The Effects of STEM Programs on Students' 21st Century Skills: A Meta-Analysis Study

Siti Sarah Faqihah Bahari, Roslinda Rosli

Research Centre of STEM Enculturation, The National University of Malaysia

DOI: https://doi.org/10.47772/IJRISS.2026.100400368

Received: 14 April 2026; Accepted: 20 April 2026; Published: 11 May 2026

ABSTRACT

This meta-analysis examines how STEM programs influence students' 21st-century skills, including critical thinking, creativity, communication, collaboration, character, and citizenship (the 6Cs). We gathered 38 empirical studies, used Hedges' g as the effect size measure, and employed the Statistical Package for the Social Sciences (SPSS) version 29. The overall mean effect size was large and statistically significant, showing that STEM interventions greatly surpass non-STEM approaches in developing these skills. High heterogeneity was detected, leading to moderator analyses. Educational level significantly influenced the effects: university programs produced the largest effect, followed by primary and secondary education. Program design did not significantly moderate outcomes, with both non-project-based and project-based learning proving effective. These findings confirm STEM's vital role in developing 21st-century skills and reflect current educational needs. The level of education affects effectiveness, likely due to differences in skill basis and intervention intensity. Limitations include incomplete data in some studies, which led to the exclusion of certain articles. Future research should examine additional moderators, such as duration and publication type. Policymakers and educators are encouraged to systematically incorporate STEM, backed by teacher training, to ready students for a rapidly changing world.

Keywords: STEM programs, 21st century skills, meta-analysis, STEM education, systematic literature review

INTRODUCTION

Twenty-first-century skills have become increasingly vital in contemporary education, aligning closely with technological advancements and the shifting landscape of global employment. The 21st Century Education Model, also known as enGauge 21st Century Skills, was launched in the United States by the North Central Regional Educational Laboratory (NCREL) and the Metiri Group. The framework was developed to synchronize educational systems with the swiftly evolving requirements of a globalized society. Its primary objective is to equip students with essential skills and competencies necessary for success in the 21st century, particularly within environments characterized by technological innovation, information abundance, and a focus on creativity. Fullan and Scott (2014) proposed a conceptual framework comprising six core competencies, referred to as the 6Cs: Critical Thinking, Creativity, Communication, Collaboration, Character, and Citizenship. These competencies are instrumental in cultivating learners who excel academically and demonstrate adaptability to the complexities and challenges presented by the modern world (Mahmud & Wong, 2022).

21st-century skills closely align with the principles of Science, Technology, Engineering, and Mathematics (STEM) education. STEM education fosters an environment conducive to collaboration, innovation, and the effective communication of findings, which are essential for developing the competencies required in the 21st century. According to Bryan et al. (2015), STEM encompasses the teaching and learning of content and practices that integrate scientific and mathematical concepts with engineering design and utilize appropriate technological tools. Following World War II, the National Science Foundation (NSF) was established. By the 1990s, the term "MET" had been introduced and was subsequently updated to "STEM" in 2001. The initial objective was to promote interest and competency in STEM fields, with particular emphasis on underrepresented groups, based on the belief that these disciplines are vital for human development, innovation, and national economic advancement. In the early 2000s, the publication of the Rising Above the Gathering Storm (2005) report accentuated the urgency of STEM reform, positioning it as a national strategy to sustain U.S. economic competitiveness. The emphasis shifted from merely cultivating interest to enhancing productivity, fostering innovation, and improving employability. Consequently, STEM education emerged as a strategic element of national policy and has been adopted worldwide.

In Malaysia, the implementation of STEM education was delineated into three distinct phases, as articulated in the Malaysia Education Blueprint 2013–2025 (PPPM 2013–2025). These phases are designated as Wave 1 (2013–2016), Wave 2 (2016–2020), and Wave 3 (2021–2025). The year 2025 marks the conclusion of Wave 3, a period during which the deployment of STEM initiatives is further strengthened by greater flexibility in execution and program management. The Ministry of Education endeavors to establish a self-sustaining system that persistently fosters innovation and development among students and educators.

Malaysia's ongoing commitment to enhancing STEM education aligns with the broader global shifts in workforce development. According to the World Economic Forum (2025), the most rapidly expanding occupations by 2030 will predominantly be driven by technological innovations such as artificial intelligence, robotics, and digitalization. These advancements necessitate robust 21st-century skills to ensure the responsible and effective application of technology. Idris et al. (2023) highlight that STEM education is increasingly essential, given its pivotal role in fostering innovation, driving economic growth, and maintaining global competitiveness. STEM learning imparts critical skills, including analytical thinking and creativity, which are highly valued in contemporary labor markets (World Economic Forum, 2025). Moreover, the development of 21st-century competencies equips learners with the capacity for lifelong learning and adaptability within dynamic environments (Mahmud & Wong, 2022; Mor, 2025). Therefore, integrating these skills into educational frameworks is crucial for cultivating technologically literate citizens who can contribute meaningfully to national economic development (Mariano & Chiappe, 2021).

STEM education provides an appropriate platform for developing these skills through its interdisciplinary approach, which encourages students to apply theoretical knowledge to real-world problems, thereby enhancing critical thinking, creativity, and collaboration (Hebebci & Usta, 2022). One notably effective pedagogical strategy is Project-Oriented Problem-Based Learning (POPBL), in which students engage in authentic, context-based problem-solving activities that substantially bolster 21st-century skills, including productivity, communication, and innovative thinking (AlAli, 2024). Additionally, Hebebci and Usta (2022) identified that an integrated STEM curriculum positively impacts problem-solving abilities and critical thinking. Furthermore, the incorporation of technologies such as 3D printing and Computer-Aided Design (CAD) fosters innovation and augments global awareness among learners (Fujiwara & Jones, 2020).

Although previous research has explored the effectiveness of STEM education, most studies have focused on academic achievement and students' interest in STEM disciplines (Siregar et al., 2019; Chang et al., 2022). Research specifically examining the influence of STEM programs on the development of 21st-century skills—including critical thinking, creativity, communication, collaboration, character, and global citizenship—remains scarce in both quantity and scope, and in generalizability. Furthermore, empirical evidence demonstrates variability across factors such as the implementation context, target populations, intervention design, and duration (Astawan et al., 2023; Kencana, Musri, & Syukri, 2020).

This variability raises questions about the effectiveness of STEM education in enhancing students' 21st-century skills. Consequently, a systematic, quantitative synthesis through meta-analysis is warranted to integrate findings from multiple studies, thereby facilitating a comprehensive assessment of STEM's overall impact and identifying moderating factors, such as educational level or program design. Accordingly, this study intends to: (1) quantify the effect size of STEM programs on the development of students' 21st-century skills, and (2) examine moderating variables that influence the efficacy of STEM interventions in these skills. It is anticipated that the findings will address existing gaps in the literature and provide valuable insights for formulating more effective educational policies and STEM implementation strategies in educational settings.

METHODOLOGY

Journal Selection Criteria

This meta-analysis encompassed studies published between 2015 and 2025 that examined the influence of STEM programs on 21st-century skills. The decade-long timeframe was chosen to capture the most pertinent and recent research within the field. The initial stage of the meta-analysis involved selecting appropriate keywords for the literature search, including “STEM approach”, “STEM-based”, “STEM programme”, and “STEM activities”. The primary electronic databases utilized for the search were SCOPUS and Web of Science (WOS).

During the initial search phase, 2,426 articles were identified. Of these, 2,136 articles were excluded prior to screening, primarily due to two reasons: duplicate records (n = 749) and titles lacking relevance to the research focus (n = 1,387). Subsequently, 290 articles advanced to abstract screening; 238 were excluded for failing to meet the predefined inclusion and exclusion criteria (see Table 1). Concerning the types of STEM programs analyzed, only two categories were considered: Project-Based Learning (PBL) and Non-Project-Based Learning (NPBL). This categorization facilitated a comparative analysis of the impact of different STEM implementation approaches on students’ 21st-century skills.

Table 1. Selection Criteria

Selection Criteria	**Details**
Publication year	2015 – 2025
Study design	Quasi-experimental (with treatment and control groups or pre-test/post-test design)
Dependent variable	21st-century skills (critical thinking, creativity, communication, collaboration, character, and global citizenship)
STEM program type	Project-based and non-project-based learning
Statistical data required	Mean and standard deviation for effect size calculation

In the final stage of the selection process, 52 articles were evaluated for quality using the assessment framework established by Mullet et al. (2017). Following this evaluation, 30 articles were retained, representing 38 distinct studies. It is noteworthy that some articles were considered as two separate studies when they reported different outcomes for multiple 21st-century skills. Table 2 lists all selected articles, and Figure 1 depicts the PRISMA flow diagram of the article selection methodology (Page et al., 2021).

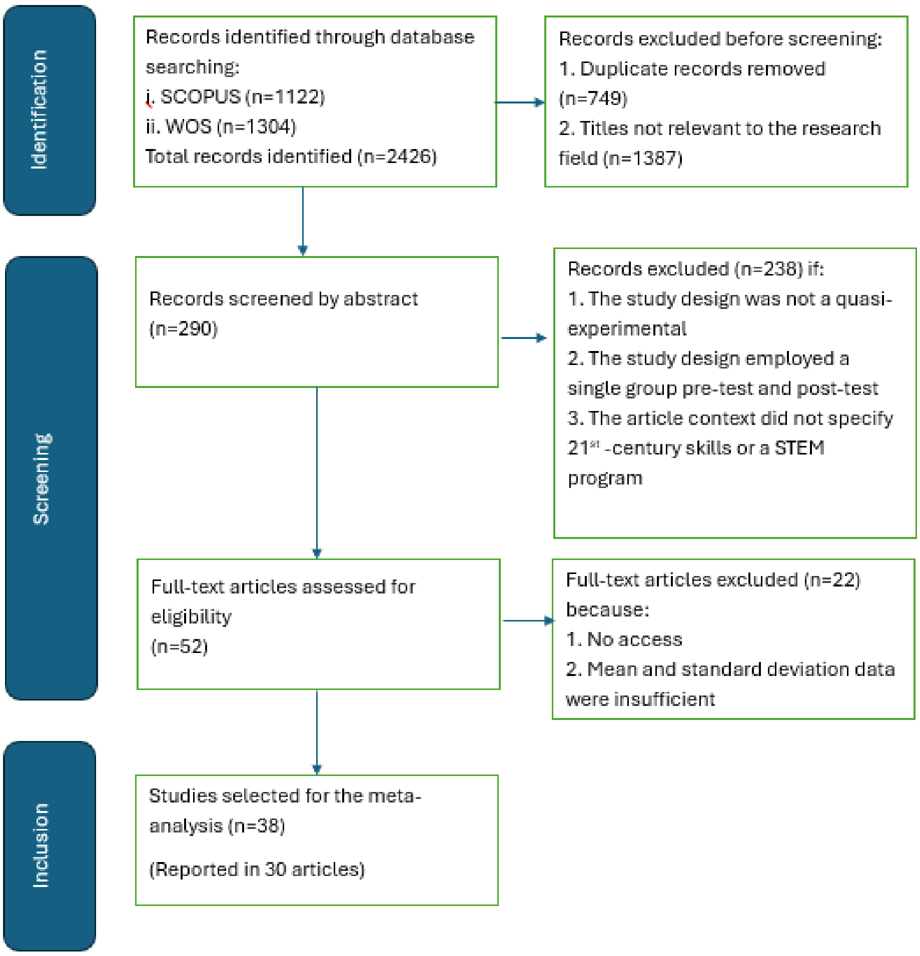

Figure 1. PRISMA Flow Diagram

Table 2. Articles Selected for Meta-Analysis

Author(s) (Year)	ID	21st-Century Skill	Educational Level	Program Design
Siew & Ambo (2018)	S1	Creative thinking	Primary	Project-based
Sumardi et al. (2023)	S2	Citizenship	University	Non-project-based
Putra et al. (2021)	S3	Critical thinking	Secondary	Project-based
Berk & Gulcu (2024)	S4a	Creative thinking	Secondary	Project-based
	S4b	Critical thinking	Secondary	Project-based
	S4c	Collaboration	Secondary	Project-based
Pertiwi et al. (2024)	S5	Critical thinking	Secondary	Project-based
Astawan et al. (2023)	S6a	Critical thinking	University	Project-based
	S6b	Creative thinking	University	Project-based
Herlina et al. (2025)	S7	Critical thinking	Secondary	Project-based
Ayverdi & Öz Aydın (2022)	S8	Creative thinking	Secondary	Project-based
Dafik et al. (2023)	S9	Meta-literacy	University	Non-project-based
Nastiti et al. (2024)	S10	STEM literacy	University	Project-based
Yuliardi et al. (2024)	S11	Creative thinking	Secondary	Project-based
Khotimah et al. (2024)	S12	Communication	University	Non-project-based
Topsakal et al. (2022)	S13	Critical thinking	Secondary	Project-based
Sharif et al. (2024)	S14	Character	Primary	Project-based
Uzun & Sen (2023)	S15	Character	Secondary	Project-based
Pahrudin et al. (2021)	S16	Critical thinking	Secondary	Project-based
Seitenova et al. (2023)	S17	Communication	Secondary	Project-based
Sudarsono et al. (2022)	S18	Critical thinking	Secondary	Non-project-based
Temirton et al. (2023)	S19	Citizenship	Secondary	Project-based
Jawad et al. (2021)	S20	Critical thinking	Primary	Non-project-based
Mater et al. (2020)	S21	Critical thinking	Secondary	Project-based
Parno et al. (2020)	S22	Creative thinking	Secondary	Project-based
Nasir et al. (2022)	S23	Critical thinking	University	Non-project-based
Ultay & Ozkurt (2024)	S24	21st-century skills	Primary	Project-based
Tsai et al. (2021)	S25	Character	Secondary	Project-based
Zainil et al. (2023)	S26	21st-century skills	Primary	Non-project-based
Zainil et al. (2024)	S27a	Character	Primary	Project-based
	S27b	Citizenship	Primary	Project-based
	S27c	Critical thinking	Primary	Project-based
	S27d	Creative thinking	Primary	Project-based
	S27e	Collaboration	Primary	Project-based
	S27f	Communication	Primary	Project-based
Lopez-Belmonte et al., 2022	S28	Character	Secondary	Non-project-based
De Oliveira Biazus & Mahtari (2022)	S29	Creative thinking	Secondary	Project-based
Sinurat et al. (2022)	S30	Creative thinking	Secondary	Project-based

Coding Process

Information extracted from each selected study was systematically coded using a coding sheet developed for this purpose. The coding variables included the author(s), publication type, participants, sample size, instruments used, statistical analyses, and type of STEM program implemented. The coding sheet served as an essential instrument for aggregating data required to compute effect sizes and compare outcomes across studies (Hansen, Steinmetz, & Block, 2021). Effect size is a quantitative measure of the magnitude of a difference or the strength of a relationship between variables in a study (Kallogjeri & Piccirillo, 2023).

Statistical Analysis

Findings were obtained from 30 studies that employed experimental designs and reported post-test scores for both the treatment and control groups. The standardized mean difference (Cohen's *d*) was calculated to synthesize and compare outcomes between these groups (Lipsey & Wilson, 2001). To correct for potential small-sample bias, *d* values were converted into unbiased estimates (*Hedges' g*) (Hedges & Olkin, 1985).

The Statistical Package for the Social Sciences (SPSS) version 29 was used to calculate *Hedges' g*, standard error, lower and upper confidence intervals, and *p*-values for each study. SPSS also computed homogeneity statistics (*Q*), I^2, and Tau^2, and conducted moderator analyses. Two moderator variables were examined based on insights from previous research on 21st-century skills:

1. Educational level (primary, secondary, and university) and
2. Program design (project-based vs. non-project-based).

RESULTS

In this meta-analysis, we reviewed 30 journal articles published between 2015 and 2025, yielding 38 independent studies that met the inclusion criteria. From an initial pool of 2,426 studies, only those satisfying all methodological and statistical requirements were retained for quantitative synthesis. Each study's effect size (Hedges' *g*), standard error, confidence interval, and *p*-value were computed to determine the magnitude and significance of the STEM program's effect on students' 21st-century skills. The results are summarized in **Table 3**.

Table 3. Effect Size for STEM Programs

Study ID	Hedges' g	Standard Error (SE)	Lower 95% CI	Upper 95% CI	p-value
S1	2.55	0.35	1.86	3.25	< 0.001
S2	10.26	0.86	8.58	11.93	< 0.001
S3	1.83	0.28	1.28	2.39	< 0.001
S4a	0.65	0.30	0.06	1.24	0.03
S4b	0.59	0.30	0.01	1.18	0.05
S4c	0.58	0.30	0.00	1.17	0.05
S5	1.51	0.27	0.98	2.03	< 0.001
S6a	1.74	0.30	1.16	2.32	< 0.001
S6b	2.23	0.32	1.60	2.86	< 0.001
S7	1.92	0.32	1.29	2.54	< 0.001
S8	1.36	0.35	0.67	2.04	< 0.001
S9	10.23	1.14	8.00	12.47	< 0.001
S10	15.52	2.07	11.47	19.57	< 0.001
S11	0.54	0.19	0.18	0.91	< 0.001
S12	1.64	0.28	1.09	2.18	< 0.001
S13	9.93	1.04	7.89	11.97	< 0.001
S14	0.90	0.10	0.70	1.09	< 0.001
S15	0.41	0.37	-0.32	1.13	0.27
S16	1.20	0.31	0.60	1.81	< 0.001
S17	-0.16	0.26	-0.67	0.35	0.54
S18	1.81	0.34	1.15	2.48	< 0.001
S19	0.31	0.26	-0.20	0.82	0.23
S20	0.64	0.36	-0.07	1.35	0.08
S21	2.06	0.33	1.42	2.70	< 0.001
S22	1.31	0.27	0.78	1.85	< 0.001

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

S23	2.85	0.56	1.76	3.95	< 0.001
S24	0.67	0.30	0.09	1.26	0.02
S25	0.40	0.30	-0.18	0.99	0.18
S26	4.55	0.38	3.79	5.30	< 0.001
S27a	1.90	0.17	1.56	2.23	< 0.001
S27b	3.11	0.21	2.70	3.52	< 0.001
S27c	5.04	0.29	4.47	5.62	< 0.001
S27d	4.74	0.28	4.20	5.29	< 0.001
S27e	2.46	0.19	2.10	2.83	< 0.001
S27f	2.11	0.18	1.77	2.46	< 0.001
S28	1.22	0.14	0.94	1.50	< 0.001
S29	1.43	0.32	0.80	2.05	< 0.001
S30	5.01	0.52	3.99	6.03	< 0.001
Overall	2.64	0.47	1.73	3.55	< 0.001

Table 3 presents an overall mean effect size of 2.64, indicating a difference in mean scores between the STEM and non-STEM programs, and a confidence interval for the mean difference of 1.73 to 3.55, suggesting that the true mean difference lies within this range. Since the interval does not include zero, the mean difference is statistically significant. Furthermore, the *p*-value of <0.001 indicates that the STEM program has a significant effect on students' 21st-century skills.

Overall Effect Size

The observed effect sizes may vary from one study to another; however, some variation is expected due to sampling error. The Q statistic measures the extent to which the effect sizes in individual studies differ from the overall mean effect size. In this study, the Q value was 982.355 ($df = 37$, $p < 0.001$), indicating heterogeneity (i.e., true effect sizes differed across studies). The I^2 value was 99.2, indicating that 99% of the observed variance reflects true heterogeneity rather than random sampling error. The estimated variance of the true effect sizes was $Tau^2 = 7.982$.

Moderator Analysis

The significant heterogeneity results indicate the possibility of moderator variables—such as educational level and program design—associated with study characteristics that may systematically or otherwise influence the set of effect sizes analyzed. For the second research question, *"What moderators influence the effectiveness of STEM programs in enhancing students' 21st-century skills?"*, further analysis of variability was conducted. Several factors were identified as influencing the impact of STEM programs on 21st-century skills, including educational level and program design. These factors are believed to play an important role in determining the effectiveness of STEM integration in developing students' 21st-century competencies.

Educational Level

The moderator analysis was conducted based on 11 studies focusing on STEM programs at the primary level, 20 at the secondary level, and 7 at the university level. The Hedges' *g* values, 95% confidence intervals, and *p*-values were calculated using SPSS software (see **Table 3**) and are described as follows:

Table 4. Moderator Analysis Based on Educational Level

Factors	**Effect Size and Confidence Interval (CI)**					**Test (2-tailed)**		**Heterogeneity**		
Group	No. of Studies	Effect Size	Standard Error (SE)	Lower CI	Upper CI	Z-value	*p*-value	Q-value	*df*(Q)	*p*-value
Primary	11	2.602	0.4812	1.658	3.545	5.406	<0.001	444.46	10	<0.001
Secondary	20	1.594	0.4192	0.772	2.415	3.801	<0.001	219.153	19	<0.001
University	7	6.146	2.0344	2.158	10.133	3.021	0.03	185.181	6	<0.001
Between groups								6.494	2	0.039

(a) Is the STEM program at the primary level more effective?

The Hedges' *g* value was 2.602, with a 95% confidence interval ranging from 1.658 to 3.545. The Z-value was 5.406, with $p < 0.001$. The *p*-value (< 0.05) indicates that the STEM program at the primary level was more effective than the non-STEM program at the same level.

(b) Is the STEM program at the secondary level more effective?

The Hedges' *g* value was 1.594, with a 95% confidence interval ranging from 0.772 to 2.415. The Z-value was 3.801, with $p < 0.001$. The *p*-value (< 0.05) indicates that the secondary-level STEM program was more effective than the non-STEM program.

(c) Is the STEM program at the university level more effective?

The Hedges' *g* value was 6.146, with a 95% confidence interval ranging from 2.158 to 10.133. The Z-value was 3.021, with $p = 0.03$. The *p*-value (< 0.05) indicates that the university-level STEM program was more effective than the non-STEM program. The test comparing the three educational levels produced a *Q* value of 6.494, with degrees of freedom (*df*) = 2 and p = 0.039. The *p*-value (< 0.05) shows that the effect of STEM programs differs significantly across educational levels.

Program Design

Table 5 presents the results of the moderator analysis by program design, including 8 studies using non–project-based learning and 30 using project-based learning. The Hedges' *g* values, 95% confidence intervals, and *p*-values were calculated using SPSS software (see **Table 5**) and are described as follows:

Table 5. Moderator Analysis Based on Program Design

Factors	**Effect Size and Confidence Interval (CI)**					**Test (2-tailed)**		**Heterogeneity**		
Group	No. of Study	Effect Size	Standard Error	Lower CI	Upper CI	Z-value	*p*-value	Q-value	*df*(Q)	*p*-value
Non-project-based	8	4.06	1.3598	1.395	6.725	2.986	0.003	233.716	7	<0.001
Project-based	30	2.23	0.4349	1.378	3.083	5.128	<0.001	744.42	29	<0.001
Between groups								1.642	1	0.2

(a) Is the STEM program using non–project-based learning more effective?

The Hedges' *g* value was 4.06, with a 95% confidence interval ranging from 1.395 to 6.725. The Z-value was 2.986, with p = 0.003. The *p*-value (< 0.05) indicates that the STEM program using non–project-based learning was more effective than the non-STEM program.

(b) Is the STEM program using project-based learning more effective?

The Hedges' *g* value was 2.23, with a 95% confidence interval ranging from 1.378 to 3.083. The Z-value was 5.128, with $p < 0.001$. The *p*-value (< 0.05) indicates that the STEM program using project-based learning was more effective than the non-STEM program. The test comparing the two program design types produced a *Q* value of 1.642, with degrees of freedom (*df*) = 1 and $p = 0.2$. The analysis showed no evidence that the effectiveness of STEM programs differed significantly by program design.

DISCUSSION

This meta-analysis was conducted to estimate the effect size of STEM programs on students' 21st-century skills and to analyze the moderating variables influencing program effectiveness. Based on the findings, STEM programs demonstrated a significant and positive impact on students' 21st-century skills, with an overall mean effect size of 2.64 (see **Table 3**). This large effect size indicates that implementing STEM programs has a substantial impact on students' development of 21st-century competencies. It also confirms the effectiveness of

STEM interventions in meeting the demands of modern education, which emphasizes critical thinking, collaboration, and creativity (Herianto, Ikhsan, & Purwastuti, 2024). The 95% confidence interval (1.73–3.55) for the mean difference indicates that the true mean difference almost certainly lies within this range and does not include zero. This provides strong statistical justification that the observed effect is genuine rather than due to chance, demonstrating a real difference between students who participated in STEM programs and those in control groups. Furthermore, the significant p-value ($p < 0.001$) indicates that the observed difference is statistically meaningful and not attributable to chance.

The analysis also revealed variation in effect sizes across studies assessing the effectiveness of STEM programs on 21st-century skills. Consequently, moderator analyses were performed to identify factors contributing to this variation. Two main moderator variables were tested: educational level and program design. Results showed that STEM programs had significant positive effects across all three educational levels (primary, secondary, and university). Although all levels showed significant outcomes, the effect sizes differed, with the highest Hedges' g observed at the university level ($g = 6.146$), followed by primary ($g = 2.602$) and secondary ($g = 1.594$). All three values had significant p-values ($p < 0.05$), confirming the high effectiveness of STEM approaches compared to non-STEM methods.

Interestingly, the comparison test across the three educational levels also indicated a statistically significant difference, suggesting that educational level is an important moderator influencing STEM program effectiveness. Several factors may explain this variation, including differences in skill requirements across primary, secondary, and tertiary students. This is supported by Nhat, Phan, and Tran (2024), who found that primary-level STEM education is essential for developing foundational skills such as critical thinking and collaboration, which are crucial for future learning. The exceptionally large effect size at the university level may be attributed to more focused study designs or more intensive interventions.

Moreover, STEM education at the tertiary level directly impacts innovation and labor market outcomes (Bianchi & Giorcelli, 2020). The integration of Computational Thinking Scaffolding (CTS) within STEM programs in higher education has also been shown to enhance higher-order thinking skills, student engagement, and practical abilities (Lee et al., 2023). The analysis based on program design revealed that both project-based and non–project-based learning approaches had significant effects on 21st-century skills. However, when the two approaches were compared, no significant difference was detected. This suggests that program design is not a significant moderator influencing STEM program effectiveness overall. Nevertheless, further investigation is needed, as project-based learning continues to demonstrate consistent effects and remains more aligned with the philosophy of STEM education, which emphasizes authentic, inquiry-driven learning experiences (AlAli, 2024; Zainil et al., 2024).

There were some limitations encountered during this study, particularly the incomplete statistical data required for effect-size calculation. Missing information, such as means, standard deviations, and sample sizes, led to the exclusion of several potentially eligible articles. This limitation restricted the scope and statistical power of the findings; therefore, the present meta-analysis is based only on studies that fully met the inclusion criteria. Future research could be extended by incorporating additional moderators, such as intervention duration and publication type. The inclusion of intervention duration is important because the length of an educational program can significantly influence learning outcomes and skill development. Meanwhile, publication type (e.g., journal article, conference proceedings, or thesis) could affect methodological rigor and reporting quality, which may, in turn, influence the accuracy and reliability of the results.

CONCLUSION

Overall, this meta-analysis finds a positive, statistically significant effect of STEM programs on students' 21st-century skills. These results underscore the potential of the STEM approach to strengthen essential competencies such as critical thinking, creativity, communication, collaboration, character formation, and global citizenship, which are vital in contemporary education. Consequently, the findings of this study should serve as a valuable reference for educational policymakers and practitioners in redesigning teaching and learning strategies toward more holistic and future-oriented approaches.

The systematic and comprehensive integration of STEM in classrooms has the potential to make learning more relevant and meaningful, empowering students to compete and thrive in an increasingly complex and uncertain world. Therefore, the implementation of STEM-based interventions must be supported by progressive education policies and continuous teacher training to ensure that educational transformation can be realized effectively. However, given that education is a dynamic and evolving field, future research is encouraged to explore unanswered questions and identify contextual factors that influence learning outcomes. Such efforts will not only strengthen the theoretical foundation of STEM education but also help develop evidence-based policies to cultivate 21st-century skills among future generations.

ACKNOWLEDGEMENT

This work was supported by funding from the National University of Malaysia (GG-2025-014).

REFERENCES

1. AlAli, R. (2024). Enhancing 21st century skills through integrated STEM education using project-oriented problem-based learning. Geo Journal of Tourism and Geosites, 53(2), 421–430. https://doi.org/10.30892/gtg.53205-1217
2. Aouaf, S., Azzouzi, L., & Housni, H. (2023). Perceived barriers to critical thinking development: The student's view. International Journal of Linguistics, Literature & Translation, 6(2), 63–69. https://doi.org/10.32996/ijllt.2023.6.2.10
3. Astawan, I. G., Suarjana, I. M., Werang, B. R., Asaloei, S. I., Sianturi, M., & Elele, E. C. (2023). STEM-based scientific learning and its impact on students' critical and creative thinking skills: An empirical study. Jurnal Pendidikan IPA Indonesia, 12(3), 482–492. https://doi.org/10.15294/jpii.v12i3.46882
4. Ayverdi, L., & Öz Aydın, S. (2022). The effects of instructional design based on the STEM approach on the teaching process of training of gifted secondary school students. Hacettepe Sosyal ve Beşerî Bilimler Dergisi.
5. Benek, İ., & Akçay, B. (2021). The effects of socio-scientific STEM activities on 21st-century skills of middle school students. Participatory Educational Research, 9(2), 25–52. https://doi.org/10.17275/per.22.27.9.2
6. Berk, G., & Gülcü, A. (2024). The effect of computer-supported STEM applications on secondary students' achievement and computational thinking skills. Participatory Educational Research, 11(4), 160–183. https://doi.org/10.17275/per.24.54.11.4
7. Bianchi, N., & Giorcelli, M. (2019). Scientific education and innovation: From technical diplomas to university STEM degrees. Journal of the European Economic Association, 18(5), 2608–2646. https://doi.org/10.1093/jeea/jvz049
8. Bryan, L. A., Moore, T. J., Johnson, C. C., & Roehrig, G. H. (2015). Integrated STEM education. In C. C. Johnson, E. E. Peters-Burton, & T. J. Moore (Eds.), STEM roadmap: A framework for integration (pp. 23–37). Taylor & Francis.
9. Chen, S., Yang, Y. C., Lin, C., & Lin, S. S. J. (2022). Dispositions of 21st-century skills in STEM programs and their changes over time. International Journal of Science and Mathematics Education, 21(4), 1363–1380. https://doi.org/10.1007/s10763-022-10288-0
10. Dafik, N., Kadir, N., Maryati, T., Sufirman, N., & Ridlo, Z. (2023). The analysis of the implementation of RBL-STEM learning materials in improving student's meta-literacy ability to solve wallpaper decoration problems using local antimagic graph coloring techniques. Heliyon, 9(6), e17433. https://doi.org/10.1016/j.heliyon.2023.e17433
11. De Oliveira Biazus, M., & Mahtari, S. (2022). The impact of project-based learning (PJBL) model on secondary students' creative thinking skills. International Journal of Essential Competencies in Education, 1(1), 38–48. https://doi.org/10.36312/ijece.v1i1.752
12. Fujiwara, Y., & Jones, L. K. (2020). Developing 21st-century skills through STEM integration and global collaboration using 3D printing and CAD. In BRILL eBooks (pp. 55–71). https://doi.org/10.1163/9789004415133_004
13. Gallagher, S. A., & Gallagher, J. J. (2013). Using problem-based learning to explore unseen academic potential. Interdisciplinary Journal of Problem-Based Learning, 7(1).

14. Hansen, C., Steinmetz, H., & Block, J. (2021). How to conduct a meta-analysis in eight steps: A practical guide. Management Review Quarterly, 72(1), 1–19. https://doi.org/10.1007/s11301-021-00247-4
15. Hebebci, M. T., & Usta, E. (2022). The effects of integrated STEM education practices on problem solving skills, scientific creativity, and critical thinking dispositions. Participatory Educational Research, 9(6), 358–379. https://doi.org/10.17275/per.22.143.9.6
16. Hedges, L. V., & Olkin, I. (1985). Statistical methods for meta-analysis. Academic Press.
17. Herianto, N., Ikhsan, J., & Purwastuti, L. A. (2024). Developing student 21st-century skills through STEM engineering design learning cycle (STEM-EDELCY) model. The Journal of Educational Research, 117(3), 137–150. https://doi.org/10.1080/00220671.2024.2346659
18. Herlina, K., Abdurrahman, A., Umam, A. N., Nurjanah, A., Rabbani, G. F., & Pratiwi, F. A. I. (2025). Expression-based E-Worksheet (EBEW): An effort to enhance student' computational thinking skills. Journal of Technology and Science Education, 15(1), 50. https://doi.org/10.3926/jotse.2210
19. Idris, R., Bacotang, J., Govindasamy, P., & Nachiappan, S. (2023). Revolutionizing STEM education: Unleashing the potential of STEM interest careers in Malaysia. International Journal of Academic Research in Business and Social Sciences, 13, 1741–1752. https://doi.org/10.6007/IJARBSS/v13-i7/17608
20. Jawad, L. F., Majeed, B. H., & ALRikabi, H. T. S. (2021). The impact of teaching using a STEM approach on the development of creative thinking and mathematical achievement among students in the fourth scientific class. International Journal of Interactive Mobile Technologies, 15(13), 172. https://doi.org/10.3991/ijim.v15i13.24185
21. Jiang, M. (2024). The negative impact of exam-oriented education on the creativity of adolescents in the 21st century. Transactions on Social Science Education and Humanities Research, 5, 177–181. https://doi.org/10.62051/fftxkc02
22. Kallogjeri, D., & Piccirillo, J. F. (2023). A simple guide to effect size measures. JAMA Otolaryngology–Head & Neck Surgery, 149(5), 447–451. https://doi.org/10.1001/jamaoto.2023.0159
23. Kencana, M. A., Musri, N., & Syukri, M. (2020). The effect of STEM on students' creative thinking skills. Journal of Physics: Conference Series, 1460(1), 012141. https://doi.org/10.1088/1742-6596/1460/1/012141
24. Kementerian Pendidikan Malaysia. (2013). Pelan Pembangunan Pendidikan Malaysia 2013–2025.
25. Khotimah, K., Suratno, S., Asyiah, I. N., & Hariyadi, S. (2024). The analysis of PLOICE model application to develop science process skills: On the coffee learning process. International Journal of Instruction, 17(4), 117–134. https://doi.org/10.29333/iji.2024.1747a
26. Lee, H., Wu, T., Lin, C., Wang, W., & Huang, Y. (2023). Integrating computational thinking into scaffolding learning: An innovative approach to enhance science, technology, engineering, and mathematics hands-on learning. Journal of Educational Computing Research, 62(2), 431–467. https://doi.org/10.1177/07356331231211916
27. Lipsey, M. W., & Wilson, D. B. (2001). Practical meta-analysis. SAGE.
28. López-Belmonte, J., Segura-Robles, A., Moreno-Guerrero, A., & Parra-González, M. E. (2022). Comparative analysis between a STEM-based learning process and traditional teaching. South African Journal of Education, 42(Supplement 1), S1–S10. https://doi.org/10.15700/saje.v42ns1a2057
29. Mahmud, M. M., & Wong, S. F. (2022). Digital age: The importance of 21st-century skills among the undergraduates. Frontiers in Education, 7. https://doi.org/10.3389/feduc.2022.950553
30. Mariano, W. K., & Chiappe, A. (2021). Habilidades del siglo XXI y entornos de aprendizaje STEAM: Una revisión. Revista de Educación a Distancia, 21(68). https://doi.org/10.6018/red.470461
31. Mater, N. R., Hussein, M. J. H., Salha, S. H., Draidi, F. R., Shaqour, A. Z., Qatanani, N., & Affouneh, S. (2020). The effect of the integration of STEM on critical thinking and technology acceptance model. Educational Studies, 48(5), 642–658. https://doi.org/10.1080/03055698.2020.1793736
32. Mor, F. (2025). Beyond skills: Redefining education for the 21st century. Journal of Educational and Social Research, 15(4), 106. https://doi.org/10.36941/jesr-2025-0125
33. Nasir, M., Cari, C., Sunarno, W., & Rahmawati, F. (2022). The effect of STEM-based guided inquiry on light concept understanding and scientific explanation. Eurasia Journal of Mathematics, Science and Technology Education, 18(11), em2175. https://doi.org/10.29333/ejmste/12499

34. Nastiti, L. R., Sunarno, W., Sukarmin, S., Saputro, S., & Baehaqi, L. (2024). Improving STEM literacy through Project-Based Geoscience Learning (PJBGL) model. Journal of Baltic Science Education, 23(4), 694–709. https://doi.org/10.33225/jbse/24.23.694
35. Nhat, N. C., Oanh, T. T. K., & Hang, P. T. T. (2024). The effect of STEM education on academic performance: A meta-analysis study. International Journal of Learning, Teaching and Educational Research, 23(11), 180–195. https://doi.org/10.26803/ijlter.23.11.9
36. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71
37. Pahrudin, A., Misbah, M., Alisia, G., Saregar, A., Asyhari, A., Anugrah, A., & Susilowati, N. E. (2021). The effectiveness of Science, Technology, Engineering, and Mathematics-Inquiry learning for 15–16-year-old students based on K-13 Indonesian curriculum: The impact on critical thinking skills. European Journal of Educational Research, 10(2), 681–692. https://doi.org/10.12973/eu-jer.10.2.681
38. Parno, P., Yuliati, L., Supriana, E., Taufiq, A., Ali, M., Widarti, A., & Azizah, U. (2020). The influence of STEM-integrated 7E learning cycle on students' creative thinking skills in the topic of temperature and heat. Proceedings of the 7th Mathematics, Science, and Computer Science Education International Seminar (MSCEIS 2019). https://doi.org/10.4108/eai.12-10-2019.2296493
39. Pertiwi, N. P., Saputro, S., Yamtinah, S., & Kamari, A. (2024). Enhancing critical thinking skills through STEM problem-based contextual learning: An integrated e-module education website with virtual experiments. Journal of Baltic Science Education, 23(4), 739–766. https://doi.org/10.33225/jbse/24.23.739
40. Putra, A. K., Sumarmi, S., Deffinika, I., & Islam, M. N. (2021). The effect of blended project-based learning with STEM approach to spatial thinking ability and geographic skill. International Journal of Instruction, 14(3), 685–704. https://doi.org/10.29333/iji.2021.14340a
41. Seitenova, S., Khassanova, I., Khabiyeva, D., Kazetova, A., Madenova, L., & Yerbolat, B. (2023). The effect of STEM practices on teaching speaking skills in language lessons. International Journal of Education in Mathematics, Science and Technology, 11(2), 388–406. https://doi.org/10.46328/ijemst.3060
42. Siew, N. M., & Ambo, N. (2018). Development and evaluation of an integrated project-based and STEM teaching and learning module on enhancing scientific creativity among fifth graders. Journal of Baltic Science Education, 17(6), 1017–1033. https://doi.org/10.33225/jbse/18.17.1017
43. Sharif, S., Muniandy, T., & Mariappan, M. (2024). The influence of a robotics program on students' attitudes toward effective communication. European Journal of Educational Research, 13(3), 1171–1184. https://doi.org/10.12973/eu-jer.13.3.1171
44. Sinurat, H. A. Y., Syaiful, S., & Muhammad, D. (2022). The implementation of integrated project-based learning Science, Technology, Engineering, Mathematics on creative thinking skills and student cognitive learning outcomes in dynamic fluid. Jurnal Penelitian & Pengembangan Pendidikan Fisika, 8(1), 83–94. https://doi.org/10.21009/1.08108
45. Siregar, N. C., Rosli, R., Maat, S. M., & Capraro, M. M. (2019). The Effect of Science, Technology, Engineering and Mathematics (STEM) program on Students' Achievement in Mathematics: A Meta-Analysis. International Electronic Journal of Mathematics Education, 1(1). https://doi.org/10.29333/iejme/5885
46. Sudarsono, S., Kartono, K., Mulyono, M., & Mariani, S. (2022). The effect of STEM model based on Bima's local cultural on problem solving ability. International Journal of Instruction, 15(2), 83–96. https://doi.org/10.29333/iji.2022.1525a
47. Sumardi, S., Puji, R. P. N., Dafik, D., & Ridlo, Z. R. (2023). The implementation of RBL-STEM learning materials to improve students' historical literacy in designing the Indonesian batik motifs. International Journal of Instruction, 16(2), 581–602. https://doi.org/10.29333/iji.2023.16231a
48. Temirton, G., Kharipova, R. E., & Kistaubayeva, A. K. (2022). The effect of STEM application on learning history and culture based on photo-documents in museums. International Journal of Education in Mathematics, Science and Technology, 11(1), 17–36. https://doi.org/10.46328/ijemst.2824
49. Topsakal, İ., Yalçın, S. A., & Çakır, Z. (2022). The effect of problem-based STEM education on students' critical thinking tendencies and their perceptions of problem-solving skills. Science Education International, 33(2), 136–145. https://doi.org/10.33828/sei.v33.i2.1

50. Tsai, L., Chang, C., & Cheng, H. (2021). Effect of a STEM-oriented course on students' marine science motivation, interest, and achievements. Journal of Baltic Science Education, 20(1), 134–145. https://doi.org/10.33225/jbse/21.20.134
51. Ültay, N., & Özkurt, İ. (2024). The impact of 4th grade students' learning about magnetism through STEM activities on success, 21st-century skills, and perspectives. Research in Science & Technological Education, 1–25. https://doi.org/10.1080/02635143.2024.2375509
52. Uziak, J., Oladiran, M. T., Eisenberg, M., & Scheffer, C. (2010). International team approach to project-oriented problem-based learning in design. World Transactions on Engineering and Technology Education, 8(2), 137–144.
53. Uzun, S., & Şen, N. (2023). The effects of a STEM-based intervention on middle school students' science achievement and learning motivation. Journal of Pedagogical Research. https://doi.org/10.33902/jpr.202319315
54. Wang, L., Chen, B., Hwang, G., Guan, J., & Wang, Y. (2022). Effects of digital game-based STEM education on students' learning achievement: A meta-analysis. International Journal of STEM Education, 9(1). https://doi.org/10.1186/s40594-022-00344-0
55. World Economic Forum. (2025). Future of Jobs Report.
56. Yavuz, M., Hasançebi, M., & Hasançebi, F. (2020). The effect of STEM application on 21st-century skills among middle school students and on students' experiences. Soft Computing, 1(1), 28–39.
57. Yuliardi, R., Kusumah, Y. S., Nurjanah, N., Juandi, D., & Suparman, S. (2024). Development of a STEM-based digital learning space platform to enhance students' mathematical creativity in future learning classrooms. Eurasia Journal of Mathematics, Science and Technology Education, 20(12), em2545. https://doi.org/10.29333/ejmste/15665
58. Zainil, M., Kenedi, A. K., Rahmatina, N., Indrawati, T., & Handrianto, C. (2022). The influence of a STEM-based digital classroom learning model and high-order thinking skills on the 21st-century skills of elementary school students in Indonesia. Journal of Education and e-Learning Research, 10(1), 29–35. https://doi.org/10.20448/jeelr.v10i1.4336
59. Zainil, M., Kenedi, A. K., Rahmatina, N., Indrawati, T., & Handrianto, C. (2024). The influence of STEM-based digital learning on 6C skills of elementary school students. Open Education Studies, 6(1). https://doi.org/10.1515/edu-2024-0039