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STEM and STEAM Approaches in Vocational Education: A Systematic Literature Review

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ABSTRACT

The accelerating transformation toward Industry 4.0 and the emerging paradigm of Industry 5.0 have fundamentally reshaped vocational education by demanding new forms of competence that integrate technical expertise, creativity, and adaptive innovation. This study explores how the integration of STEM (Science, Technology, Engineering, and Mathematics) and STEAM (Science, Technology, Engineering, Arts, and Mathematics) pedagogical frameworks, supported by Project-Based Learning (PjBL), can address these evolving educational demands. Using a Systematic Literature Review (SLR) methodology, this research synthesizes findings from international and regional studies published between 2015 and 2025 to examine the alignment of STEM/STEAM-PjBL with vocational education reform. The review identifies key trends in teacher readiness, digital pedagogy, curriculum innovation, and competency outcomes. Findings reveal that STEM enhances analytical reasoning and technical proficiency, while STEAM expands learning by incorporating creativity, design thinking, and aesthetic awareness attributes crucial for human-centered innovation. PjBL emerges as the pedagogical bridge connecting theoretical knowledge with industrial practice, fostering critical thinking, collaboration, and problem-solving skills. However, the review also highlights challenges such as limited teacher training, insufficient infrastructure, and fragmented institutional support that hinder implementation. The study concludes that integrating STEM/STEAM through PjBL represents a comprehensive educational paradigm capable of producing vocational graduates who are not only technically proficient but also innovative, digitally literate, and adaptable to the rapidly evolving global industry landscape. These insights contribute to future-oriented policy and pedagogical reform, positioning STEM/STEAM-PjBL as a transformative model for sustainable vocational education.

Key Word *STEM Education, STEAM Integration, Project-Based Learning (PJBL)*

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INTRODUCTION

Technological disruption associated with the rise of digitalization, automation, and intelligent manufacturing in Industry 4.0 and the transition toward Industry 5.0 has significantly reshaped competence requirements for vocational graduates. Contemporary workplaces increasingly demand individuals who possess not only strong technical expertise but also interdisciplinary understanding, creativity, critical thinking, and adaptability in response to continuous technological evolution (Waziana et al., 2025; Feng & Hou, 2023). This transformation challenges vocational institutions to move beyond traditional, theory-centered instruction and embrace integrative, technology-enhanced pedagogies that connect classroom knowledge to real-world industrial applications (Rahmadhani, 2024; Misrianto et al., 2024). In this new educational landscape, learners are expected to develop hybrid competencies that blend digital literacy, problem-solving, and design innovation skills that are essential for navigating complex production systems, automation processes, and innovation-driven markets (Asmanijar et al., 2023; Elvianasti et al., 2024; Syahrul et al., 2023; Widodo et al., 2025).

Within this context, STEM (Science, Technology, Engineering, and Mathematics) education has emerged as a transformative framework that bridges theoretical scientific concepts with practical engineering and technological applications. Empirical studies demonstrate that STEM-oriented instruction fosters analytical reasoning, mathematical proficiency, and applied problem-solving key competencies that underpin industrial precision, efficiency, and innovation (Agussuryani et al., 2021; Purnamawati & Mumpuniarti, 2025). The interdisciplinary nature of STEM aligns strongly with the objectives of vocational education, which aims to produce graduates who are both conceptually competent and technically skilled. STEM's ability to link conceptual understanding with operational practice has made it a foundational pillar for aligning vocational curricula with the evolving demands of Industry 4.0 environments (Feng & Hou, 2023; Supianti et al., 2025; Sari et al., 2024; Nugroho & Prasetyo, 2025).

However, scholars increasingly argue that technical mastery alone is insufficient to prepare learners for the multifaceted challenges of the modern industrial ecosystem. The inclusion of the Arts dimension into STEM forming STEAM (Science, Technology, Engineering, Arts, and Mathematics) represents a paradigm shift toward human-centered innovation. The STEAM model integrates creativity, aesthetic reasoning, empathy, and design thinking into technical learning, ensuring that graduates are not only problem solvers but also innovators capable of producing sustainable, user-oriented, and socially responsive solutions (Hayat, 2023; Supianti et al., 2025). STEAM, therefore, extends beyond the cognitive and technical domains to include affective and creative dimensions of learning, emphasizing the integration of design literacy and imagination within scientific inquiry and technological production (Indahwati et al., 2023; Elvianasti et al., 2024; Rachmadiarti et al., 2023; Hanif et al., 2024). This integrative approach resonates strongly with vocational education's mission to produce versatile professionals capable of functioning across disciplinary boundaries in collaborative, technology-mediated environments.

Despite increasing global attention on STEM and STEAM as pedagogical models, their practical implementation within vocational institutions continues to face significant barriers. Studies reveal persistent challenges such as limited teacher preparedness, insufficient interdisciplinary curriculum design, inadequate infrastructure, and the scarcity of instructional materials capable of supporting integrated learning (Purnamawati & Mumpuniarti, 2025; Rahmadhani, 2024). Morever, many educators struggle to translate conceptual awareness into effective classroom practice due to limited access to professional training and digital resources. Research by Waziana et al. (2025) and Misrianto et al. (2024) underscores that without structured professional development and institutional support, efforts to implement STEM/STEAM remain fragmented and unsustainable. Addressing these barriers requires systemic interventions that strengthen institutional readiness, empower educators with digital and creative pedagogical skills, and align curricula with both industrial innovation and cultural contexts (Septiani et al., 2025; Asmanijar et al., 2023; Widodo et al., 2025; Hanif et al., 2024).

To overcome these challenges, Project-Based Learning (PjBL) has been identified as the most effective pedagogical vehicle for operationalizing STEM and STEAM in vocational education. PjBL fosters experiential and inquiry-based learning by immersing students in authentic projects that simulate real industrial problems, requiring them to apply scientific reasoning, engineering design, technological tools, mathematical analysis, and creative thinking in tandem (Feng & Hou, 2023; Agussuryani et al., 2021). The integration of PjBL with STEM/STEAM enhances learner engagement, technical competence, and higher-order thinking skills while promoting collaboration and innovation attributes central to 21st-century workforce readiness (Indahwati et al., 2023; Waziana et al., 2025; Nugroho & Prasetyo, 2025; Sari et al., 2024). Studies demonstrate that PjBL-STEM/STEAM environments effectively bridge the gap between theoretical understanding and industrial application, enabling learners to experience the iterative processes of design, testing, and refinement characteristic of real engineering and technological workflows (Elvianasti et al., 2024; Hayat, 2023; Rachmadiarti et al., 2023; Hanif et al., 2024).

Given these educational imperatives, this study employs a Systematic Literature Review (SLR) methodology to comprehensively examine the integration of STEM and STEAM within vocational education systems. It synthesizes empirical and conceptual findings from global and regional contexts to identify trends, challenges, and best practices related to teacher preparedness, curriculum innovation, instructional strategies, and competency outcomes. The study further explores how the combination of STEM/STEAM and PjBL frameworks supports digital transformation, enhances creativity, and strengthens the alignment between vocational education and industrial needs. Through this analysis, the research aims to provide a structured synthesis that informs policy, pedagogical reform, and the future design of vocational learning ecosystems (Snyder, 2019; Purnamawati & Mumpuniarti, 2025; Septiani et al., 2025; Misrianto et al., 2024). Ultimately, this study positions STEM/STEAM-PjBL integration as a comprehensive educational paradigm capable of producing technically proficient, creatively adaptive, and innovation-driven vocational graduates who can thrive in the evolving global economy.

RESEARCH METHOD

This study employed a Systematic Literature Review (SLR) methodology to synthesize, interpret, and critically evaluate the implementation and impact of STEM (Science, Technology, Engineering, and Mathematics) and STEAM (Science, Technology, Engineering, Arts, and Mathematics) pedagogical approaches within the domain of vocational education. The SLR method was selected due to its ability to provide a rigorous and transparent synthesis of diverse sources, ensuring comprehensive coverage of empirical and theoretical insights relevant to Industry 4.0 and 5.0 educational contexts (Kitchenham, 2007; Snyder, 2019; Agussuryani et al., 2021; Feng & Hou, 2023). The review process followed established international standards for systematic research, adopting procedures consistent with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure accuracy, reproducibility, and methodological integrity (Moher et al., 2009; Snyder, 2019).

The research began by formulating a central question: how can STEM and STEAM frameworks be effectively applied in vocational education to strengthen project-based learning, digital pedagogy, and creative innovation? This guiding question was accompanied by secondary inquiries addressing teacher readiness, curriculum design, competency outcomes, and institutional transformation. To answer these questions, a comprehensive literature search was undertaken using electronic databases such as Scopus, ScienceDirect, SpringerLink, DOAJ, ERIC, and Google Scholar. Boolean operators and keyword combinations such as "STEM vocational education," "STEAM project-based learning," "digital pedagogy in vocational schools," and "educational reform Industry 4.0" were used to identify relevant studies published between 2015 and 2025. This temporal window was chosen to capture recent developments in educational reform during the digital transformation era (Waziana et al., 2025; Supianti et al., 2025).

Each retrieved study underwent a rigorous screening process based on inclusion and exclusion criteria to ensure methodological reliability. The inclusion parameters required that articles be peer-reviewed, published in English, and directly address the integration of STEM or STEAM in vocational or technical education contexts. Excluded materials included non-peer-reviewed reports, conference abstracts, and studies outside the scope of technical or vocational education. Following this selection process, seventy-two papers were initially identified, from which twenty-five studies met the quality criteria and were included for final synthesis (Rahmadhani, 2024; Indahwati et al., 2023). The quality assessment process was guided by PRISMA and SLR best practices to ensure that only studies with robust methodological designs and clearly defined learning outcomes were incorporated (Moher et al., 2009; Misrianto et al., 2024).

After identification and selection, data extraction was carried out systematically using a coding matrix that captured critical information, including author, year, context, methodology, sample characteristics, and major findings. This data was subsequently analyzed through thematic synthesis, identifying recurring trends across five dimensions: teacher readiness, instructional design, project-based learning integration, digital pedagogy, and institutional reform. The analytical framework applied in this review combined both inductive and deductive approaches. Inductive coding enabled emerging themes to surface organically from the literature, while deductive reasoning aligned those findings with existing theoretical constructs such as constructivism, experiential learning, and design-based pedagogy (Supianti et al., 2025; Hayat, 2023; Elvianasti et al., 2024). This methodological balance ensured both conceptual depth and empirical consistency, allowing for nuanced interpretations of how STEM/STEAM frameworks operate within vocational learning ecosystems.

The synthesis phase employed a mixed-methods analytical strategy that integrated narrative and thematic approaches. Quantitative findings such as improvements in students' technical competencies or learning outcomes were summarized descriptively, while qualitative findings such as teacher perceptions and institutional challenges were examined through thematic coding. This dual analytical approach enabled a holistic understanding of the relationship between instructional innovation and vocational competency development (Feng & Hou, 2023; Waziana et al., 2025). The review revealed that STEM and STEAM pedagogies converge effectively when combined with Project-Based Learning (PjBL), producing measurable gains in student creativity, critical thinking, and technical accuracy. Furthermore, digital media integration was identified as an essential catalyst for effective interdisciplinary instruction, supporting both engagement and flexibility in learning (Asmanijar et al., 2023; Misrianto et al., 2024).

Quality assurance procedures were embedded throughout the research process. Triangulation was applied to validate consistency across sources, and inter-coder reliability checks ensured accuracy during thematic analysis. Methodological validity was also reinforced through adherence to established SLR criteria, including transparency in inclusion decisions, traceability of sources, and reproducibility of analytical procedures (Kitchenham, 2007; Snyder, 2019; Moher et al., 2009). To ensure intellectual integrity, all sources were properly cited following APA 7th edition guidelines, and interpretive bias was mitigated by cross-referencing findings across multiple disciplinary perspectives, including pedagogy, educational psychology, and curriculum studies.

The methodological foundation of this research rests on its systematic and integrative nature. Unlike traditional literature reviews that may focus narrowly on descriptive summaries, the SLR approach enabled the researcher to derive interpretive insights linking pedagogical theory with practical application in vocational education. The combination of PRISMA standards and multi-source triangulation enhanced credibility by ensuring that each selected study contributed meaningfully to the conceptual and empirical synthesis. As a result, this study not only provides a descriptive account of existing research but also constructs a meta-framework illustrating how STEM/STEAM-PjBL integration can inform curriculum innovation, teacher training, and policy development for vocational education reform (Septiani et al., 2025; Purnamawati & Mumpuniarti, 2025).

In conclusion, the research method employed in this study ensured a rigorous, transparent, and multi-dimensional analysis of the intersection between STEM/STEAM education and vocational learning. By systematically combining empirical evidence, theoretical models, and contextual insights, the methodology validated that STEM and STEAM pedagogies particularly when implemented through project-based and digital learning modalities serve as transformative instruments for educational modernization. The methodological framework thus contributes to the growing body of evidence supporting systemic educational reform in alignment with 21st-century industrial and technological demands (Feng & Hou, 2023; Rahmadhani, 2024; Supianti et al., 2025).

RESULT AND DISCUSSION

The results of this extended systematic literature review reveal a deeply interconnected framework for understanding the implementation and outcomes of STEM and STEAM pedagogical models in vocational education. The review draws upon empirical, theoretical, and meta-analytic sources, synthesizing insights from both national and international studies to build a comprehensive understanding of educational transformation in the context of Industry 4.0 and 5.0 (Agussuryani et al., 2021; Feng & Hou, 2023; Supianti et al., 2025). Overall, the reviewed literature indicates that the integration of STEM and STEAM strengthens the alignment between vocational curricula and industrial competency needs by merging technical proficiency with creativity, innovation, and digital fluency (Waziana et al., 2025; Rahmadhani, 2024).

Teachers' readiness and perception emerge as the critical determinants of successful STEM/STEAM implementation. Many educators acknowledge the potential of these frameworks to promote interdisciplinary learning and problem-solving skills; however, substantial gaps in digital literacy, material development, and professional support remain (Purnamawati & Mumpuniarti, 2025; Misrianto et al., 2024). Research from Waziana et al. (2025) demonstrates that digital media integration within classroom practice encourages interactive learning and bridges the technological divide between students and teachers. Similarly, Supianti et al. (2025) identify that the application of STEAM through project-based learning (PjBL) encourages creativity and higher-order thinking. Studies such as Indahwati et al. (2023) and Elvianasti et al. (2024) reveal that embedding PjBL-STEM/STEAM into practical tasks fosters measurable improvements in technical accuracy, collaboration, and analytical reasoning, reinforcing the idea that experiential, inquiry-based education drives sustainable competence.

The review also identifies that validated instructional materials, particularly STEM-based student worksheets (LKPD), serve as effective mediators of interdisciplinary learning. Agussuryani et al. (2021) highlight that the development of STEM-LKPD leads to high validity and practicality scores, enabling direct application of mathematical and engineering principles to industrial tasks. Furthermore, Elvianasti et al. (2024) indicate that incorporating eco-printing and sustainable design principles within STEAM activities not only enhances creativity but also nurtures environmental awareness, thereby widening the social dimension of technical education. Studies consistently demonstrate that such integrative approaches strengthen learners' conceptual understanding, improve their engagement, and foster transferable cognitive abilities required for future industrial contexts (Feng & Hou, 2023; Rahmadhani, 2024).

Table 1.
Summary of Reviewed STEM/STEAM Research Findings in Vocational Education

Theme	Key Findings	Educational Implications	Sources
Teacher Readiness	Teachers demonstrate conceptual awareness of STEM/STEAM but need structured digital training and pedagogical support.	Professional development in technology-integrated pedagogy.	Waziana et al., 2025; Purnamawati & Mumpuniarti, 2025
Instructional Materials	STEM-based LKPD and modular designs yield strong validity and practicality outcomes.	Standardize STEM-based learning resources for vocational curricula.	Agussuryani et al., 2021; Supianti et al., 2025
Learning Approaches	Project-based STEM/STEAM increases creativity, critical thinking, and teamwork skills.	Embed interdisciplinary projects into competency-based curricula.	Indahwati et al., 2023; Elvianasti et al., 2024
Competency Outcomes	Learners show significant gains in technical precision, CNC programming, and innovation.	Align PjBL with industry standards and real-work simulations.	Feng & Hou, 2023; Rahmadhani, 2024
Educational Reform	Culturally responsive	Integrate cultural values and supervision systems	Septiani et al., 2025; Misrianto et

	supervision strengthens sustainability of innovation-driven teaching.	in vocational policy.	al., 2024

The cumulative evidence points to the pivotal role of project-based learning (PjBL) as the pedagogical bridge connecting STEM/STEAM principles with hands-on vocational skills. Learners who engage in PjBL-STEM environments display improved adaptability, reflective practice, and confidence in applying theoretical knowledge to industrial applications. According to Feng and Hou (2023), the structured project cycle replicates real manufacturing processes, allowing learners to understand operational workflows and decision-making structures. The synergy between scientific inquiry, technological tools, engineering design, artistic innovation, and mathematical reasoning consolidates into an ecosystem that fosters analytical thinking, creativity, and lifelong learning dispositions essential for Industry 5.0 workplaces.

Discussion

The discussion section situates these empirical results within broader educational and pedagogical frameworks, expanding the implications of STEM and STEAM implementation for long-term reform in vocational education. The interplay between technical mastery and creative cognition reveals that vocational education must evolve into a transformative learning system emphasizing interdisciplinary fluency, digital innovation, and cultural adaptability. This transformation aligns with global trends emphasizing competency-based and human-centered education systems (Septiani et al., 2025; Hayat, 2023). While existing STEM initiatives focus on strengthening technical foundations, the integration of STEAM provides an expanded perspective by embedding design thinking and aesthetic creativity into problem-solving processes, thereby enhancing learner engagement and innovation potential (Supianti et al., 2025; Elvianasti et al., 2024).

At the institutional level, the effectiveness of STEM/STEAM integration depends on systemic support mechanisms that include teacher empowerment, infrastructure development, and curriculum flexibility. Purnamawati and Mumpuniarti (2025) highlight that educators require sustained training to implement interdisciplinary methodologies effectively. Complementary studies from Waziana et al. (2025) and Misrianto et al. (2024) confirm that leadership support and digital learning tools significantly impact the quality and sustainability of instructional reform. Similarly, Rahmadhani (2024) argues that technological and pedagogical readiness are equally crucial, as innovation cannot thrive without synchronized organizational commitment. These insights echo the idea that reform must occur across pedagogical, institutional, and policy levels.

Moreover, the discussion expands to include the pedagogical dimensions of supervision and cultural responsiveness. Septiani et al. (2025) emphasize that culturally grounded supervision in schools fosters a sense of ownership and localized innovation, ensuring that reforms resonate with the unique values of each educational context. This cultural layer is essential in vocational education, where learning environments are closely tied to regional industries and community practices. Such supervision approaches ensure that STEM/STEAM practices are not merely imported but adapted, promoting both innovation and inclusivity in educational transformation (Asmanijar et al., 2023; Suwarni, 2022).

The intersection of digital pedagogy and vocational innovation also emerges as a key trend. Waziana et al. (2025) demonstrate how digital media tools, when aligned with STEAM principles, promote collaborative and creative engagement among learners. These digital learning strategies transform traditional workshop settings into interactive knowledge ecosystems. Similarly, recent studies in pedagogical design suggest that digital tools can act as mediators of cognitive engagement, linking abstract technical concepts with multimodal representation and experiential learning. As emphasized by Hayat (2023) and Indahwati et al. (2023), the success of such approaches lies in combining technological immersion with reflective inquiry, where learners co-construct understanding through projects and real-world experimentation.

Another crucial discussion point involves sustainability and long-term capacity building. Integrating STEM/STEAM should not be perceived as isolated innovation but as a systemic paradigm requiring alignment between policymakers, educators, and industries. Collaboration with industrial partners provides students with authentic problem contexts while enhancing the relevance of academic programs (Feng & Hou, 2023; Rahmadhani, 2024). The sustainability of such partnerships depends on continuous professional dialogue, cross-sectoral feedback, and ongoing curriculum evaluation. Moreover, to prepare students for Industry 5.0, where automation is intertwined with ethics and sustainability, vocational education must embrace transdisciplinary approaches that integrate environmental literacy, socio-emotional learning, and digital ethics into STEM/STEAM curricula.

Finally, the pedagogical philosophy underlying STEM/STEAM integration redefines vocational education as a space for innovation, creativity, and lifelong learning. The synthesis of findings suggests that learning outcomes extend beyond technical proficiency to encompass collaboration, cultural sensitivity, and entrepreneurial thinking. As articulated by Septiani et al. (2025) and Waziana et al. (2025), future reforms must therefore move beyond curriculum modification toward a holistic transformation of educational culture. When integrated effectively, STEM/STEAM frameworks supported by project-based learning can create a new generation of vocational graduates who are technically competent, creatively empowered, and ethically grounded equipped not only to participate in but to lead innovation in the evolving industrial landscape.

CONCLUSION

The comprehensive synthesis of this study concludes that integrating STEM and STEAM pedagogies through Project-Based Learning (PjBL) represents a pivotal transformation in vocational education. Evidence consistently demonstrates that these frameworks do not only enhance technical proficiency but also cultivate creativity, critical thinking, and adaptability skills that are indispensable in Industry 4.0 and 5.0 contexts (Agussuryani et al., 2021; Feng & Hou, 2023; Supianti et al., 2025). The reviewed literature reveals that while STEM solidifies learners' analytical and technical competencies, STEAM extends this learning to include design thinking, digital creativity, and human-centered innovation (Elvianasti et al., 2024; Hayat, 2023). Moreover, embedding these models within PjBL ensures that theoretical understanding is directly connected to practical application, thus reinforcing the alignment between vocational training and industrial expectations (Indahwati et al., 2023; Rahmadhani, 2024).

However, successful implementation depends on systemic readiness across multiple layers of educational structures. Teachers' capacity to integrate interdisciplinary approaches remains crucial, requiring consistent professional development and leadership support (Waziana et al., 2025; Misrianto et al., 2024). Similarly, institutional reform and culturally grounded supervision are necessary to sustain these innovations, ensuring that STEM/STEAM adoption aligns with local educational values and national vocational priorities (Septiani et al., 2025; Purnamawati & Mumpuniarti, 2025). Furthermore, digital pedagogy and technological adaptation emerge as critical enablers of these transformations, allowing more dynamic, inclusive, and creative learning environments that bridge cognitive, affective, and psychomotor dimensions of vocational education (Waziana et al., 2025; Asmanijar et al., 2023). Thus, the integration of STEM and STEAM within PjBL frameworks not only represents a pedagogical shift but also redefines vocational education as a holistic ecosystem fostering innovation, sustainability, and lifelong learning.

In conclusion, the convergence of interdisciplinary learning, cultural adaptation, and digital pedagogy positions STEM/STEAM-PjBL as a comprehensive educational paradigm. When supported by leadership, infrastructure, and policy reform, it empowers educators and learners to co-create knowledge, innovate responsibly, and contribute meaningfully to socio-technical development in the evolving industrial landscape. This systemic transformation, grounded in evidence-based pedagogy and inclusive educational practices, is essential for preparing vocational graduates to thrive as creative, ethical, and adaptive professionals in a future characterized by rapid technological advancement and human-centered innovation.

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