of the factors that contribute to effective STEM education and to identify best practices that enhance student learning and engagement.

Method

Research Design

The method used in this research is meta-analysis. It combines the quantitative findings of multiple studies into a single conclusion (Field & Gillett, 2010; Şen & Yıldırım, 2020). Hence, the meta-analysis approach provides researchers with summative and comprehensive information about multiple studies (Borenstein et al., 2021; Strube & Hartmann, 1983), and an overall judgment can be obtained (Pigott & Polanin, 2020). In this direction, the approach of meta-analysis can enable us to calculate a general effect size of STEM practices on problem solving skills by combining results from various studies and see a holistic picture.

Sample

The data collected is secondary data, derived from articles published in Web of Science, SCOPUS and ERIC databases. Studies in which the terms “the effects of STEM on problem solving skills”, “the effects of STEM teaching on problem solving skills”, “the influence of STEM on problem solving skills”, and “STEM and problem-solving skills” were used in search process. Studies from these three databases—Web of Science, SCOPUS, and ERIC—published up until the end of May 2024 were included, without a specific start date restriction. After removing duplicate studies from these databases, several filters were applied in the search process. First, only studies written in English were included, while those published in other languages were excluded (Criterion 1). Secondly, only studies with full text available were included (Criterion 2). Thirdly, scientific journal articles, book chapters, proceedings, and theses were included, while publications such as practices, letters to editors, corrections, and guest editorials were excluded (Criterion 3). Next, studies that did not assess the effects of STEM education on students’ problem-solving skills were considered out of scope and thus excluded (Criterion 4). Finally, experimental studies examining the effects of diverse integrated STEM approaches on students’ problem-solving skills were included, while studies lacking descriptive statistics or effect sizes were excluded (Criterion 5). Because, to calculate effect size accurately, experimental studies that provide the necessary data for such calculations are needed.

By applying these criteria, the search process aimed to ensure the inclusion of relevant studies while excluding those that did not meet the specified criteria. So, articles that met the following inclusion criteria were selected for the analysis. At the end of the selection process, twenty-five articles that met the criteria were determined to be included. Flow chart of meta-analysis study selection process was given in Figure 1.

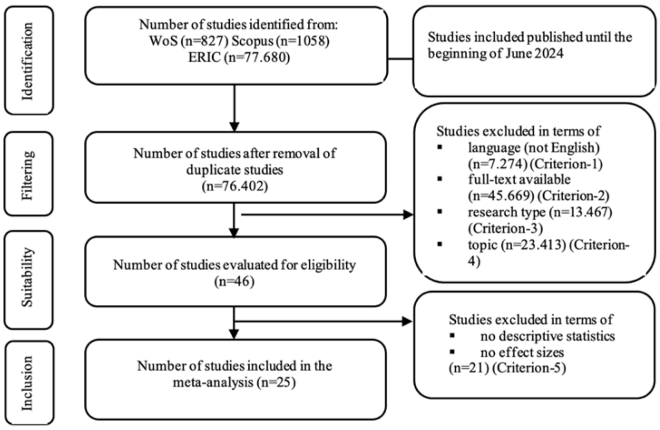

Figure 1. Flow Chart of Meta-analysis Study Selection Process

Data Analyzing Method

After identifying studies to be included based on the criteria, these steps were followed in the data analyzing process, which are 1) determining the formulas to investigate the effect sizes for each study 2) calculating the effect sizes of each study according to the appropriate formulas 3) characterizing each effect size 4) calculating the average effect size.

The following statistical factors are used in the calculation of effect sizes:

Table 2. How to Determine the Effect Size

Statistic Data	Formula	Formula Code
Average in one group (pre-test, post-test)	$ES = \frac{\bar{X}_{post} - \bar{X}_{pre}}{SD_{pre}}$	F1
Average in each group (experimental, control)	$ES = \frac{\bar{X}_{experiment} - \bar{X}_{control}}{SD_{control}}$	F2
Average in each group (experimental, control, pre-test, post-test)	$ES = \frac{(\bar{X}_{post} - \bar{X}_{pre})_E - (\bar{X}_{post} - \bar{X}_{pre})_C}{\frac{SD_{preC} + SD_{preE} + SD_{postC}}{3}}$	F3

1. *Average in one group (pre-test, post-test):* For studies utilizing a pre-test and post-test design within a single group to assess whether an intervention (STEM practices) leads to significant improvements in

the dependent variable (problem-solving skills), the effect size is calculated by comparing the average scores obtained before and after the intervention. This method standardizes the difference using the standard deviation of the pre-test scores, allowing for a clearer interpretation of the magnitude of change in relation to the inherent variability in the pre-test data.

2. *Average in each group (experimental, control):* For studies employing control and experimental groups to evaluate whether an intervention (STEM practices) results in significant improvements in the dependent variable (problem-solving skills), the effect size is calculated by comparing the average scores of the experimental and control groups. This difference is standardized using the standard deviation of the control group, which facilitates comparisons across studies by providing a consistent metric for effect size.
3. *Average in each group (experimental, control, pre-test, post-test):* For studies utilizing both experimental and control groups to assess the effectiveness of an intervention (STEM practices) on the dependent variable (problem-solving skills), the effect size is calculated by examining the change in scores from pre-test to post-test for each group. This analysis employs the average of the standard deviations across all relevant groups to account for variability.

Effect sizes are then characterized using the following criteria after being calculated using the appropriate formula (Thalheimer & Cook, 2002):

effect size ≤ 0.15 negligible effects

0.15 < effect size ≤ 0.40 small effect

0.40 < effect size ≤ 0.75 medium effect

0.75 < effect size ≤ 1.10 high effect

1.10 < effect size ≤ 1.45 very high effect

Results

In this section, the analysis of the effect sizes for each article identified as a sample was presented, including the descriptive statistics for the calculation of the effect size formula. Additionally, the analysis of the effect sizes categorized based on their education levels, teaching methods/techniques, topics, and durations was also presented. The effect sizes that some studies (R4, R6, R8, R10, R11, R17, R18, R21, R22, R25) clearly stated in their papers were used directly without calculation in this current study. If the effect sizes were not stated, they were calculated by using the three formulas mentioned in Table 2 as F1, F2, and F3. Additionally, each effect size was categorized as negative, negligible, small, medium, high, or very high based on the Thalheimer and Cook's (2002) criteria.

The mean values ($\bar{X}$) and standard deviations (SD) for each study whose effect sizes were calculated using the F1, F2, and F3 formulas were given in Tables 3, 4, and 5, respectively. Specifically, the F1 formula was used for studies that designed pre- and post-tests (see Table 3), the F2 formula was used for studies that designed experiment and control groups (see Table 4), and the F3 formula was used for studies that designed both pre- and post-tests as well as experiment and control groups (see Table 5).

Table 3. Descriptive Statistics of the Studies Used F1

	Pre-test		Post-test	
	$\bar{X}_{pre}$	SD_{pre}	$\bar{X}_{post}$	SD_{post}
R5	89.65	9.42	92.26	11.96
R9	139.20	18.67	151.10	19.51
R19	2.72	0.62	3.92	0.81
R20	44.95	19.607	79.37	12.581
R23	69	8.36	92	7.19

Table 4. Descriptive Statistics of the Studies Used F2

	Experiment	Control	
	$\bar{X}_e$	$\bar{X}_c$	SD_c
R12	78.77	73.04	7.955
R16	58.48	41.56	12.38

Table 5. Descriptive Statistics of the Studies Used F3

	Experimental			Control			
	Pre-test		Post-test	Pre-test		Post-test	
	$\bar{X}$	SD_{preE}	$\bar{X}$	$\bar{X}$	SD_{preC}	$\bar{X}$	SD_{postC}
R1	3.79	0.22	3.84	2.81	0.46	3.42	0.48
R2	132.5	22.8	134.5	130.9	18.9	139.8	18.1
R3	54.45	8.606	51.09	55.59	9.127	52.86	8.055
R7	13.04	4.44	23.80	13.48	5.13	17.72	3.66
R13	93.38	15.23	104.14	93.47	10.31	94.04	14.21
R14	81.72	7.5	88.50	83.18	4.06	84.31	5.91
R15	30.11	5.08	38.37	30.78	4.75	32.83	3.91
R24	4.00	2.05	10.10	3.32	1.80	3.79	1.72

The effect sizes of 25 articles that focused on the effects of STEM practices on problem-solving skills, and their average effect size, were given in Table 6. According to Table 6, it can be seen that three of the 25 articles were labeled as having a negative effect size, one was labeled as negligible, one as small, seven as medium, two as high, and eleven as very high. It is obvious that it is clear that the number of studies with a very high effect size is exactly 11 out of 25. As a result, the average effect size across all the analyzed studies is very high, at 1.217.

Table 6. The Effect Sizes of Each Article

Article Code	Source Article	Effect Sizes	Category	Formulas
R1	(Kurt & Benzer, 2020)	-1.451	Negative	F3
R2	(Nağaç & Kalaycı, 2021)	-0.346	Negative	F3
R3	(Sarican & Akgunduz, 2018)	-0.073	Negative	F3

Article Code	Source Article	Effect Sizes	Category	Formulas
R4	(Purwaningsih et al., 2020)	0.057	Negligible	-
R5	(Asigigan & Samur, 2021)	0.242	Small	F2
R6	(Zhang et al., 2023)	0.435	Medium	-
R7	(Sudarsono et al., 2022)	0.493	Medium	F3
R8	(Ahmadi et al., 2022)	0.510	Medium	-
R9	(Çakır & Altun-Yalçın, 2021)	0.623	Medium	F2
R10	(Parno et al., 2021a)	0.651	Medium	-
R11	(Karamustafaoğlu & Pektaş, 2023)	0.720	Medium	-
R12	(Li & Gu, 2023)	0.720	Medium	F1
R13	(Zengin et al., 2022)	0.769	High	F3
R14	(Hebebci & Usta, 2022)	0.970	High	F3
R15	(Şahin, 2021)	1.356	Very High	F3
R16	(Muzana et al., 2021)	1.360	Very High	F1
R17	(Parno et al., 2019)	1.410	Very High	-
R18	(Parno et al., 2020)	1.650	Very High	-
R19	(Puchongprawet & Chantraukrit, 2022)	1.662	Very High	F2
R20	(Rasyid et al., 2023)	2.089	Very High	F2
R21	(Parno et al., 2021c)	2.554	Very High	-
R22	(Parno et al., 2021b)	2.642	Very High	-
R23	(Kartini, 2021)	2.949	Very High	F2
R24	(Yalçın & Erden, 2021)	3.033	Very High	F3
R25	(Parno et al., 2021d)	5.200	Very High	-
	Average	**1.217**	**Very High**	

In addition to calculating the effect sizes of the studies, the effect sizes were categorized based on the education levels of the samples used in the studies. As shown in Table 7, the effect sizes from highest to lowest were: pre-school (2.195), high school (1.673), middle school (0.645), higher education (0.623), and elementary school (0.506). Additionally, the studies most frequently used high school students (n=11) and middle school students (n=9) in their samples, compared to pre-school students (n=2), elementary school students (n=2), and higher education students (n=1).

Table 7. The Distribution of Effect Sizes of Each Article Based on Their Education Levels

Education Levels	Article Codes	Effect sizes	Category
Pre-school	R15	1.356	Very High
	R24	3.033	Very High
	Average	**2.195**	**Very High**
Elementary school	R5	0.242	Small
	R13	0.769	High

Education Levels	Article Codes	Effect sizes	Category
	Average	**0.506**	**Medium**
Middle school	R1	-1.451	Negative
	R2	-0.346	Negative
	R3	-0.073	Negative
	R6	0.435	Medium
	R8	0.510	Medium
	R12	0.720	Medium
	R14	0.970	High
	R20	2.089	Very High
	R23	2.949	Very High
	Average	**0.645**	**Medium**
High school	R4	0.057	Negligible
	R7	0.493	Medium
	R10	0.651	Medium
	R11	0.720	Medium
	R16	1.360	Very High
	R17	1.410	Very High
	R18	1.650	Very High
	R19	1.662	Very High
	R21	2.554	Very High
	R22	2.642	Very High
	R25	5.200	Very High
	Average	**1.673**	**Very High**
Higher education	R9	0.623	Medium
	Average	**0.623**	**Medium**

The effect sizes were categorized based on the teaching methods, techniques, or models that were specifically used in the STEM practices of the studies. As shown in Table 8, the effect sizes ranged from lowest to highest as follows: 5E learning model (-0.346), gamified-based STEM (0.242), Montessori approach (0.623), inquiry-based learning (0.720), problem-based learning (1.568), project-based learning (1.777), design thinking model (3.033), and experiential learning (5.2).

Table 8. The Distribution of Effect Sizes of Each Article Based on Their Teaching Methods/Techniques

Teaching Methods or Technique/Models	Article Codes	Effect sizes	Category
5E learning model	R2	-0.346	Negative
	Average	**-0.346**	**Negative**
Gamified based STEM	R5	0.242	Small
	Average	**0.242**	**Small**

Teaching Methods or Technique/Models	Article Codes	Effect sizes	Category
Montessori approach	R9	0.623	Medium
	Average	**0.623**	**Medium**
Inquiry-based learning	R11	0.720	Medium
	Average	**0.720**	**Medium**
Problem-based learning	R10	0.651	Medium
	R17	1.410	Very High
	R22	2.642	Very High
	Average	**1.568**	**Very High**
Project-based learning	R4	0.057	Negligible
	R16	1.360	Very High
	R18	1.650	Very High
	R20	2.089	Very High
	R21	2.554	Very High
	R23	2.949	Very High
	Average	**1.777**	**Very High**
Design thinking model	R24	3.033	Very High
	Average	**3.033**	**Very High**
Experiential learning	R25	5.200	Very High
	Average	**5.200**	**Very High**

The effect sizes were categorized based on their topics that were specifically mentioned in these studies. As shown in Table 9, the effect sizes based on the topics ranged from lowest to highest as follows: electrical conduction (-0.762), light and sound (-0.073), matter and heat (0.210), fluid statistics (0.651), force and motion (0.795), electromagnetic (1.618), energy (1.707), optics (2.026), and the earth layer and disaster (2.949). Also, the topics of “electrical conduction,” “matter and heat,” “force and motion,” “electromagnetic,” “energy,” and “optics” were studied more than once.

Table 9. The Distribution of Effect Sizes of Each Article Based on Their Topics

Topics	Article Codes	Effect sizes	Category
Electrical Conduction	R1	-1.451	Negative
	R3	-0.073	Negative
	Average	**-0.762**	**Negative**
Light and Sound	R3	-0.073	Negative
Matter and Heat	R2	-0.346	Negative
	R3	-0.073	Negative
	Average	**0.210**	**Negative**
Fluid Statistics	R10	0.651	Medium
Force and Motion	R3	-0.073	Negative

	R19	1.662	Very High
	Average	**0.795**	**Medium**
Electromagnetic (Induction)	R18	1.650	Very High
	R21	2.554	Very High
	Average	**1.618**	**Very High**
Energy	R8	0.510	Medium
	R19	1.662	Very High
	Average	**1.707**	**Very High**
Optics	R22	2.642	Very High
	R17	1.410	Very High
	Average	**2.026**	**Very High**
The Earth Layer and Disaster	R23	2.949	Very High
	Average	**2.949**	**Very High**

The effect sizes were categorized based on their durations that were specifically mentioned as the implementation period of these studies. As shown in Table 10, the effect sizes based on the durations ranged from lowest to highest as follows: 4-5 weeks (-0.210), 8-10 weeks (0.743), 14-16 weeks (1.010), and 6-7 weeks (2.960).

Table 10. The Distribution of Effect Sizes of Each Article Based on Their Durations

Durations	Article Codes	Effect sizes	Category
14-16 weeks (1 semester)	R6	0.435	Medium
	R9	0.623	Medium
	R14	0.970	High
	R16	1.360	Very High
	R19	1.662	Very High
	Average	**1.010**	**High**
8-10 weeks	R1	-1.451	Negative
	R5	0.242	Small
	R8	0.510	Medium
	R13	0.769	High
	R15	1.356	Very High
	R24	3.033	Very High
	Average	**0.743**	**Medium**
6-7 weeks	R11	0.720	Medium
	R25	5.200	Very High
	Average	**2.960**	**Very High**
4-5 weeks	R2	-0.346	Negative
	R3	-0.073	Negative
	Average	**-0.210**	**Negative**

Discussion

Although examining the effects of STEM practices on the improvements of students' 21st century skills, including problem-solving skills has attracted wide attention recently (Amelia & Santoso, 2021; Baran et al., 2021; Koyunlu-Ünlü & Dökme, 2022; Tytler, 2020), there is a lack of study examining holistically the overall effect size of them. To gain a comprehensive understanding about multiple studies, meta-analysis method that enable us to combine the results of individual studies (Borenstein et al., 2021; Strube & Hartmann, 1983) was used in this current study aiming to find the general effect size of STEM practices on problem solving skills. Additionally, the effect sizes of 25 research studies were categorized based on their education levels, teaching methods/techniques, topics, and durations.

According to the analysis, it was seen that the number of studies with a very high effect size is exactly 11 out of 25, and the average effect size across all the analyzed studies was very high, at 1.217 although three of 25 research having negative effect sizes. Similarly, positive effects of STEM practices on problem solving skills can be seen in other studies (Akcay-Malcok, 2022; Hebebci & Usta, 2022; Ince & Ekmekçi, 2023; Ince et al., 2018; Kavak, 2019; Köngül, 2019; Martaningsih et al., 2022; Özkızılcık & Cebesoy, 2020; Şimşek, 2020; Taşçı, 2019) rather than analyzed studies in this current study. This can be attributed the fact that STEM activities have been designed in a way that they can improve participants' 21st century skills, including problem-solving skills (Azriyanti, 2023; Gümüş & Eroğlu, 2024). In these activities, students are expected to follow the stages of the engineering design process, which involves identify need/problem, research need/problem, develop possible solutions, select best possible solution, construct a prototype, test and evaluate solution, communicate the solution, redesign, completion decision (Hynes et al., 2011). Under this process, students are also following the problem-solving stages, which involve understanding the problem, devising a plan, carrying out the plan, and looking backward (Polya, 2004). Both iterative processes have some similar and common features, with some differences (Hynes et al., 2011; Polya, 2004). This is particularly evident in problem-based STEM implementations that focus on solving problems (Angelle, 2018). Despite the overall finding of a very high effect size, there exist some studies that have reported negligible or even negative impacts of STEM practices on problem-solving skills. Furthermore, if we accept that problem-solving skills are related to critical thinking, higher-order thinking and cognitive ability, the result of the current study's very high effect size can be supported by the meta-analysis studies that have found positive effects in these areas (Zeng et al., 2018; Zulyusri et al., 2023). This is not a surprising outcome, as students with high competence in problem-solving are likely to also demonstrate high competence in critical thinking, higher-order thinking, and cognitive skills (Lewis & Smith, 1993).

According to the analysis of the effect sizes from studies based on education levels, the average effect sizes ranged from highest to lowest as follows: pre-school (2.195), high school (1.673), middle school (0.645), higher education (0.623), and elementary school (0.506). Additionally, the studies most frequently used high school students (n=11) and middle school students (n=9) in their samples, compared to fewer studies involving pre-school students (n=2), elementary school students (n=2), and higher education students (n=1). The analysis reveals a notable lack of studies examining the effects of STEM practices on the problem-solving skills of students at the higher education, pre-school, and elementary school levels. Instead, the majority of the studies were conducted with middle school and high school students. When comparing the average effect sizes of the studies using middle school students (medium effect size) and high school students (very high effect size), it appears that STEM practices have more positive effects on the development of problem-solving skills in high school students compared to middle school students. In other words, the improvement of problem-solving skills is more successful among high school students than middle school students. This difference could be attributed to various factors, such as differences in the problem's characteristics, instructor's feedback, learners' meta cognitive strategies (Park & Jang, 2010), learners' curiosity, openness to learning, self-direction and self-evaluation, access to information (Bayrakçı & Dindar, 2015).

According to the analysis of the effect sizes of studies based on the teaching methods, techniques, or models, the average effect sizes from lowest to highest were found as follows: 5E learning model (-0.346), gamified-based STEM (0.242), Montessori approach (0.623), inquiry-based learning (0.720), problem-based learning (1.568), project-based learning (1.777), design thinking model (3.033), and experiential learning (5.2). Based on the analysis, the most effective instructional method for improving students' problem-solving skills within STEM contexts appears to be experiential learning, while the least effective is the 5E learning model. However, it is difficult to generalize these effect size findings, as only one study was included for each category, with the exception of problem-based and project-based learning approaches. This analysis highlights a notable gap in the literature, as there is a lack of studies investigating the effects of several STEM instructional methods on students' problem-solving skills, including the 5E learning model, gamified-based STEM, Montessori approach, inquiry-based learning, design thinking model, and experiential learning. Therefore, it is reliable to focus the comparison on the two most frequently employed methods in STEM implementation: problem-based and project-based learning (Angelle, 2018; Arifin & Mahmud, 2021; Thibaut et al., 2018). These two approaches differ in their emphasis, with project-based learning prioritizing the construction of products and teacher guidance, while problem-based learning prioritizes the problem-solving process and the application of knowledge (Angelle, 2018; Asghar et al., 2012).

The present analysis found that project-based learning (1.777) was more effective than problem-based learning (1.568) in developing students' problem-solving skills within STEM contexts. However, this difference may be attributable to various other factors. This finding aligns with studies claiming that project-based STEM learning is more effective than problem-based STEM learning in enhancing problem-solving skills (Angelle, 2018; Monika et al., 2023). Therefore, it is recommended that further meta-analyses or comparative studies be conducted to better understand the differential effects of various instructional approaches utilized within STEM education.

According to the analysis of the effect sizes of studies based on the topics, the average effect sizes from lowest to highest were found as follows: electrical conduction (-0.762), light and sound (-0.073), matter and heat (0.210), fluid statistics (0.651), force and motion (0.795), electromagnetic (1.618), energy (1.707), optics (2.026), and the earth layer and disaster (2.949). These differences in effect sizes may also be a result of variations in the implementation methods and content of the activities (Thibaut et al., 2018). Additionally, the topics of "electrical conduction," "matter and heat," "force and motion," "electromagnetic," "energy," and "optics" were studied more than once. Researchers could investigate the effects of STEM practices on problem-solving skills in other topics, such as light and sound, fluid statics, the earth layer and disaster, and other areas that were not extensively covered in the existing literature. Based on the analysis, it appears that the focus of most of the STEM activities was on the physics discipline, with the exception of the topic related to the earth layer and disaster. Interestingly, the topic of the earth layer and disaster seemed to have a greater effect on problem-solving skills compared to the other topics. The greater attention given to the physics discipline in STEM activities may be attributed to the fact that the concrete products designed at the end of hands-on activities usually involve principles of physics (Chandrasekar & Geib, 2003). Additionally, students can develop an understanding of the application of physics concepts such as energy, machines, and motion by engaging in hands-on activities (Hong et al., 2012; Zubrowski, 2002). In contrast, Akarsu's study (2010) found that compared to chemistry and biology, physics is the less preferred discipline among pre-service teachers when designing hands-on activities. The reason for this was explained as "chemistry is easier to generate any hands-on activity than other science disciplines and easy to understand by both students and teachers themselves because its logic is straightforward, but physics requires more theoretical background and higher-order thinking in addition" (Akarsu, 2010). On the other hand, this result may support the ideas of some researchers who criticize that other disciplines, such as chemistry, biology, mathematics, or engineering, have been ignored or given less attention in STEM education compared to physics (Fitzallen, 2015; Just & Siller, 2022; Maass et al., 2019; Stohlmann, 2018). As a result, this finding suggests a need to design more STEM activities that prioritize other scientific disciplines, such as chemistry or biology, and to incorporate more mathematical concepts rather than using them only as calculation or measurement tools in the activities. Additionally, possible reasons for why researchers choose to use fewer biology and chemistry STEM activities should be investigated.

According to the analysis of the effect sizes of studies based on the durations, the average effect sizes from lowest to highest were found as follows: 4-5 weeks (-0.210), 8-10 weeks (0.743), 14-16 weeks (1.010), and 6-7 weeks (2.960). Based on these results, it is difficult to conclude that the duration of STEM implementation is unrelated to the effectiveness of these practices on students' problem-solving skills. While the number of weeks of implementation appears to increase, the corresponding effect sizes do not increase proportionately. Disrupting this pattern is the 6-7 weeks category, which was found to be the most effective one. This is likely due to the fact that the study with a very high effect size (5.200) contributed to the increased average effect size for the 6-7 weeks category. Apart from this, it was found that implementations lasting 14-16 weeks or one semester had a very high effect size of 1.010, while the 4-5 weeks category had a negative effect size of -0.210. This suggests that the duration of STEM interventions may play a role in their impact on problem-solving skills, with longer implementations (a semester or more) potentially yielding more positive results. Because it is not surprising that students who participated in longer STEM applications were able to develop their problem-solving skills more effectively (Kim, 2015). The development of skills often requires a certain amount of time and exposure (Ericsson, 2003; Kim, 2015). However, the reasons why a few weeks of application may have a negative effect on problem-solving skills could be due to various other variables, such as the specific instructional approaches, content, or the level of student engagement (Bayrakçı & Dindar, 2015; Park & Jang, 2010). Therefore, if the goal is to improve 21st-century skills, it would be beneficial to implement STEM practices within a semester or longer timeframe, as this appears to produce more positive results based on the findings.

Conclusion

The effect sizes of 25 research studies were categorized based on their education levels, teaching methods/techniques, topics, and durations. When examining the effect sizes by educational levels, the largest impacts were found for preschool (2.195) and high school (1.673) students, compared to lower effect sizes for middle school (0.645), higher education (0.623), and elementary school (0.506) students. In terms of teaching methods and techniques, the highest average effect sizes were associated with experiential learning (5.2), the design thinking model (3.033), and approaches focused on the earth's layers and disaster-related topics (2.949). In contrast, lower effect sizes were found for the 5E learning model (-0.346) and content related to electrical conduction (-0.762). The duration of STEM interventions also appeared to influence their effectiveness. Studies with the longest durations of 6-7 weeks (2.960) and 14-16 weeks (1.010) demonstrated greater impacts on problem-solving skills compared to shorter 4-5 week (-.210) and 8-10 week (0.743) interventions.

Recommendations

Developing strong problem-solving skills is significant for individuals, as it provides them with a powerful toolkit for navigating daily life and achieving their goals, preparing them to be part of the next generation of problem-solvers (Allen & Van der Velden, 2012; Antonenko et al., 2014; Zelazo et al., 1997). In this context, the role of STEM practices in developing problem-solving skills is of crucial importance, as the current study found a very high effect size in this regard. Based on the analysis, it is recommended that future studies examining the effects of STEM practices on problem-solving skills should consider samples from higher education, pre-school, and elementary school levels. Additionally, there appears to be a lack of research investigating the comparative effects of various STEM instructional methods on students' problem-solving skills. It is suggested that studies explore the impacts of different approaches, such as the 5E learning model, inquiry-based learning, design thinking, and experiential learning, to help researchers, curriculum designers, and educators determine the most effective teaching strategies for developing problem-solving skills. Furthermore, it could be insightful to investigate the effects of STEM activities that prioritize science disciplines beyond physics, such as chemistry, biology, and mathematics, on problem-solving skills. This would provide a more comprehensive understanding of the relationship between STEM education and the development of problem-solving competencies. Lastly, the current analysis highlights the need for further examination of the optimal duration of STEM interventions and their influence on problem-solving skills. Exploring the relationship between the length of STEM implementation and its effectiveness in enhancing problem-solving skills could yield valuable insights for educational practitioners.

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