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Learning from Failure: The Paradigm of Failure as a Part of the STEM Project-Based Learning Process

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Abstract

This study examines the role of failure in STEM Project-Based Learning (PjBL) as a productive learning mechanism rather than an outcome to be avoided. In contemporary STEM education, failure is increasingly recognized as a critical component that supports deeper conceptual understanding, resilience, and the development of learner identity. However, its implementation remains inconsistent, necessitating a comprehensive synthesis of recent research. This study employs a qualitative approach using a Systematic Literature Review (SLR) method, analyzing peer-reviewed journal articles from reputable databases such as Scopus, Web of Science, and Google Scholar. Data were collected through a structured screening process based on inclusion and exclusion criteria, and analyzed using thematic and content analysis to identify key patterns related to cognitive, affective, and pedagogical dimensions of failure in STEM PjBL. The findings reveal that failure enhances higher-order thinking skills (HOTS), problem-solving abilities, and conceptual retention, while also fostering resilience and growth mindset. Structured models such as Return on Failure (RoF), Failure Analysis (FA), and productive failure approaches are shown to be effective in optimizing learning outcomes. Nevertheless, challenges such as cognitive load, time constraints, and negative emotional responses persist. In conclusion, failure can serve as a powerful instructional strategy when supported by appropriate scaffolding and a psychologically safe learning environment.

Keywords: *Failure, STEM Education, Project-Based Learning, Productive Failure, Higher-Order Thinking Skills*

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Introduction

The integration of failure as a meaningful pedagogical component in STEM Project-Based Learning (PjBL) has gained increasing attention in contemporary educational research, particularly as education systems shift toward fostering higher-order thinking skills (HOTS), resilience, and authentic problem-solving competencies. Traditionally, failure in educational contexts has been perceived negatively, often associated with poor performance, lack of competence, and undesirable learning outcomes. However, recent developments in STEM education challenge this conventional paradigm by positioning failure not as an endpoint but as a critical epistemic tool that facilitates deeper conceptual understanding and iterative learning. This paradigm shift is particularly relevant in STEM PjBL environments, where learners engage in complex, open-ended problems that inherently involve

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uncertainty, iteration, and the possibility of failure. Despite this growing recognition, the practical implementation and conceptual framing of “learning through failure” remain inconsistent across educational settings, revealing a significant gap between theoretical discourse and classroom practice.

Empirical evidence indicates that failure and errors are essential components of learning, particularly in engineering design and STEM-related problem-solving processes. Studies have demonstrated that failure provides valuable feedback mechanisms that enable learners to identify misconceptions, refine strategies, and develop more robust conceptual frameworks (Bing & Leong, 2024; Leong, 2025; Jackson et al., 2021). Within the context of STEM PjBL, failure is not merely an incidental outcome but a deliberate and structured element of the learning process. Jackson et al. (2021) emphasize that failure in design-based learning environments can trigger reflective thinking, uncover hidden misunderstandings, and strengthen learners’ identity as novice engineers or designers, provided that the learning environment supports psychological safety. This suggests that the role of failure extends beyond cognitive development to include affective and identity-related dimensions, which are crucial for sustained engagement in STEM fields.

However, the phenomenon observed in many educational contexts reveals that failure is still largely stigmatized and inadequately integrated into instructional design. In practice, students often perceive failure as a threat to their academic achievement rather than as an opportunity for growth. Lin-Siegler et al. (2023) found that students’ interpretation of failure significantly influences their learning orientation; those who label an experience as “failure” tend to focus on performance outcomes rather than learning processes, which can hinder deep engagement and conceptual understanding. This phenomenon is exacerbated in high-stakes educational environments where assessment systems prioritize grades over process-oriented learning. Consequently, the potential benefits of failure in STEM PjBL are often undermined by negative emotional responses, such as anxiety, frustration, and decreased motivation, particularly when the classroom climate does not support risk-taking and iterative experimentation (Jackson et al., 2021; Lin-Siegler et al., 2023).

Furthermore, although various instructional models have been developed to operationalize the concept of productive failure, their implementation remains fragmented and context-dependent. For instance, the Return on Failure (RoF) model introduced by Bing and Leong (2024) emphasizes the systematic analysis of project failures, encouraging students to identify root causes and propose improvements. Similarly, the integration of Failure Analysis (FA) into PjBL frameworks has been shown to enhance students’ technical skills, design thinking abilities, and resilience by incorporating structured processes such as root cause analysis, simulation, and reflective evaluation (Leong, 2025). In the domain of computer programming, the productive failure approach has demonstrated its effectiveness in improving long-term conceptual retention and reducing cognitive load in subsequent learning tasks, even when initial performance is comparable to direct instruction (Suriyaarachchi et al., 2024). These findings highlight the potential of structured failure-based approaches to transform STEM learning experiences.

Despite these promising developments, a critical research gap persists regarding the systematic synthesis of failure-related strategies within STEM PjBL and their alignment with broader educational objectives, such as 21st-century competencies. Existing studies tend to focus on specific interventions or isolated contexts, lacking a comprehensive framework that integrates cognitive, affective, and pedagogical dimensions of failure in STEM learning. Moreover, there is limited attention to how different instructional designs can balance the benefits and challenges associated with failure, particularly in terms of cognitive load, time constraints, and the need for scaffolding (Leong, 2025; Chang & Chen, 2022; Lestari et al., 2024). This gap is further compounded by the absence of a unified perspective on how failure can be effectively embedded within interdisciplinary STEM curricula to promote creativity, collaboration, and critical thinking.

In addition, while the literature acknowledges the role of failure in fostering resilience and growth mindset, there is insufficient exploration of the socio-emotional dynamics that influence students’ responses to failure. For example, Seo et al. (2024) highlight that failure can contribute to the development of a growth mindset and interdisciplinary orientation, yet these outcomes are highly contingent on the learning environment and instructional support. Without a psychologically safe classroom climate, students may experience negative emotions that hinder their engagement and learning outcomes. This underscores the need for a more nuanced understanding of how instructional design, classroom culture, and assessment practices interact to shape students’ experiences of failure in STEM PjBL contexts.

Another important gap lies in the integration of failure-based learning with authentic, interdisciplinary problem contexts that characterize contemporary STEM education. Research has shown that STEM PjBL and Problem-Oriented Project-Based Learning (PoPBL) can enhance critical thinking, creativity, collaboration, and communication skills, particularly when learners engage with real-world, interdisciplinary challenges (Alali, 2024; Diana et al., 2021; Gutiérrez-Berraondo et al., 2025; Sarwi et al., 2021; Halawa et al., 2024; Rahmania, 2021; Chistyakov et al., 2023; Darmawansah et al., 2023; Le et al., 2023; Lu et al., 2021; Wang & Lv, 2025). However, the role of failure within these authentic learning environments has not been sufficiently theorized or empirically examined. Specifically, there is a lack of research that investigates how failure can be strategically designed and leveraged to enhance interdisciplinary learning outcomes and prepare students for complex, real-world problem-solving.

The novelty of this study lies in its effort to synthesize recent research on failure in STEM Project-Based Learning and to conceptualize failure as a structured, multidimensional learning mechanism that integrates cognitive, affective, and pedagogical components. Unlike previous studies that examine failure in isolated contexts or through specific instructional models, this research seeks to provide a comprehensive overview of how failure can be systematically embedded within STEM PjBL frameworks to enhance learning outcomes. This includes identifying key design principles for creating psychologically safe learning environments, structuring failure through iterative cycles of exploration, analysis, and revision, and aligning failure-based learning with 21st-century competencies. By bridging the gap between theoretical insights and practical implementation, this study contributes to the development of a more holistic and integrative approach to STEM education.

Moreover, this research introduces a conceptual framework that positions failure not merely as an outcome of learning but as a deliberate instructional strategy that can be designed, scaffolded, and assessed. This perspective challenges traditional deficit-oriented views of failure and redefines it as a productive and necessary component of meaningful learning. In doing so, the study addresses the need for a paradigm shift in STEM education, where failure is normalized and leveraged as a catalyst for innovation, critical thinking, and resilience. This approach is particularly relevant in the context of rapidly changing technological and societal demands, where the ability to learn from failure is increasingly recognized as a key competency.

Based on the identified research gaps and the proposed novelty, the primary objective of this study is to systematically analyze and synthesize recent research on the role of failure in STEM Project-Based Learning, with the aim of developing an integrative framework that highlights its pedagogical potential, associated challenges, and implications for instructional design. This objective is expected to provide valuable insights for educators, curriculum developers, and policymakers in designing more effective and inclusive STEM learning environments that embrace failure as an essential component of the learning process.

Methodology

This study employs a qualitative approach using a systematic literature review (SLR) design to comprehensively analyze and synthesize recent research on the role of failure in STEM Project-Based Learning (PjBL). The selection of this method is aligned with the research objective, which seeks to develop an integrative conceptual framework based on existing empirical and theoretical studies. Data collection was conducted through a structured and rigorous search of reputable academic databases, including Scopus, Web of Science, and Google Scholar, focusing on peer-reviewed journal articles published within the last five to seven years to ensure the relevance and currency of the findings. The inclusion criteria consisted of (1) studies explicitly addressing failure, productive failure, or error-based learning within STEM PjBL or Problem-Based Learning (PBL) contexts, (2) empirical or review articles published in indexed journals, and (3) studies discussing cognitive, affective, or pedagogical impacts of failure. Meanwhile, exclusion criteria included non-peer-reviewed sources, opinion articles without empirical grounding, and studies not directly مرتبط with STEM education. The data collection technique followed a systematic process involving keyword identification (e.g., “failure in STEM learning,” “productive failure,” “STEM project-based learning”), screening of titles and abstracts, full-text review, and final selection based on relevance and quality.

The data analysis in this study utilized a thematic analysis approach combined with qualitative content analysis to identify, categorize, and synthesize recurring patterns across the selected literature. Initially, all selected articles were coded using open coding to extract key concepts related to the roles,

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benefits, challenges, and instructional design implications of failure in STEM PjBL. These codes were then grouped into broader themes, such as cognitive development, affective responses, instructional strategies, and implementation challenges. Subsequently, axial coding was applied to explore relationships between themes, enabling the construction of an integrative framework that reflects the multidimensional nature of failure as a learning mechanism. To enhance the validity and reliability of the findings, the analysis followed a constant comparative method, where data from different studies were continuously compared and contrasted to ensure consistency and depth of interpretation. The results of this analysis were then synthesized narratively to highlight key insights, research gaps, and practical implications for STEM education, particularly in designing learning environments that effectively integrate failure as a productive and structured component of the learning process.

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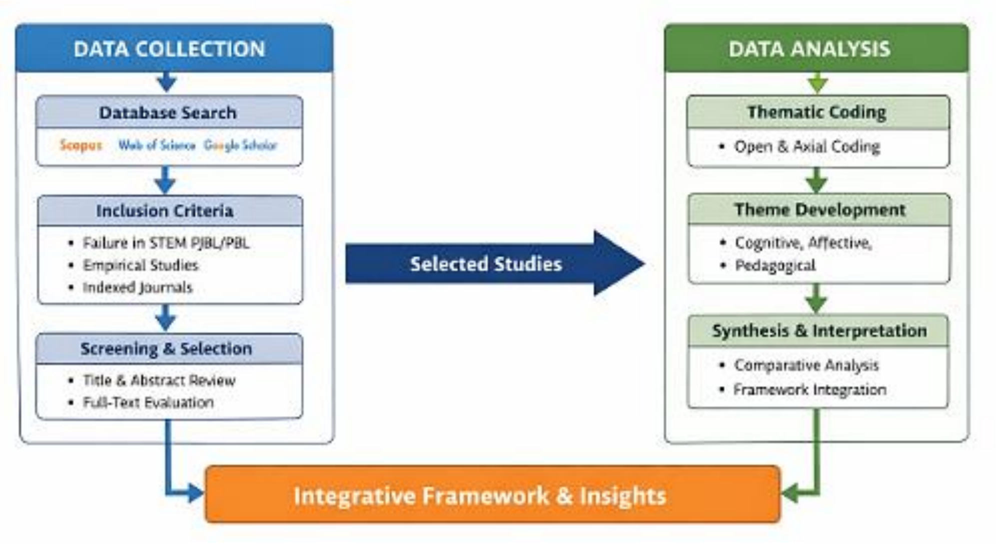

Figure 1. Diagram Conceptual Research

Results and Discussion

Based on the systematic literature review conducted, the synthesized findings reveal several key dimensions regarding the role of failure in STEM Project-Based Learning (PjBL). These dimensions include cognitive outcomes, affective development, pedagogical strategies, and implementation challenges. The table below presents a structured summary of the main findings derived from the selected studies, highlighting the relationship between the role of failure, its educational benefits, associated challenges, and supporting references.

Table 1. Synthesis of Findings on Failure in STEM Project-Based Learning

Dimension	Role of Failure in STEM PjBL	Benefits	Challenges	Key References
Cognitive Development	Failure as a trigger for reflection and conceptual restructuring	Enhances problem-solving skills, critical thinking, and conceptual understanding (HOTS)	High cognitive load, requires scaffolding	Bing & Leong (2024); Leong (2025); Suriyaarachchi et al. (2024); Sarwi et al. (2021)
Affective Domain	Failure as a mechanism to build resilience and growth mindset	Develops resilience, motivation, and positive learning orientation	Negative emotions (anxiety, frustration) if environment is not supportive	Jackson et al. (2021); Lin-Siegler et al. (2023); Seo et al. (2024)

Identity Development	Failure strengthens identity as a designer/engineer through iterative learning	Builds confidence, self-efficacy, and persistence	Risk of decreased self-confidence if failure is stigmatized	Jackson et al. (2021); Leong (2025)
Pedagogical Strategy	Structured failure through models (RoF, FA, Productive Failure)	Improves analytical skills, innovation, and technical competencies	Requires careful instructional design and longer instructional time	Bing & Leong (2024); Leong (2025); Chang & Chen (2022)
Interdisciplinary Skills	Failure embedded in authentic, real-world STEM problems	Enhances collaboration, creativity, communication, and interdisciplinary thinking	Complexity of integrating multiple disciplines	Alali (2024); Diana et al. (2021); Le et al. (2023); Lu et al. (2021)
Instructional Environment	Importance of psychologically safe learning environments	Encourages risk-taking, experimentation, and reflective learning	Classroom culture may still prioritize grades over process	Jackson et al. (2021); Lin-Siegler et al. (2023); Chang & Chen (2022)

The findings presented in Table 1 indicate that failure in STEM PjBL functions as a multidimensional construct that significantly contributes to both cognitive and affective learning outcomes. From a cognitive perspective, failure facilitates deeper conceptual understanding by encouraging students to engage in reflective thinking and iterative problem-solving processes. This aligns with the principles of higher-order thinking skills (HOTS), where learners actively construct knowledge through experience and revision. From an affective standpoint, failure plays a crucial role in fostering resilience, growth mindset, and learner identity, particularly when supported by a psychologically safe learning environment.

However, the table also highlights several critical challenges that must be addressed to optimize the integration of failure in STEM education. These include the potential for increased cognitive load, negative emotional responses, and the need for well-designed instructional scaffolding. Additionally, the successful implementation of failure-based learning requires a shift in classroom culture, moving from a performance-oriented approach to a process-oriented paradigm. Overall, the synthesis suggests that while failure holds substantial pedagogical potential, its effectiveness is highly contingent on instructional design, environmental support, and alignment with broader educational objectives.

Discussion

The findings of this systematic literature review reveal that failure in STEM Project-Based Learning (PjBL) should be reconceptualized as a productive and integral component of the learning process rather than a negative outcome to be avoided. This perspective aligns with the primary objective of this study, which is to synthesize recent research and develop an integrative understanding of how failure contributes to cognitive, affective, and pedagogical dimensions in STEM education. Drawing upon the synthesized data presented in Table 1, the discussion highlights that failure functions as a catalyst for deeper learning, particularly within complex, iterative design processes that characterize STEM PjBL environments. In this context, failure enables learners to engage in reflective thinking, identify misconceptions, and reconstruct their understanding through iterative problem-solving cycles. As emphasized by Bing and Leong (2024) and Leong (2025), failure and errors are not incidental but essential sources of knowledge in engineering projects, where trial-and-error processes are fundamental to innovation and design optimization. This reinforces the argument that failure-based learning aligns closely with constructivist and experiential learning theories, where knowledge is actively constructed through interaction with challenges and errors.

From a cognitive perspective, the role of failure in enhancing higher-order thinking skills (HOTS) is particularly significant. The findings indicate that structured engagement with failure promotes analytical reasoning, critical thinking, and problem-solving abilities, especially when learners are required to diagnose the causes of failure and propose alternative solutions. This is evident in instructional models such as Return on Failure (RoF) and Failure Analysis (FA), which explicitly incorporate systematic reflection and root cause analysis into the learning process (Bing & Leong, 2024; Leong, 2025). These approaches encourage students to move beyond surface-level understanding and engage in deeper cognitive processing, thereby strengthening conceptual retention and transferability. Furthermore, the productive failure approach in programming contexts demonstrates that although students may initially struggle, the long-term benefits include improved conceptual understanding and reduced cognitive load in subsequent tasks (Suriyaarachchi et al., 2024). This finding is consistent with the notion that productive struggle, when properly scaffolded, can enhance meaningful learning outcomes. However, the effectiveness of failure in promoting cognitive development is contingent upon the availability of adequate instructional support, as excessive cognitive load without guidance may hinder learning (Chang & Chen, 2022; Lestari et al., 2024).

In addition to cognitive outcomes, the affective dimension of failure plays a crucial role in shaping students' learning experiences and attitudes toward STEM. The review highlights that failure can foster resilience, persistence, and a growth mindset, which are essential attributes for success in STEM fields. Leong (2025) and Seo et al. (2024) emphasize that engaging with failure in a supportive environment can enhance students' confidence and motivation, enabling them to view challenges as opportunities for growth rather than threats to their competence. This is particularly important in STEM PjBL contexts, where learners are often required to navigate complex and ambiguous problems. However, the findings also reveal that the affective impact of failure is highly dependent on how it is perceived and framed within the learning environment. Lin-Siegler et al. (2023) demonstrate that students' labeling of experiences as "failure" can significantly influence their learning orientation, with negative labeling leading to a focus on performance outcomes rather than learning processes. Similarly, Jackson et al. (2021) argue that without a psychologically safe classroom climate, failure may trigger negative emotions such as anxiety and frustration, which can impede learning and reduce engagement. Therefore, the integration of failure in STEM PjBL requires careful consideration of the emotional and motivational dimensions of learning, ensuring that students are supported in interpreting failure as a constructive and valuable experience.

Another critical aspect highlighted in the findings is the role of failure in shaping students' identity as designers, engineers, and problem-solvers. In design-based learning environments, failure is not only a cognitive and affective experience but also a formative element in the development of professional identity. Jackson et al. (2021) suggest that engaging with failure in iterative design processes can strengthen students' sense of belonging and competence within STEM disciplines, particularly when they are encouraged to view themselves as active participants in authentic problem-solving activities. This identity formation is further reinforced through structured failure-based instructional models, such as FA and RoF, which emphasize the importance of reflection, iteration, and continuous improvement (Bing & Leong, 2024; Leong, 2025). By positioning failure as a natural and expected part of the design process, these approaches help students internalize the values and practices of professional engineers and scientists. However, the development of positive identity through failure is contingent upon the presence of supportive instructional practices and classroom cultures that normalize mistakes and encourage experimentation.

From a pedagogical perspective, the findings underscore the importance of designing structured learning experiences that intentionally incorporate failure as a core component. The success of models such as RoF, FA, and productive failure demonstrates that failure must be carefully scaffolded and integrated into the learning process rather than left to occur randomly. These models typically involve iterative cycles of exploration, failure, analysis, and revision, which align with the principles of design thinking and engineering practices (Bing & Leong, 2024; Leong, 2025; Suriyaarachchi et al., 2024). By providing students with opportunities to analyze their mistakes and refine their solutions, these approaches promote deeper engagement and sustained learning. However, implementing such pedagogical strategies presents several challenges, including increased instructional time, the need for teacher expertise in facilitating reflective learning, and the requirement for appropriate assessment methods that value process over product (Chang & Chen, 2022; Lestari et al., 2024). These challenges highlight the need for systemic changes in curriculum design and assessment practices to support the effective integration of failure in STEM education.

Furthermore, the findings reveal that failure plays a significant role in fostering interdisciplinary skills and 21st-century competencies, particularly when embedded in authentic, real-world problem contexts. STEM PjBL and Problem-Oriented Project-Based Learning (PoPBL) have been shown to enhance critical thinking, creativity, collaboration, and communication skills, especially when learners engage with complex, interdisciplinary challenges (Alali, 2024; Diana et al., 2021; Gutiérrez-Berraondo et al., 2025; Sarwi et al., 2021; Halawa et al., 2024; Rahmania, 2021; Chistyakov et al., 2023; Darmawansah et al., 2023; Le et al., 2023; Lu et al., 2021; Wang & Lv, 2025). In such contexts, failure serves as a critical learning mechanism that drives innovation and collaborative problem-solving. When students encounter failure in interdisciplinary projects, they are required to integrate knowledge from multiple domains, negotiate solutions with peers, and adapt their strategies in response to feedback. This process not only enhances their technical and cognitive skills but also prepares them for the complexities of real-world STEM careers. However, the integration of failure in interdisciplinary contexts also introduces additional challenges, such as increased task complexity and the need for effective coordination among different subject areas.

The discussion also highlights the importance of creating a psychologically safe learning environment as a prerequisite for the effective integration of failure in STEM PjBL. A safe learning environment is characterized by openness to risk-taking, tolerance for mistakes, and an emphasis on learning processes rather than performance outcomes. Jackson et al. (2021) and Lin-Siegler et al. (2023) emphasize that students are more likely to engage productively with failure when they feel supported and valued, rather than judged or penalized. Chang and Chen (2022) further argue that instructional strategies should explicitly address students' emotional responses to failure, providing scaffolding and feedback that guide them toward constructive reflection and improvement. This aligns with the broader shift in educational paradigms toward formative assessment and learner-centered approaches, which prioritize growth and development over summative evaluation. Without such supportive environments, the potential benefits of failure may be undermined by negative emotional experiences and disengagement.

In addressing the challenges associated with failure-based learning, the findings suggest that effective scaffolding is essential to balance the cognitive and emotional demands of engaging with failure. Scaffolding can take various forms, including guided reflection, structured feedback, collaborative learning, and the use of technological tools to support analysis and simulation. For example, the integration of simulation tools in FA models allows students to test and refine their solutions in a controlled environment, reducing the risk of overwhelming cognitive load while maintaining the benefits of experiential learning (Leong, 2025). Similarly, collaborative learning environments enable students to share experiences of failure, learn from peers, and develop collective problem-solving strategies. These approaches not only enhance learning outcomes but also contribute to the development of social and interpersonal skills, which are essential for success in STEM fields.

Overall, the findings of this study demonstrate that failure in STEM Project-Based Learning is a complex and multifaceted phenomenon that encompasses cognitive, affective, and pedagogical dimensions. By synthesizing recent research, this study provides a comprehensive understanding of how failure can be effectively integrated into STEM education to enhance learning outcomes and prepare students for the challenges of the 21st century. The discussion highlights that while failure holds significant pedagogical potential, its successful implementation requires careful design, supportive learning environments, and alignment with broader educational goals. In this regard, the study contributes to the ongoing discourse on innovative teaching and learning strategies in STEM education, emphasizing the need to embrace failure as a valuable and necessary component of meaningful learning.

Conclusion

The conclusion of this study demonstrates that failure in STEM Project-Based Learning (PjBL) is not merely an undesirable outcome but a structured and productive learning mechanism that significantly contributes to students' cognitive, affective, and pedagogical development. In line with the research objective, the synthesis of recent studies confirms that failure facilitates deeper conceptual understanding, enhances higher-order thinking skills (HOTS), and strengthens students' resilience, growth mindset, and identity as emerging designers or engineers. Moreover, structured approaches such as Return on Failure (RoF), Failure Analysis (FA), and productive failure models have proven effective in transforming failure into a meaningful learning experience through iterative cycles of exploration, analysis, and revision. However, the effectiveness of failure-based learning is highly dependent on the presence of adequate instructional scaffolding, psychologically safe learning environments, and curriculum designs that prioritize process over outcomes. Therefore, this study concludes that integrating failure systematically within STEM PjBL frameworks is essential to fostering 21st-century competencies, provided that its implementation is carefully designed to balance cognitive demands and emotional support.

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