

Enhancing Learning Outcomes: A Meta-Analysis of the Effectiveness of STEM Education Approaches

Annisa Tishana^{1*}, Ganefri², Asmar Yulastri³, Giatman⁴, Fuji Astuti⁵, Dedy Irfan⁶, Hansi Effendi⁷

¹ Universitas Negeri Padang, Padang, Indonesia; annisatishana01@gmail.com

² Universitas Negeri Padang, Padang, Indonesia; ganefri@unp.ac.id

³ Universitas Negeri Padang, Padang, Indonesia; yun064@fpp.unp.ac.id

⁴ Universitas Negeri Padang, Padang, Indonesia; giatman@ft.unp.ac.id

⁵ Universitas Negeri Padang, Padang, Indonesia; astuti@fbs.unp.ac.id

⁶ Universitas Negeri Padang, Padang, Indonesia; dedy_irf@unp.ac.id

⁷ Universitas Negeri Padang, Padang, Indonesia; hans_79@ft.unp.ac.id

ARTICLE INFO

Keywords:

STEM education outcomes;
Vocational High School;
Meta Analysis

Article history:

Received 2024-12-24

Revised 2025-06-17

Accepted 2025-06-30

ABSTRACT

This study investigates the effectiveness and variability of STEM education implementation in Indonesian vocational (SMK) and senior secondary (SMA) schools. Given the growing emphasis on STEM to enhance critical 21st-century skills, understanding the consistency and influencing factors of its outcomes is essential. A meta-analysis was conducted, incorporating multiple studies on STEM education implementation. The analysis focused on effect size, heterogeneity, and the factors contributing to outcome variability. Data visualization techniques and statistical models were employed to assess consistency across studies. The analysis revealed a high degree of heterogeneity among the studies ($I^2 = 82.604\%$), indicating substantial differences in research design, methods, and participant characteristics. Despite this variability, the combined effect size was significant (intercept estimate = 0.307, $p < 0.001$), with a 95% confidence interval of 0.128–0.485. This confirms that the STEM approach consistently yields positive outcomes, particularly in fostering critical thinking, creativity, and collaboration. The findings suggest that despite contextual differences, STEM education provides meaningful benefits. However, variations in implementation—driven by factors such as teaching quality, resources, and institutional support—impact effectiveness. To reduce this disparity, policy integration is needed to support teacher training, industry collaboration, and resource allocation. A holistic, well-supported, and context-sensitive approach to STEM education is essential. Strengthening teacher competency, ensuring adequate facilities, and aligning with industry needs can enhance the effectiveness and sustainability of STEM initiatives in secondary education.

This is an open access article under the [CC BY-NC-SA](https://creativecommons.org/licenses/by-nc-sa/4.0/) license.



Corresponding Author:

Annisa Tishana

Universitas Negeri Padang, Padang, Indonesia; annisatishana01@gmail.com

1. INTRODUCTION

In the 21st century, the growing demand for a workforce proficient in science, technology, engineering, and mathematics (STEM) has prompted countries worldwide to integrate STEM education into school curricula. STEM is widely recognized as an effective approach to equip students with the critical thinking, problem-solving, and innovation skills required to meet the demands of an increasingly complex global economy (Thies et al., 2024). Through project-based and interdisciplinary learning, STEM fosters deeper engagement by emphasizing hands-on, contextualized experiences rather than rote memorization (Kiromah et al., 2020). It promotes collaboration, creativity, and analytical thinking, offering students the opportunity to explore, ask questions, and devise solutions to real-world problems (Ni'mah et al., 2019). This dynamic learning model not only strengthens students' academic achievement but also prepares them for the evolving needs of the professional world.

Moreover, STEM education supports the cultivation of both technical and soft skills, such as communication, adaptability, and leadership—qualities that are crucial in diverse and technology-driven industries (Ruijuan et al., 2023). Collaborative, project-based learning encourages students to work in teams, thereby enhancing their interpersonal skills and capacity to navigate multicultural work environments. By integrating science, mathematics, engineering, and technology into coherent learning experiences, students gain a holistic understanding of how these disciplines intersect and contribute to solving complex challenges (Çevik et al., 2024). This alignment with real-world contexts not only enhances students' motivation but also promotes a lifelong curiosity for learning.

In addition, STEM learning environments foster flexibility in thinking, resilience in facing failure, and experimentation with new ideas—traits essential for success in uncertain and rapidly evolving industries (Asunda et al., 2023). Beyond theoretical understanding, students are encouraged to engage in practical inquiry, design prototypes, and reflect on their outcomes, allowing them to develop a mindset conducive to innovation. These learning processes offer students the chance to take initiative, refine their decision-making, and grow more confident in their academic abilities and career trajectories.

However, despite the well-documented benefits of STEM education, significant challenges remain in its effective implementation. One major issue is the gap between policy aspirations and practical execution in classrooms. Many educators struggle to design and deliver integrated STEM experiences due to a lack of training, insufficient resources, and limited support systems (Amahoroe, 2021; Hansen, n.d.). Additionally, the interdisciplinary nature of STEM often presents difficulties in assessment, as evaluating students' innovation, problem-solving, and collaboration skills requires more complex tools than traditional tests (Sintia Devi et al., 2021). The research gap here lies in the limited empirical understanding of how these implementation barriers affect student outcomes, particularly in diverse educational contexts such as vocational and senior high schools. While prior studies have focused largely on STEM's academic benefits, fewer have examined the structural and pedagogical conditions necessary to sustain its success or how different stakeholders' involvement influences the quality of implementation.

This study aims to address that gap by investigating the impact of STEM education in vocational and senior high schools, with particular attention to its effects on student learning outcomes, engagement, and skill development. The novelty of this research lies in its holistic exploration of how stakeholder collaboration—including schools, government, and industry—supports or constrains effective STEM integration. Unlike existing studies that often isolate the classroom as the sole unit of analysis, this research considers broader systemic factors and real-world partnerships that shape student learning experiences.

The study is guided by the following research questions: (1) How does the implementation of STEM education influence students' academic performance and soft skill development in vocational and senior high school settings? (2) What challenges do educators face in integrating interdisciplinary STEM approaches? (3) How does collaboration among government, schools, and industry affect the

effectiveness and sustainability of STEM programs? These questions are critical to understanding the full landscape of STEM implementation and to informing policies that enhance its reach and impact.

The significance of this research lies in its potential to contribute to both theory and practice. From a theoretical perspective, it expands the discourse on STEM education by offering insights into the institutional and collaborative dimensions that facilitate or hinder its success. Practically, the findings can guide education policymakers, curriculum developers, and school leaders in designing more responsive and sustainable STEM programs. By highlighting the roles of stakeholder engagement, teacher preparedness, and contextual adaptation, this study seeks to build a framework for inclusive and high-impact STEM education. In turn, such efforts can help create a generation of learners who are not only academically capable but also equipped with the creativity, resilience, and leadership needed to address future global challenges (Tuong, 2023; Jones et al., 2020).

Ultimately, the effective integration of STEM education holds transformative potential—not only for improving student outcomes but also for aligning educational systems with the needs of modern economies. Through thoughtful implementation, supported by professional development, adequate resources, and cross-sector collaboration, STEM learning can become a powerful catalyst for educational reform and workforce development.

2. METHODS

2.1 Research Methods

This study focused on the period from 2018 to 2023 to ensure the inclusion of relevant and current data. A comprehensive literature review was conducted by searching for articles using specific keywords across various electronic databases. The databases utilized included Crossref, Google Scholar, Scopus, Web of Science, Semantic Scholar, ScienceDirect, and Publish or Perish (Harzing), aiming to identify relevant studies. Additional searches were performed to capture any articles that might have been overlooked in the primary database queries. The keywords employed in the searches included: a. "education, teaching, learning," b. "experimental," c. "Vocational School," d. "Senior High School," e. "STEM learning outcomes," and f. "STEM effectiveness."

This systematic approach to the literature search was designed to ensure broad and relevant data coverage so that the analysis could lead to robust and reliable conclusions. The time span of 2018 to 2023 was chosen to ensure that only recent and relevant research was used, given the evolving dynamics of STEM education. The use of various electronic databases, such as Scopus and Web of Science, allows access to high-quality scholarly sources, while Google Scholar and Semantic Scholar provide wider coverage for articles that may not be available in major databases. In addition, the use of specific but diverse keywords ensures that research covers various aspects related to STEM education, from learning methods to the effectiveness of learning outcomes. With a combination of manual and automated searches through platforms like Publish or Perish, the risk of missing relevant articles is minimized. This process ensures the integrity and validity of the literature used in the research, providing a solid foundation for further analysis (Altuntaş & Barut, 2023).

The results of this comprehensive literature search process were then analyzed in depth to identify patterns, trends and gaps in research related to STEM education. This analysis focused not only on the main findings of each article, but also on the research methods used, the geographical context and the level of education in focus. As such, it provides a holistic picture of how STEM approaches have been implemented and evaluated in various educational settings (Nurtanto et al., 2020). In addition, the identification of research gaps provides the basis for recommendations for further studies, such as the development of more inclusive STEM methods or the adaptation of STEM curricula to local needs. This approach not only enriches theoretical insights but also provides practical guidance for educators, policy makers and researchers who want to improve the effectiveness of STEM education globally (Yamamoto et al., 2022).

2.2 Article Selection Criteria

This study employed checklists and flowcharts from the PRISMA guidelines to enhance the quality of the systematic review. Details of the literature screening process are illustrated in Figure 1. To assess the impact of STEM on learning in vocational and high schools, specific criteria were applied for article selection: the study must focus on the effects of STEM in vocational (SMK) and high schools (SMA), be conducted between 2018 and 2023, written in Indonesian, utilize an experimental research design, and report complete data, including sample size, mean, and standard deviation (SD), to enable Effect Size calculations. Out of an initial pool of 2,543 articles identified, only 25 met these criteria after screening. These included 12 studies on STEM implementation in SMK and 13 studies on STEM learning in SMA.

The use of PRISMA guidelines in this study ensured that the literature review process was conducted in a systematic and transparent manner, thus minimizing bias in the selection of articles. Strict selection criteria ensured that only relevant and high-quality articles were analyzed, providing reliability to the research results (Rivera et al., 2016). By choosing an experimental research design, this study focuses on strong empirical evidence of the effect of STEM learning on learning outcomes in vocational and high schools. Data collection that includes sample size, mean and standard deviation allows for accurate effect size calculations, providing a quantitative and comprehensive picture of the impact of STEM. The screening process from 2,543 articles to 25 articles shows how important rigorous literature selection is to obtain valid results. The findings from this study not only illustrate the effectiveness of STEM at the two levels of education, but also provide a basis for the development of better educational policies and learning practices in the future.

With the selection resulting in 25 shortlisted articles, this study provides a deep insight into the application of STEM in learning contexts in vocational and high schools. Analysis of the data from these articles allows the identification of trends in STEM effectiveness, including the most successful learning strategies and the challenges faced in their implementation. In addition, the findings can be used to develop more adaptive and relevant approaches for students, such as the integration of digital technologies or the use of contextualized problem-based projects (Mukhlis et al., 2023). The results also provide an opportunity to compare the effectiveness of STEM in SMK, which is more oriented towards practical skills, with SMA, which focuses more on mastering theoretical concepts. Thus, this research not only contributes to the development of STEM education, but also serves as an important reference for policymakers in designing innovative curricula that meet the needs of the 21st century.

2.3 Coding Phase

The study was coded after identifying eligible literature. The coding focused on various aspects, including the experimental discipline, grade level, learning outcome type, and learning model. The specific coding framework was as follows: Experimental disciplines: Civil Engineering, Automotive Engineering, Physics, Mathematics, Accounting, and Hospitality. Grade level: Vocational High School and Senior High School. Learning outcomes: Achievement, Creativity, Problem-Solving, Thinking Skills, Project Competency Achievement Test, Achievement Test, Learning Motivation, Interest in Technology, Desire to explore technology subjects in depth, Aspiration to engage with STEM in the future, Self-efficacy and independence in dealing with technology, Recognition of the need for physics knowledge in technology, and Gender equality in STEM learning (Hidayah et al., 2021).

The systematic coding approach in this study allows for a structured and in-depth analysis of various aspects of STEM learning. By covering experimental disciplines such as Civil Engineering, Physics and Accounting, this study demonstrates the flexibility of the STEM approach to be applied in various scientific fields (Kristensen et al., 2023). In addition, the grade levels covering both SMK and SMA provide an opportunity to compare the effectiveness of STEM at two educational levels that have different characteristics and learning needs. The variety of learning outcomes coded, such as academic achievement, creativity, critical thinking skills and interest in technology, strengthens the understanding of the holistic impact of STEM. Also included is the influence of STEM on students' motivation, independence and confidence in facing technological challenges, confirming the

importance of STEM not only in cognitive aspects, but also the development of affective attitudes and skills. By including a gender perspective, the research also highlights the equal access and potential of female and male students in STEM, strengthening the argument that this approach can support inclusive and equitable learning (Seskir et al., 2024).

Furthermore, the results of this coding analysis can serve as a basis for designing STEM learning strategies that are more specific and relevant to the needs of each student group. For example, a STEM approach in SMK could focus more on practical applications and vocational skills relevant to the world of work, while in SMA it could focus on strengthening theoretical concepts that prepare students for higher education (Yilmaz, 2022). Deep coding also allows the identification of specific challenges faced in the implementation of STEM across different disciplines, so that more effective solutions can be designed. In addition, the emphasis on the influence of STEM on students' interest and motivation towards technology opens up opportunities to integrate more elements of current technologies, such as artificial intelligence or the Internet of Things, in the curriculum. Thus, the STEM approach not only enriches students' learning experiences, but also strengthens the link between education and real-world needs, preparing students to become competent and future-ready individuals (ASLI & ZSOLDOS-MARCHIS, 2021).

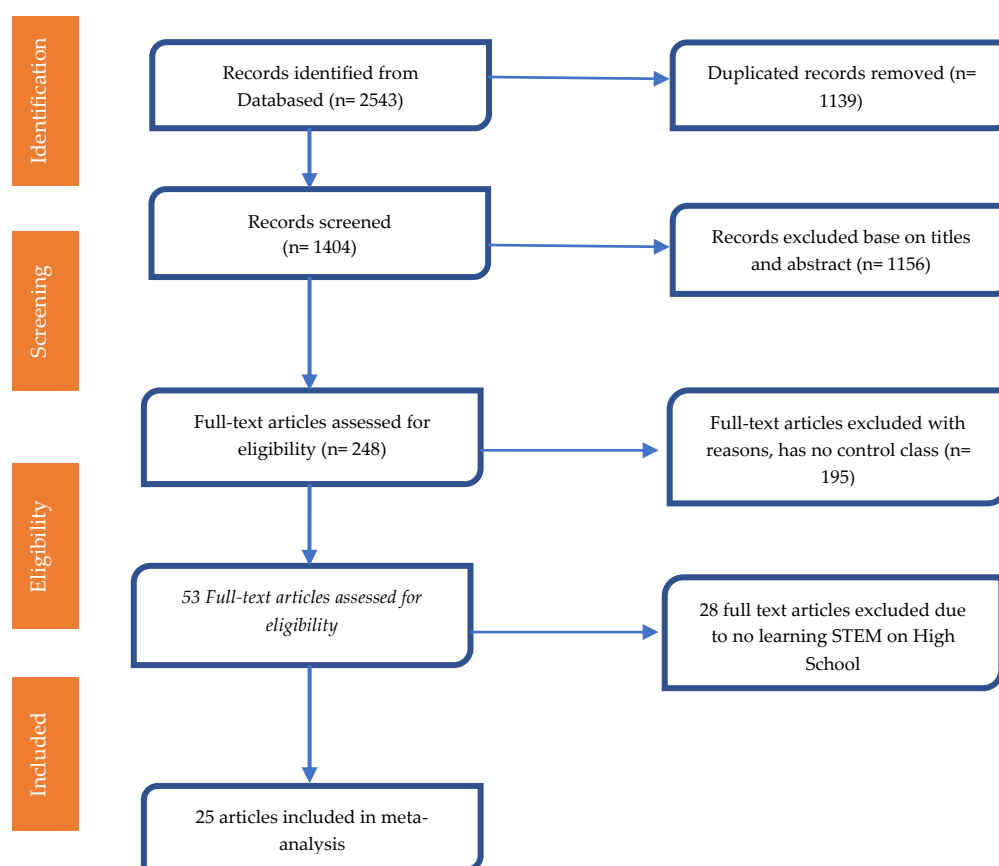


Figure 1. Article Filter Process

3 FINDINGS AND DISCUSSION

3.1 Effect Size Result

Table 1. Inteshep Coefficients Table

	Estimate	Standard Error	Z	p	95% Confidence Interval	
					Lower	Upper
intercept	0.307	0.091	3.367	< .001	0.128	0.485

The intercept estimate of 0.307 reflects the average combined effect across all analyzed studies. This means that, assuming all other factors remain constant, the average impact of a specific approach or intervention is 0.307. The p-value, which is less than 0.001, indicates that the result is statistically significant, with an extremely low likelihood of occurring by chance. The confidence interval (95%: 0.128 to 0.485) represents the range within which the average combined effect is expected to fall with 95% certainty. The relatively narrow range suggests a low level of uncertainty in the result. Although the average combined effect size (0.307) is small, its statistical significance confirms that the approaches or interventions analyzed have a measurable impact. In summary, the average combined effect is 0.307, statistically significant, and associated with a high confidence level and minimal uncertainty. While modest in scale, this effect is meaningful and indicates a real influence.

The intercept estimate of 0.307 represents the average combined effect found across the studies analyzed, indicating that if all other variables are considered fixed, the impact generated by the approach or intervention is 0.307. The very small p value of less than 0.001 indicates that this result is highly statistically significant. This means that the likelihood of the result occurring by chance is very small, so we can be confident that the observed effect is real and not the result of random fluctuations. In addition, the 95% confidence interval ranging from 0.128 to 0.485 indicates that with a 95% confidence level, the average combined effect falls within this range. This fairly narrow range reflects that the uncertainty in the estimation of these results is low. Although the value of the combined effect is relatively small at 0.307, it still indicates a noticeable impact, even if the scale is not very large. Overall, although the effect is small, this result is statistically significant and can be considered important, with a high level of confidence and uncertainty.

3.2 Publication Bias

Kendall's τ value of 0.073 ($p = 0.627$) and Egger's test result ($z = 0.227$, $p = 0.820$) indicate no significant evidence of funnel plot asymmetry. This suggests that there is no substantial publication bias, and the data included in the meta-analysis is sufficiently representative and not influenced by selective publication. The symmetrical funnel plot, with study points distributed in line with sample sizes, supports the conclusion that publication bias is not a concern based on these statistical tests.

The results of the analysis using Kendall's τ of 0.073 with a p-value of 0.627, as well as Egger's test ($z = 0.227$, $p = 0.820$), showed that there was no strong evidence for asymmetry in the funnel plot. Asymmetry in funnel plots is often considered an indication of publication bias, which can occur if studies that are not significant or have negative results are not published. However, in this case, with high p-values in both tests, we can conclude that the data used in this meta-analysis is not affected by significant publication bias. These results show that the distribution of study points on the funnel plot is quite symmetrical and spread out according to the sample size, indicating that the selection of studies is unbiased and reflects a representative picture of the wider study population. Overall, there were no signs of publication bias based on the results of these statistical tests, which strengthens the validity and credibility of the findings in the meta-analysis (Çengel et al., 2019).

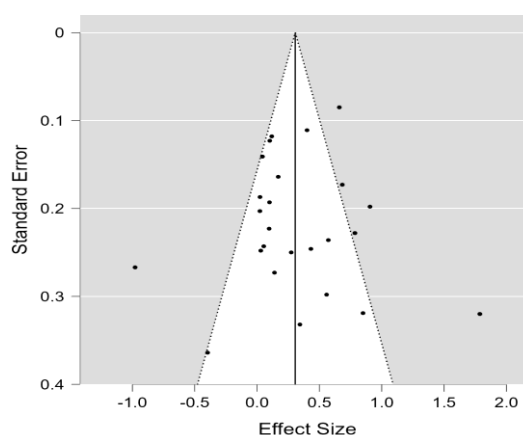


Figure 2. Funnel Plot

Based on the results of the analysis using Kendall's τ and Egger's test, it can be concluded that there is no strong indication of publication bias in this meta-analysis. The high p-value in both tests indicates that the distribution of study points on the funnel plot tends to be symmetrical, with study points spread according to the sample size, which indicates that the data used is representative enough and not affected by publication selection. In other words, the results of this analysis strengthen the validity and credibility of the research findings, as it shows that the selection of studies was done objectively without any significant bias. Overall, no evidence was found to support the existence of publication bias, so the findings in this meta-analysis can be considered valid and reliable for further inference.

3.3 STEM impact in senior high school and vocational high school

High Degree of Heterogeneity ($I^2 = 82.604\%$), This value shows that 82.604% of the variation in results across the analyzed studies is due to differences in study characteristics (heterogeneity) rather than random chance. In other words, substantial variability exists in aspects such as research design, methods, populations, or other variables among the studies. Despite this heterogeneity, the combined effect across all studies is statistically significant, as indicated by confidence intervals that do not include zero, confirming the presence of a real effect. Confidence Interval (95%), The confidence interval for the I^2 statistic ranges from 71.617% to 92.723%. This indicates that even under the most favorable conditions, a high degree of heterogeneity persists, with variability consistently falling within this range. $H^2 = 5.748$. This value provides another measure of heterogeneity, showing that the variability between studies exceeds what would be expected from random error by more than five times. This highlights the significant differences in study outcomes due to factors beyond random variation.

The high level of heterogeneity, indicated by the I^2 value of 82.604%, indicates that most of the variation among the results of the analyzed studies (about 82.6%) is due to factors related to differences in research design, methods used, population studied, or other variables, rather than to random error. This means that although there is a large variation in results between studies, the differences are not due to chance or random fluctuations. The (95%) confidence intervals for I^2 that ranged from 71.617% to 92.723% indicated that the high degree of heterogeneity remained consistent even when the best conditions were considered, providing confidence that the variation between studies was indeed significant. The H^2 value of 5.748 also reinforces this finding, as this figure indicates that the variability between study results is more than five times that of what would be expected if there was only random error. Nonetheless, the combined effect of all studies was still found to be statistically significant, as the confidence interval for the combined effect value did not include zero, indicating a real effect despite the high variation.

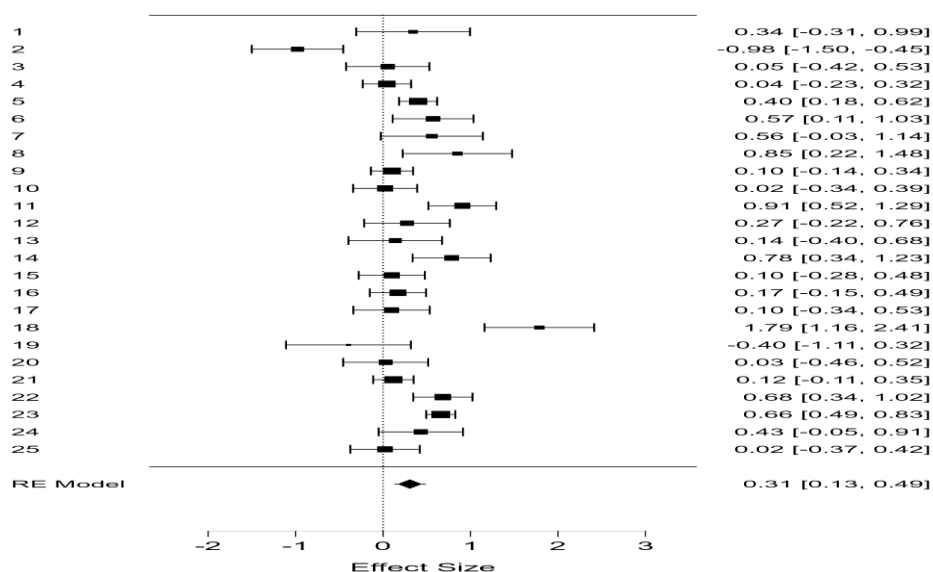


Figure 3. Forest Plot

The STEM approach enables learners to enhance their abilities in logical problem-solving, conducting research, exploring new ideas, collaborating, analyzing, and critically evaluating information. It also facilitates easier access to information, adaptability to change, decision-making, creativity, responsibility, curiosity, and effective interaction within social and cultural contexts. Furthermore, this approach supports the development of leadership and entrepreneurial skills (Briyanda et al., 2023). To maximize student achievement, it is essential to reduce learning barriers by implementing active teaching methods. This strategy aims to provide a more meaningful and high-quality learning experience (Sa’adhah et al., 2019).

Furthermore, the application of the STEM approach can encourage students to develop critical skills that are not only useful in academic contexts, but also in their professional and personal lives. By applying project-based learning and real-world challenges, students are encouraged to think creatively and innovatively in solving complex problems (Kulakoglu & Kondakci, 2023). They are trained to work collaboratively in teams, develop effective communication skills, and be able to adapt to technological developments and the rapidly changing world. This approach also provides space for students to explore various fields of science and discover their interests and potential more deeply. Along with that, teachers are expected to act as facilitators who support students in this process, by creating an inclusive, participatory and reflective learning environment. Therefore, consistent and appropriate implementation of STEM education can produce a generation that not only excels academically, but is also ready to face the challenges of an increasingly complex and diverse world (Cain et al., 2024).

3.4 Discussion

The STEM approach in vocational education is crucial for advancing the learning and development of both students and educators. By integrating science, technology, engineering, and mathematics, STEM enables students to develop creative problem-solving abilities within a multidisciplinary framework. Studies indicate that implementing STEM not only enhances students' technical competencies but also positively influences their behavior and attitudes. Learners engaged in STEM-based education often exhibit greater collaboration, creativity, communication, and critical thinking—key skills essential for navigating the complexities of the modern workforce (Arifin et al., 2020). The STEM approach in vocational education makes a significant contribution in preparing students to face the challenges of an increasingly complex and dynamic world of work. The integration of science, technology, engineering, and math not only hones technical skills but also encourages

students to think more critically and creatively when solving problems. This is very relevant to the needs of the industrial world that demands workers with multidisciplinary and adaptive abilities (Meirani & Intania, 2023). Moreover, this approach also shapes students' positive attitudes and behaviors, such as the ability to work in teams, communicate effectively, and think analytically (Agussuryani et al., 2022).

To ensure the successful implementation of STEM in vocational education, it is important for educational institutions to adopt an approach that focuses on project-based learning and problem-solving. Through this approach, students not only acquire theoretical knowledge, but are also directly involved in the practical application of the knowledge they learn. Collaboration between students, educators and industry is also crucial in creating learning experiences that are relevant to the needs of the working world. This cooperation can help students understand the real context in which their technical and soft skills are tested, as well as provide opportunities to acquire practical skills that can be directly applied in the field. In addition, educators need to be involved in ongoing training programs to update their skills, so they can adapt teaching methods that are more in line with technological developments and industry trends. With the right support, the STEM approach will be able to produce a workforce that is ready, innovative and can adapt quickly to changes in the industry (Suryaman et al., 2023).

The STEM approach brings transformative changes to teaching practices for educators, encouraging cross-disciplinary collaboration and the integration of concepts from various subjects to enhance students' understanding. However, implementing STEM comes with challenges, particularly in assessing student progress. Effective assessment must measure problem-solving abilities and the exploration of innovative ideas (Marsiti et al., 2023). Successful STEM implementation requires strong support from governments, schools, and industries. This includes teacher training, adequate resources, and industry partnerships to strengthen the approach and produce workforce-ready graduates. This article highlights STEM as a vital strategy for equipping students with essential future skills while offering new perspectives for teachers in vocational education. Despite its challenges, STEM holds significant potential to elevate the quality of vocational education, prepare students for real-world demands, and contribute to national development (Dona et al., 2021).

The STEM approach brings profound changes in teaching methods for educators, who are now faced with the challenge of integrating multiple disciplines within an integrated learning framework. This approach requires educators to develop a more collaborative and real problem-based way of teaching, where students learn to connect knowledge from science, technology, engineering and math to solve challenges. One of the major challenges in STEM implementation is more holistic assessment, which measures not only theoretical understanding, but also students' ability to think critically, solve problems and innovate. Therefore, assessments in STEM education should be designed to evaluate students' thought processes, not just the end result. To support this implementation, support from various parties is essential. Governments, schools, and industries need to work together to provide the right training for teachers, as well as adequate resources and opportunities for students to collaborate with the industry. That way, STEM education not only improves academic quality, but also prepares students with practical skills that are ready to be used in the world of work, contributing to national development.

3.5 Implications

Implementing the STEM approach significantly enhances students' critical, analytical, and creative thinking skills, preparing them to navigate the complexities of today's workforce. It nurtures independence, collaboration, and innovation in solving real-world problems (Chalim et al., 2019). This approach also encourages educators to adopt more interactive and project-based teaching methods. Its interdisciplinary nature demands the integration of diverse concepts, which enriches the overall learning experience. However, effective assessment remains a challenge, as accurately evaluating students' problem-solving, innovation, and collaboration abilities requires refined tools and methods

(Mirawati, 2019). Successful STEM implementation also hinges on strong institutional support, including comprehensive teacher training, adequate resources, and robust partnerships with industry. Support from governments and educational bodies plays a critical role in maximizing its impact. Ultimately, by equipping students with essential 21st-century skills, the STEM approach contributes directly to enhancing national workforce quality and competitiveness (Rahayu & Suhartini, 2020).

4. CONCLUSION

Implementing the STEM approach in vocational and senior high schools has demonstrated a significant positive impact on students' learning outcomes, particularly in enhancing critical, analytical, creative, and collaborative thinking skills—abilities essential for success in the modern workforce. STEM fosters technical competencies and promotes essential soft skills such as communication, leadership, and teamwork. By integrating interdisciplinary content and promoting interactive, project-based learning, STEM modernizes traditional teaching methods and better aligns education with real-world demands. However, the research also identifies several limitations. Key challenges include the need for curriculum alignment, limited teacher preparedness, and insufficient resources and infrastructure to support effective STEM learning. These constraints hinder the full realization of STEM's potential impact.

To address these limitations, future research should explore effective strategies for integrating STEM into existing curricula, with particular attention to scalable teacher training models and sustainable resource allocation. Further investigation is also needed into innovative assessment methods that accurately measure higher-order skills such as problem-solving, innovation, and collaboration. Moreover, examining the impact of school-industry partnerships on student engagement and employability could offer valuable insights into strengthening the link between education and the workforce. By addressing these areas, future studies can contribute to more effective, inclusive, and impactful implementation of STEM education across diverse educational contexts.

Conflicts of Interest: The authors declare no conflicts of interest related to the publication of this study. All analyses, interpretations, and conclusions presented in this research were conducted independently and without any influence from funding bodies, institutions, or external stakeholders. The research is solely intended to contribute to the academic and practical understanding of STEM education's impact on learning outcomes in vocational and senior high schools. Any potential affiliations or collaborations mentioned in the study are purely academic and aimed at enhancing the study's scope and quality.

REFERENCES

- Agussuryani, Q., Sudarmin, S., Sumarni, W., Cahyono, E., & Ellianawati, E. (2022). STEM literacy in growing vocational school student HOTS in science learning: A meta-analysis. *International Journal of Evaluation and Research in Education*, 11(1), 51–60. <https://doi.org/10.11591/ijere.v11i1.21647>
- Altuntaş, E. Ç., & Barut, N. B. (2023). Forest education experiences of vocational high school students. *EJERCongress*, 463–475.
- Amahoroe, R. (2021). Pengembangan Desain Praktikum Berbasis Stem Pada Pembuatan Tempe Dari Fermentasi Biji Nangka (*Artocarpus Heterophyllus*) Untuk Meningkatkan Literasi Siswa Smk. *Molluca Journal of Chemistry Education (MJoCE)*, 11(2), 129–140. <https://doi.org/10.30598/mjocev11iss2pp129-140>
- Ananingtyas, R. S. A., Sakti, R. E., Hakim, M. H., & Putra, F. N. (2022). Pengembangan Media Pembelajaran Berbasis Arduino pada Pembelajaran STEM dalam Meningkatkan Literasi Sains dan Digital. *Briliant: Jurnal Riset Dan Konseptual*, 7(1), 178. <https://doi.org/10.28926/briliant.v7i1.795>

- Arifin, A. M., Pujiastuti, H., & Sudiana, R. (2020). Pengembangan media pembelajaran STEM dengan augmented reality untuk meningkatkan kemampuan spasial matematis siswa. *Jurnal Riset Pendidikan Matematika*, 7(1), 59–73. <https://doi.org/10.21831/jrpm.v7i1.32135>
- Artika, T. D., & Widiani, K. A. (2024). Penggunaan STEM Worksheet Sebagai Upaya Melatih kemampuan Berpikir Kritis Siswa SMP dalam Pembelajaran IPA. *Seminar Nasional IPA XIV*, 601–611.
- Asigigan, S. I., & Samur, Y. (2021). The effect of gamified stem practices on students' intrinsic motivation, critical thinking disposition levels, and perception of problem-solving skills. *International Journal of Education in Mathematics, Science and Technology*, 9(2), 332–352. <https://doi.org/10.46328/IJEMST.1157>
- ASLI, A., & ZSOLDOS-MARCHIS, I. (2021). Teaching applications of Mathematics in other disciplines: teachers' opinion and practice. *Acta Didactica Napocensia*, 14(1), 142–150. <https://doi.org/10.24193/adn.14.1.11>
- Asunda, P., Faezipour, M., Tolemy, J., & Do Engel, M. T. (2023). Embracing Computational Thinking as an Impetus for Artificial Intelligence in Integrated STEM Disciplines through Engineering and Technology Education. *Journal of Technology Education*, 34(2), 43–63. <https://doi.org/10.21061/jte.v34i2.a.3>
- Briyanda, D., Nurjanah, N., & Setiawati, T. (2023). E-Modul Berbasis STEM Mata Pelajaran Boga Dasar Untuk Siswa SMK Jasa Boga Kelas X. *Pedagogik: Jurnal Pendidikan*, 18(1), 19–27. <https://doi.org/10.33084/pedagogik.v18i1.4724>
- Cain, E. J., Valauri, A., Perry, J. R., & Deloach, A. (2024). Exploring How Rural Schools and Communities Influence the Academic Journeys of College Students in STEM Majors. *Rural Educator*, 45(3), 15–33. <https://doi.org/10.55533/2643-9662.1417>
- Çengel, M., Alkan, A., & Yıldız, E. P. (2019). Evaluate the attitudes of the pre-service teachers towards STEM and STEM's sub dimensions. *International Journal of Higher Education*, 8(3), 257–267. <https://doi.org/10.5430/ijhe.v8n3p257>
- ÇEVİK, M., BAKIOĞLU, B., & TEMİZ, Z. (2024). The Effects of Out-of-School Learning Environments on STEM Education: Teachers' STEM Awareness and 21st-Century Skills. *Kuramsal Eğitim Bilim*, 17(1), 57–79. <https://doi.org/10.30831/akukeg.1309078>
- Chalim, M. N., Mariani, S., & Wijayanti, K. (2019). Kemampuan Komunikasi Matematis Siswa SMK Ditinjau dari Self Efficacy pada Setting Pembelajaran Project Based Learning Terintegrasi STEM. *PRISMA, Prosiding Seminar Nasional Matematika*, 2, 540–550. <https://journal.unnes.ac.id/sju/index.php/prisma/article/view/29049/12789>
- Dona, M., Usboko, R., Made Parsa, I., Zet, D., Baitanu, Y., Pendidikan, P., Elektro, T., Nusa, U., & Adisucipto, C. J. (2021). Penerapan Pembelajaran Stem Dengan Model Pjbl Di Kelas Xi Titl Smk N 2 Kupang Untuk Meningkatkan Kemampuan Berpikir Kreatif Siswa. *Jurnal SPEKTRO*, 4(1), 9–11. <https://ejournal.undana.ac.id/index.php/spektr0/article/view/5006>
- Doolittle, P., Wojdak, K., & Walters, A. (2023). Defining Active Learning: A Restricted Systematic Review. *Teaching and Learning Inquiry*, 11. <https://doi.org/10.20343/teachlearninqu.11.25>
- Fitriyana, N., Wiyarsi, A., Pratomo, H., & Marfuatun, M. (2024). the Importance of Integrated Stem Learning in Chemistry Lesson: Perspectives From High School and Vocational School Chemistry Teachers. *Journal of Technology and Science Education*, 14(2), 418–437. <https://doi.org/10.3926/jotse.2356>
- Hansen, M. (n.d.). *EdWorkingPaper No . 24-1024 STEM teacher workforce in high-need schools resilient despite shrinking supply and increasing demand*. 24, 0–43.
- Hidayah, R. N., Wiyono, K., & Ismet. (2021). Analisis Kebutuhan Elearning Berbasis Stem Mata Pelajaran Fisika Di Smkn Sumatera Selatan. *Redesain Pembelajaran IPA Yang Adaptif Di Masa Pandemi Covid-19*, 1–8.
- Hussim, H., Rosli, R., Mohd Nor, N. A. Z., Maat, S. M., Mahmud, M. S., Iksan, Z., Rambely, A. S., Mahmud, S. N., Halim, L., Osman, K., & Lay, A. N. (2024). A Systematic Literature Review of

- Informal STEM Learning. *European Journal of STEM Education*, 9(1), 1–10. <https://doi.org/10.20897/ejsteme/14609>
- Jones, M. G., Childers, G., & Stanley, R. (2020). Science Instruction in STEM and Non-STEM High Schools. *Electronic Journal for Research in Science & Mathematics Education*, 24(4), 69–90.
- Kiromah, A., Sudarti, S., & Rohatin, R. (2020). ANALISIS AKTIVITAS BELAJAR SISWA PADA PEMBELAJARAN FISIKA MENGGUNAKAN MODEL PROBLEM BASED LEARNING DENGAN PENDEKATAN STEM (Pokok Bahasan Gaya dan Hukum Newton). *Jurnal Pembelajaran Fisika*, 9(4), 165. <https://doi.org/10.19184/jpf.v9i4.17983>
- Kristensen, M. A., Larsen, D. M., Seidelin, L., & Svabo, C. (2023). The Role of Mathematics in STEM Activities: Syntheses and a Framework from a Literature Review. *International Journal of Education in Mathematics, Science and Technology*, 12(2), 418–431. <https://doi.org/10.46328/ijemst.3357>
- Kulakoglu, B., & Kondakci, Y. (2023). STEM Education as a Concept Borrowing Issue: Perspectives of School Administrators in Turkey. *ECNU Review of Education*, 6(1), 84–104. <https://doi.org/10.1177/20965311221107390>
- Mahendra, C., Prabowo, R. E., Paath, D. K., Mili, W. N., & Annawati, B. D. (2023). Gamifikasi dalam Pendidikan STEM : Transformasi Pembelajaran dan Pemberdayaan Siswa menuju Industri 5 . 0. *Inovasi Pendidikan Fisika*, 12(3), 92–100.
- Mansour, N., Çevik, M., Yağci, A., Alotaibi, S. B. M., & El-Deghaidy, H. (2024). Modeling the Factors Influencing Secondary Students' Performance in Stem Subjects. *Journal of Baltic Science Education*, 23(3), 518–535. <https://doi.org/10.33225/JBSE/24.23.518>
- Marsiti, C. I. R., Santyasa, I. W., Sudatha, I. G. W., & Sudarma, I. K. (2023). Pengembangan Multimedia Pembelajaran Pada Elemen Pengolahan Makanan Dan Minuman Sub Elemen Hidangan Soup. *Jurnal Pendidikan Teknologi Dan Kejuruan*, 20(1), 35–45.
- McSween, V. K. (2024). An Integrative Approach to STEM Workforce Preparation in a Biomedical Science Course [Quality Improvement]. *International Journal on Social and Education Sciences*, 6(2), 174–187. <https://doi.org/10.46328/ijonses.653>
- Meirani, R. K., & Intania, N. (2023). Key Elements of Total Quality Management Implementation in Vocational High School. *Proceedings of International Conference on Research in Education and Science*, 9(1), 424–439.
- Mirawati, N. (2019). Penerapan model pembelajaran berbasis STEM pada siswa SMK dengan Program Kejuruan ATPH. *Prosiding Diskusi Panel Nasional Pendidikan Matematika*, 0812(50), 45–50. <https://proceeding.unindra.ac.id/index.php/DPNPMunindra/article/view/231>
- Mukhlis, M., Suwandi, S., Rohmadi, M., & Setiawan, B. (2023). Higher Order Thinking Skills in Reading Literacy Questions at Vocational High Schools in Indonesia. *International Journal of Language Education*, 7(4), 615–632. <https://doi.org/10.26858/ijole.v7i4.37603>
- Ni'mah, A., Mariani, S., & Prabowo, A. (2019). Kemampuan koneksi matematis dan entrepreneurship siswa SMK dalam model pembelajaran Project Based Learning dengan pendekatan terintegrasi STEM. *Prosiding Seminar Nasional MIPA Kolaborasi 2018, November*, 100–113.
- Nurtanto, M., Pardjono, P., Widarto, W., & Ramdani, S. D. (2020). The effect of STEM-EDP in professional learning on automotive engineering competence in vocational high school. *Journal for the Education of Gifted Young Scientists*, 8(2), 633–649. <https://doi.org/10.17478/JEGYS.645047>
- Periatna, D., Putri Mubarika, M., & Yaniawati, P. (2019). Implementasi pendekatan Science Technology Engineering and Mathematics (STEM) untuk meningkatkan kemampuan pemecahan masalah siswa SMK. *Pasundan Journal of Mathematics Education : Jurnal Pendidikan Matematika*, 9(Vol 9 No.2), 56–68. <https://doi.org/10.23969/v9i2.2713>
- Rahayu, P., & Suhartini, R. (2020). Peran Pembelajaran Stem Dalam Penerapan Adobe Animate Terhadap Hasil Belajar Siswa Smk Tata Busana. *Universitas Negeri Surabaya*, 11.
- Rivera, S., Kiiza, I., Kavanagh, K., Dewaters, J., Galluzzo, B., & Ramsdell, M. (2016). *Challenges & Opportunities for STEM Teachers in Rural Schools : A Case Study*. 420–432.
- Ruijuan, L., Srikhoa, S., & Jantharajit, N. (2023). Blending of collaborative and active learning

- instructional methods to improve academic performance and self-motivation of vocational students. *Asian Journal of Education and Training*, 9(4), 130–135. <https://doi.org/10.20448/edu.v9i4.5211>
- Sa'adhah, E., Yuniarti, N., Pendidikan, S., & Mekatronika, T. (2019). the Implementation of Science, Technology, Engineering and Mathematics Learning Model As an Basic in Improving Activity and Results of Student Learning in Electrical and Electronic Study Subject Matter in Vocational Secondary School 1 Nanggulan. *Jurnal Pendidikan Teknik Mekatronika*, 9(1), 40–46. <http://journal.student.uny.ac.id/ojs>
- Salcedo, O. H., Carrejo, D. J., & Luna, S. (2023). Engineering Praxis Ethos: Designing Experiences to Support Curricular and Instructional Improvement in STEM Education. *International Journal of Education in Mathematics, Science and Technology*, 12(1), 20–39. <https://doi.org/10.46328/ijemst.3218>
- Seskir, Z. C., Goorney, S. R., & Chiofalo, M. L. (2024). Educating to the “Culture” of Quantum Technologies: A Survey Study on Concepts for Public Awareness. *European Journal of STEM Education*, 9(1), 1–9. <https://doi.org/10.20897/ejsteme/14193>
- Setyabudi, D., & Sari, L. N. (2020). Pengembangan Modul IPA berbasis Science Technology Engineering and Mathematics (STEM) untuk SMK Kelas X. *Prosiding Seminar Nasional Pendidikan Biologi 2020*, 11–22.
- Sintia Devi, B., Subali, B., & Artikel, S. (2021). 2021 Unnes Physics Education Journal Terakreditasi SINTA 3 Jurusan Fisika, Fakultas Matematika dan Ilmu Pengetahuan Alam. *Upej*, 10(2), 50229. <http://journal.unnes.ac.id/sju/index.php/upej>
- Suglo, E. K. (2024). Exploring the Impact of Deep Learning Activities in the Mathematics Classroom on Students' Academic Performance: A Comprehensive Study. *Online Submission*. <https://doi.org/10.20944/preprints202403.1551.v1>
- Suh, E. K., Zollman, A., & Hoffman, L. (n.d.). *STEM SMART : Unpacking the Research on Teachers ' Beliefs about Essential Life Skills and Dispositions*. 28(2), 1–16.
- Suryaman, Zaki, A., Suharyanto, & Winoto, S. (2023). Tripartite Interconnection to Serve High Quality and Competitiveness of Vocational School Students in Industry. *Journal of Social Studies Education Research*, 14(2), 75–96.
- Thies, S. L. J., Knobloch, N. A., Wang, H., & Nelson, B. J. (2024). *High School Students ' Motivation Regarding an Integrated STEM Food System Project*. 68(2020), 107–118.
- Tishana, A., Ahyuardi, A., Irfan, D., & Effendi, H. (2024). Developing Android-Based E-Modules for Project-Based Learning in Basic Electrical. *AL-ISHLAH: Jurnal Pendidikan*, 16(2), 1757–1770. <https://doi.org/10.35445/alishlah.v16i2.5267>
- Tuong, H. A. (2023). Teaching In Vietnam : Developing Students ' Real-World. *Journal of Technology and Science Education*, 13(1), 73–91.
- Twaddle, J., & Smith, T. (2023). STEM Pedagogical Content Knowledge of Preservice Teachers. *International Journal of Multidisciplinary Perspectives in Higher Education*, 8(1), 168–182.
- Wahono, B., Sholihah, I. M., & Narulita, E. (2023). Visual Content Analysis of STEM-Related Content in Indonesian Vocational High Schools Biology Textbooks. *Journal of Science Learning*, 6(3), 281–293. <https://doi.org/10.17509/jysl.v6i3.53772>
- Wannapiroon, P., Nilsook, P., Techakosit, S., & Kamkhuntod, S. (2021). STEM Literacy of Students in Vocational Education. *International Journal of Technology in Education and Science*, 5(4), 527–549. <https://doi.org/10.46328/ijtes.253>
- Yamamoto, S., Alverson, C., McCoid-Goudy, L., Castle, H., & Burr, J. (2022). STEM and High School Students with Disabilities: A Qualitative Review of the Research Literature. *Journal of Science Education for Students with Disabilities*, 25(1), 1–24. <https://doi.org/10.14448/jsted.14.0006>
- Yekti, S. M. P., & Perdana, R. D. P. (2019). Analisis Kebutuhan Pengembangan Modul Matematika Berbasis STEM (Science, Technology, Engineering, And Mathematics) sebagai Upaya Penguatan Karakter Dan Peningkatan Daya Saing Lulusan SMK. *Dharma Pendidikan*, 14(April 2019), 56–67. <http://journal.stkipnganjuk.ac.id/index.php/jdp/article/view/105%0Ahttp://journal.stkipnganjuk>

[ac.id/index.php/jdp/article/download/105/138](https://www.uin-suka.ac.id/index.php/jdp/article/download/105/138)

Yilmaz, H. S. (2022). A Study of Determination of Benchmarks during the New Formation of Integrated STEM Leader Preparation Program. *European Journal of STEM Education*, 7(1), 1–13. <https://doi.org/10.20897/ejsteme/12634>