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Advancing STEM Education through Teacher Development: A Narrative Review of Global Strategies and Challenges

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ABSTRACT

In an era defined by rapid technological advancement and the imperative to equip learners with 21st-century skills, STEM (Science, Technology, Engineering, and Mathematics) education has emerged as a global priority. Central to the success of STEM initiatives is the role of well-trained teachers who can deliver interdisciplinary, inquiry-based instruction that aligns with the Sustainable Development Goals and evolving educational standards. This narrative literature review synthesises findings from empirical studies that explore diverse global strategies in STEM teacher professional development (TPD). The review was conducted using a narrative synthesis approach, which enabled an integrative and thematic exploration of diverse research contexts. Major academic databases, including ERIC, Google Scholar, and Web of Science, were searched using keywords related to STEM education and teacher training. Key findings reveal that successful TPD programs promote interdisciplinary curriculum integration, strengthen teacher self-efficacy, support technological and digital pedagogical competencies, and rely on context-specific and sustained delivery models. Furthermore, the review identifies institutional support and regional equity as critical enablers of impactful TPD. This study contributes to the growing discourse on educational reform by highlighting evidence-based practices and structural challenges in STEM TPD across different educational systems. It calls for policymakers, institutions, and researchers to design inclusive, scalable, and adaptable teacher development models that ensure long-term pedagogical transformation and equitable access to quality STEM education.

Keywords: STEM education, teacher professional development, instructional strategies, and program evaluation

INTRODUCTION

In today's knowledge-based and innovation-driven economy, the demand for individuals equipped with advanced STEM skills is accelerating. STEM education has thus emerged as a global imperative, recognized not only for its role in economic development but also for its contribution to achieving several United Nations Sustainable Development Goals (SDGs), including quality education, gender equality, and industry innovation (Kopnina, 2020; Aslam et al., 2023). Governments and educational institutions worldwide are now prioritising STEM integration across curricula to prepare students for complex real-world challenges and future careers in high-growth sectors (Felder, 2021; Hoeg & Bencze, 2017).

Central to the effective delivery of STEM education is the teacher, acting as both a facilitator of knowledge and a guide in fostering interdisciplinary thinking, innovation, and inquiry-based learning. However, despite this recognition, many educators face challenges in implementing integrated STEM instruction, including insufficient content knowledge across disciplines, limited experience with active learning methodologies, and inadequate institutional support (Lau & Jong, 2022; Huang et al., 2022). Addressing these challenges necessitates robust and adaptive TPD programs that not only enhance pedagogical and technological competencies but also build teachers' confidence and foster long-term instructional change (Jong, 2019; Margot & Kettler, 2019).

Over the last decade, diverse STEM TPD initiatives have emerged globally, ranging from short-term workshops and mentoring to long-term collaborative and hybrid learning models. These initiatives vary

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significantly in structure, delivery, objectives, and outcomes. While some studies have shown notable improvements in instructional practices, teacher self-efficacy, and student engagement (Stonier et al., 2023; Chan et al., 2023), others have revealed gaps in sustainability, contextual relevance, and equitable access (Rehman et al., 2025; Meng & Lihong, 2023).

To contribute to this growing body of research, this study presents a narrative review of recent global literature on STEM teacher professional development. It aims to examine and synthesise strategies, practices, and challenges in TPD programs that seek to advance STEM education. By offering thematic insights and comparative perspectives, the review provides an evidence-informed foundation for policymakers, educators, and researchers striving to design more effective, inclusive, and context-responsive STEM TPD initiatives. Specifically, this study seeks to explore and synthesise global strategies, outcomes, and challenges in STEM teacher professional development programs and to identify practices that contribute to practical, inclusive, and context-specific STEM education.

The research questions guide this review: (1) What are the common goals, strategies, and reported outcomes of STEM teacher professional development programs globally, and how do they contribute to advancing interdisciplinary and inquiry-based teaching practices? (2) How do variations in delivery format, duration, technological integration, and institutional support influence the effectiveness and sustainability of STEM TPD programs across different educational and regional contexts? The contributions of this review lie in its ability to consolidate fragmented knowledge, highlight context-specific challenges, and present practical recommendations for designing inclusive and scalable TPD frameworks. It also identifies key research gaps that can inform future empirical investigations into the long-term impact of STEM teacher development on educational equity and instructional innovation.

REVIEW OF LITERATURE

STEM and Teacher Professional Development

The growing importance of STEM education has underscored the need to train teachers for effective, integrated, and interdisciplinary instruction. While traditional TPD focused on subject-specific training, integrated STEM requires broader content mastery and classroom application (Lo, 2021; Huang, Jong, & Chai, 2022). Many educators still feel ill-equipped to deliver STEM lessons due to limited exposure to interdisciplinary strategies (Lau & Jong, 2022). Song and Zhou (2021) found that novice teachers benefited from TPD but were hampered by low confidence and limited experience. Lyu et al. (2022) identified curriculum design challenges and inadequate communication among 12 teachers based in Beijing.

Teacher self-efficacy significantly influences STEM adoption. Stonier et al. (2023) observed an improvement in STEM interest and confidence among Chinese students in early childhood education following hands-on training. Huang et al. (2022) emphasised the link between teacher attitudes, knowledge, and instructional quality. In the long term, continuous professional development (PD) is more effective than one-off workshops for promoting authentic STEM teaching (Nadelson & Seifert, 2017; Lin et al., 2022).

Effective Strategies in STEM TPD

Key strategies for impactful STEM TPD include inquiry-based and hands-on learning. Ong et al. (2022) employed the 5E model with 78 science teachers, leading to improved pedagogical skills. So et al. (2021) promoted collaboration between teachers and STEM professionals, enhancing engagement and innovation. Digital platforms and interactive tools also play a central role. Lin et al. (2023) found that online courses with personalised feedback improved student satisfaction. Wu and Zhang (2022) demonstrated that a human-computer interaction training platform facilitates the development of design thinking among STEM teachers.

Programs emphasising TPACK (Technological Pedagogical Content Knowledge) effectively enhance teaching practices. Chai et al. (2020) highlighted TPACK as crucial for STEM integration. Lo (2021) found that effective programs provide teaching models, collaboration opportunities, and peer support to overcome interdisciplinary challenges. Lin et al. (2022) linked continuous support with improved communication and

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student engagement, while Huang et al. (2021) used the ODR (Observation-Discussion-Reflection) model to enhance instructional quality.

METHODOLOGY

This study adopts a narrative literature review approach, which is particularly suitable for synthesising diverse studies and providing a holistic understanding of complex educational interventions such as STEM TPD. Unlike systematic reviews, which focus on narrowly defined questions and rigid inclusion criteria, narrative reviews offer greater flexibility in interpreting findings across diverse contexts, educational systems, and teacher development models. The significance of this method lies in its ability to accommodate heterogeneous studies and draw thematic insights that are not limited by strict methodological filters. This approach enables the exploration of broad trends, patterns, and contextual factors influencing TPD effectiveness. Given the global nature of STEM education reform and the diversity of TPD programs across regions, a narrative review is best suited to capture the complexity of practices and outcomes.

FINDINGS AND DISCUSSION

The review of global literature on STEM TPD reveals several converging findings and emerging challenges that influence the effectiveness of STEM education initiatives. The analysis reveals patterns across geographic regions and educational levels, particularly highlighting strategies that enhance teacher competencies, foster instructional innovation, and promote systemic alignment. These findings are discussed under key thematic areas:

Promoting Interdisciplinary Teaching and Curriculum Innovation

One of the most prominent findings is the emphasis on interdisciplinary teaching as a core goal of STEM TPD. Studies consistently demonstrate that successful TPD programs are those that help teachers break disciplinary silos and integrate science, technology, engineering, and mathematics into cohesive learning experiences (Huang et al., 2022; Ong et al., 2022). For instance, Stonier et al. (2023) found that even short-term experiential learning programs significantly increased teachers' willingness and capacity to link multiple STEM subjects in lesson planning. In China, curriculum reforms have prioritised integrated STEM projects that combine engineering design with scientific inquiry, promoting real-world problem-solving (Rehman et al., 2023). This focus on curriculum innovation is supported by Lo (2021), who observed that STEM TPD programs with embedded design-thinking principles and collaborative planning tools were more effective in transforming instructional practices. However, interdisciplinary integration remains a challenge due to gaps in teacher preparation and institutional alignment. Many teachers report limited experience with cross-disciplinary instruction and a lack of models or examples to follow (Lyu et al., 2022; Song & Zhou, 2021). Thus, the review suggests that TPD must move beyond content delivery to offer hands-on planning tools, exemplar units, and collaborative curriculum design sessions.

Enhancing Teacher Self-Efficacy and Instructional Confidence

A recurring outcome across studies is the improvement in teacher self-efficacy following participation in TPD programs. Teacher confidence in delivering STEM content, particularly through inquiry-based or problem-based approaches, plays a vital role in the successful adoption of new pedagogies (Chan et al., 2023). For example, Huang et al. (2022) observed that teachers who participated in sustained TPD exhibited increased confidence and STEM literacy, which in turn translated to more student-centred practices. This increase in self-efficacy is especially critical for early-career or pre-service teachers, who often report anxiety about implementing complex STEM concepts. Stonier et al. (2023) demonstrated that hands-on training and mentoring helped mitigate these fears and increased their willingness to take instructional risks. However, the impact was often short-lived unless supported by ongoing feedback and professional learning communities. The review highlights that self-efficacy is not merely a byproduct of content mastery but also pedagogical and peer support structures embedded within the TPD program (Lin et al., 2022). Thus, future TPD designs must embed mechanisms that foster confidence, including mentoring, peer observation, and reflective practice cycles.

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Integrating Technology and Digital Pedagogies

The increasing reliance on technology in education has necessitated the inclusion of digital competencies in STEM TPD programs. Studies such as Wu and Zhang (2022) and Lin et al. (2023) emphasise the growing success of online and blended professional development formats. Their findings show that interactive, feedback-rich digital environments can offer scalable and practical training experiences.For instance, Wu and Zhang (2022) implemented an IoT-based remote learning platform that significantly enhanced teacher collaboration and their use of design thinking. Similarly, Lin et al. (2023) found that structured online learning modules improved teachers' perceptions of digital learning and supported flexible, personalised professional growth. Nonetheless, challenges persist in ensuring equitable access and digital literacy. Teachers from under-resourced areas often lack the infrastructure or support to engage effectively with these digital platforms (Meng & Lihong, 2023). This raises questions about how to bridge the digital divide in STEM TPD and highlights the need for context-aware technological training.

Effectiveness of Delivery Models and Duration of TPD

The structure and duration of professional development have a significant impact on its effectiveness. While short-term workshops are practical for introducing concepts and generating interest, they often fall short in facilitating sustained instructional change (Stonier et al., 2023). In contrast, long-term engagements that include mentoring, follow-up sessions, and collaborative projects result in more profound instructional transformation (Lin et al., 2022; McCarthy Hintz et al., 2025). Lo (2021) and Dong et al. (2020) stress that TPD models that span several months or include cycles of feedback, reflection, and peer support are more likely to lead to pedagogical shifts and classroom innovation. Programs like the Observation-Discussion-Reflection (ODR) model further amplify these effects by encouraging critical self-assessment and shared learning (Huang et al., 2021). Moreover, the format of TPD matters. While face-to-face formats remain popular, hybrid and online models are gaining popularity due to their flexibility and scalability (Ong et al., 2022). However, as Wu and Zhang (2022) caution, the effectiveness of online TPD hinges on the quality of interaction, not just the delivery medium. Effective TPD must ensure active engagement, collaborative tasks, and contextual application, regardless of format.

Systemic and Regional Support Mechanisms

Institutional and policy-level support play a vital role in enabling and sustaining teacher development. Studies from Hong Kong and mainland China (So et al., 2021; Rehman et al., 2025) underscore the importance of school-professional collaborations and government-funded initiatives that promote inquiry-based STEM education. Moreover, support systems such as professional learning communities (PLCs), mentoring programs, and cross-sector partnerships provide essential scaffolding for teachers navigating STEM reform (Chan et al., 2023). Without these systemic supports, even the most well-designed TPD programs may falter due to teacher burnout, lack of coherence, or contextual misalignment (Dong et al., 2020). Regional disparities in access to quality TPD continue to be a challenge, particularly in rural or under-resourced contexts (Meng & Lihong, 2023). These areas often struggle with infrastructure deficits, a lack of qualified trainers, and poor alignment with national STEM goals. Addressing these disparities is critical for ensuring equity in STEM education advancement.

Limitations and Future Research Directions

Despite its insights, this review has limitations. Many studies relied heavily on self-reported data, such as surveys and interviews, which may introduce bias and limit the objectivity of results (Lin et al., 2023; Rehman et al., 2025). Future research should include classroom observations, student achievement data, and other direct measures to validate the impact of TPD. Another limitation is the scarcity of longitudinal studies assessing the sustainability of TPD outcomes over time (Stonier et al., 2023; So et al., 2021). Long-term investigations are necessary to assess the lasting effects on teacher practice and student engagement. There is also limited use of experimental and quasi-experimental designs, which hinders causal inferences about the effectiveness of TPD models (Chan et al., 2023; Zhan et al., 2021). Researchers should adopt mixed-method and experimental approaches to strengthen validity. Additionally, regional disparities and contextual

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challenges in under-resourced areas are underexplored (Meng & Lihong, 2023). Future studies should focus on these settings and examine how localised policies and cultural factors shape TPD outcomes.

CONCLUSION

This review highlights the transformative impact of teacher professional development on advancing STEM education worldwide. The synthesis of 23 empirical studies highlights that effective TPD initiatives share several critical characteristics: a focus on interdisciplinary teaching, enhancement of teacher self-efficacy, integration of digital tools, and sustained engagement through long-term or blended delivery models. These features are essential not only for updating pedagogical skills but also for enabling teachers to navigate the complexities of integrated STEM instruction confidently. Notably, the findings reveal that professional development is most impactful when supported by institutional policies, mentoring frameworks, and collaborative environments. Programs embedded within school-university partnerships, supported by local or national reforms, tend to offer richer, more context-sensitive training experiences. Conversely, short-term or fragmented TPD efforts often fail to deliver lasting instructional change.

The significance of this review lies in its ability to capture broad global trends while also addressing the contextual nuances that affect TPD implementation, particularly in under-resourced or geographically diverse regions. The narrative approach enabled a comprehensive understanding of both structural enablers and persistent challenges, providing a nuanced lens through which future initiatives can be developed. Moving forward, there is an urgent need for more rigorous, longitudinal, and mixed-method studies that explore the long-term impacts of TPD on teacher practice and student learning outcomes. In addition, scalable, hybrid models that blend online flexibility with localised mentorship and peer collaboration should be prioritised to bridge regional disparities in teacher access and support. Ultimately, investing in strategic, inclusive, and evidence-informed teacher professional development is fundamental to realising the full potential of STEM education in building innovative, equitable, and future-ready learning ecosystems worldwide.

Ethical Consideration

Ethical Approval

The present study is a comprehensive review paper; therefore, no primary data were used at any stage of the research, and no ethical approval is required.

Conflict of Interest

The authors disclose that there is no conflict of interest.

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