

Empowering STEAM Educators through AI: A Conceptual Framework for Adaptive, Inclusive Professional Development

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Abstract. *The growing demand for interdisciplinary Science, Technology, Engineering, Arts, and Mathematics (STEAM) education has placed increasing pressure on secondary education teachers to develop integrative, technology-enhanced pedagogical competencies. However, conventional models of professional development (PD) often fall short in addressing the complex, practice-based learning needs required for effective STEAM instruction. This conceptual study explores the potential of Artificial Intelligence (AI) to transform teacher PD by synthesizing recent high-impact literature (2018–2025) across the fields of educational technology, learning sciences, and AI ethics. Four thematic strands are identified: personalization of learning, enhancement of Technological Pedagogical Content Knowledge (TPACK), support for collaboration and reflection, and challenges related to ethics, equity, and teacher readiness. In response, the paper proposes the Adaptive AI-STEAM PD Cycle (A²SPDC) – a six-phase framework that integrates AI-driven assessment, personalized pathways, practice environments,*

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feedback, peer collaboration, and reflective analytics. The framework aims to promote context-sensitive, teacher-centered, and ethically responsible professional learning. While conceptual in nature, this work contributes a theoretically grounded model to guiding future empirical research and policy design, with the broader goal of supporting equitable, innovative, and socially responsive teacher development in STEAM education.

Keywords: *Artificial Intelligence, teacher professional development, STEAM education, TPACK, educational equity, design-based research.*

Introduction

The increasing imperative for secondary education systems to equip students with competencies in *Science, Technology, Engineering, Arts, and Mathematics* (STEAM) reflects a global shift toward interdisciplinary, future-oriented learning (Perignat & Katz-Buonincontro, 2019; Anderson & Li, 2020). Beyond disciplinary mastery, students must develop transversal skills such as creativity, computational thinking, and problem-solving in order to thrive in complex, rapidly evolving societies (OECD, 2019; European Commission, 2025). This shift imposes new demands on teachers, requiring not only deep content knowledge but also the ability to facilitate integrated, technology-enhanced, student-centered learning experiences (Quigley & Herro, 2019).

However, conventional models of teacher *Professional Development* (PD) often fall short in preparing educators for the complexities of integrated STEAM instruction. These models are frequently generic, lacking adaptability to teachers' disciplinary backgrounds, prior experience, or specific classroom contexts (Darling-Hammond et al., 2017; Kennedy, 2016). Furthermore, most PD initiatives inadequately address the development of *Technological Pedagogical Content Knowledge* (TPACK), especially as it relates to emerging technologies such as *Artificial Intelligence* (AI) (Mishra & Koehler, 2006; Yue et al., 2024).

Scientific problem. There is a misalignment between the specialized demands of STEAM education – particularly those involving AI integration – and the structure of traditional teacher PD models. This gap hinders effective pedagogical innovation and slows down the adoption of interdisciplinary, AI-informed teaching practices.

Object of the research. The object of this conceptual study is the professional development of secondary school teachers for integrated STEAM education, enhanced through the strategic use of AI.

Aim of the research. The research aims to conceptualize a theoretically grounded, adaptive professional development framework that leverages AI technologies to support secondary teachers in delivering effective, integrated STEAM instruction.

Research objectives:

1. To conduct a targeted literature review (2018–2025) on AI applications in teacher PD, with an emphasis on STEAM education.

2. To identify and synthesize major pedagogical and technological themes relevant to AI-enhanced PD.
3. To propose the *Adaptive AI-STEAM PD Cycle* (A²SPDC) framework based on these findings.
4. To outline a *Design-Based Research* (DBR) methodology suitable for the future empirical validation of the framework.
5. To critically discuss the implications, feasibility, and limitations of applying AI to STEAM teacher PD.

Theoretical framework

This study is grounded in contemporary literature (2018–2025) examining the intersection of *Artificial Intelligence in Education* (AIED), teacher *Professional Development* (PD), and integrated STEAM teaching. A structured review of high-impact sources revealed four thematic strands that underpin the conceptual framework presented in this paper. These themes synthesize the affordances and challenges of AI-enhanced PD and directly inform the design of the *Adaptive AI-STEAM PD Cycle* (A²SPDC).

Theme 1: AI for personalized and adaptive professional development experiences

AI offers significant potential for delivering personalized, adaptive PD experiences, which contrast with the often-generic structure of the conventional PD (Ouyang et al., 2022; Zawacki-Richter et al., 2019). Techniques such as learner profiling, knowledge tracing, and predictive analytics enable AI to tailor content delivery, scaffold learning progressions, and dynamically adjust the task complexity based on each teacher's profile and performance (Aleven et al., 2016; Bond & Buntins, 2022). The rise of *Large Language Models* (LLMs) introduces additional support capabilities, including lesson adaptation, resource generation, and formative planning guidance (Kasneci et al., 2023; Huang et al., 2024).

In terms of *framework relevance*, this theme informs the diagnostic assessment and personalized learning pathway components of the A²SPDC, ensuring individualized support and dynamic adaptability over time.

Theme 2: AI enhancing STEAM pedagogical capabilities with a focus on TPACK

The TPACK framework highlights the complex integration of technological, pedagogical, and content knowledge required for effective technology-mediated teaching (Mishra & Koehler, 2006). Many educators remain underprepared in AI-specific knowledge domains (CK, TK) and in applying AI within interdisciplinary STEAM contexts (Yue et al., 2024; Sanusi et al., 2023). AI can serve both as a subject of PD (in developing AI literacy) and a mechanism for delivering PD, through offering simulations, virtual

teaching environments, and interactive tools to build confidence and competence across TPACK dimensions (Luckin & Cukurova, 2019; Southgate, 2020).

In terms of *framework relevance*, this theme is embodied in the A²SPDC's emphasis on AI-powered practice environments designed to support the acquisition and integration of TPACK specifically for STEAM education.

Theme 3: AI as a tool for collaboration, reflection, and feedback

Collaborative inquiry, reflective practice, and meaningful feedback are essential for sustained professional learning (Timperley, 2011; Vescio et al., 2008). AI supports these points through multimodal feedback systems, analysis of teacher inputs (e.g., teaching artifacts or simulation performance), and dialogic tools like LLMs that aid reflection, summarization, and peer interaction (Martinez-Maldonado et al., 2021; Grob et al., 2024). AI can also mediate collaborative PD activities and help surface hidden patterns in practice, but feedback must move beyond surface metrics in order to foster deeper pedagogical reflection (Ifenthaler, 2022).

In terms of framework relevance, these functions are operationalized in the framework through collaborative AI partnering tools, multi-modal AI feedback mechanisms, and a reflective analytics dashboard.

Theme 4: Critical challenges – ethics, equity, data privacy, and teacher readiness

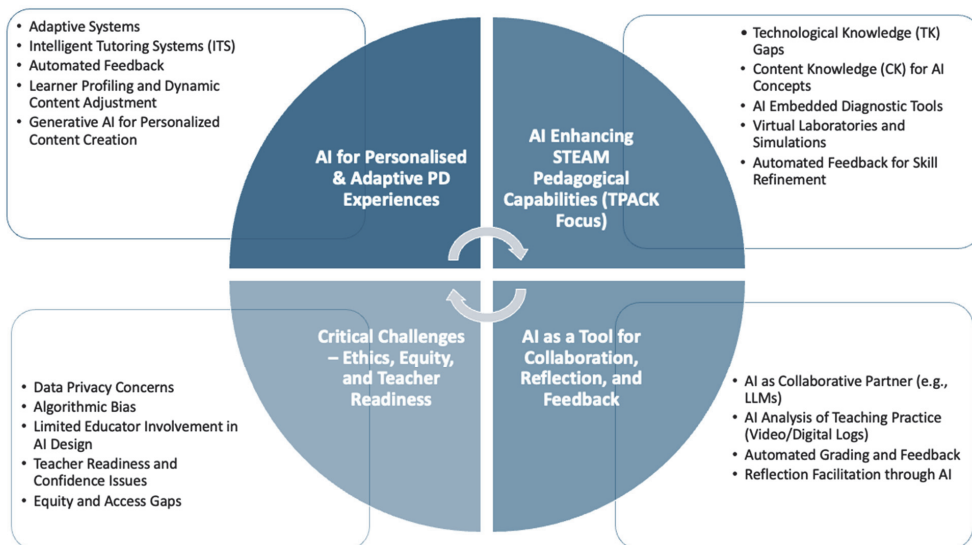
While AI holds promise, numerous challenges persist. Concerns include data privacy, algorithmic bias, lack of transparency in AI-generated outputs, and the potential for surveillance or technocratic control over teaching (Selwyn, 2022; Crompton & Burke, 2023). Studies also critique the weak pedagogical foundations of many AIED tools and the limited involvement of teachers in their design (Holmes et al., 2022; Bond et al., 2024). Disparities in infrastructure, digital literacy, and support structures further complicate equitable implementation (Elish, 2019; Reich, 2019). Teacher readiness, which is shaped by self-efficacy, prior knowledge, and attitudes, remains a barrier to meaningful engagement with AI-enhanced PD (Alalwan et al., 2023).

In terms of *framework relevance*, the A²SPDC addresses these concerns by embedding teacher agency, offering choice and voice in PD pathways, emphasizing ethical use, and scaffolding AI-related TPACK growth through supportive practice and feedback cycles.

Collectively, these themes shape a comprehensive understanding of how AI can both enhance and complicate professional development for STEAM teachers (Figure 1). They provide the theoretical structure for the design of a responsive, pedagogically grounded framework that seeks to operationalize AI not as a replacement for educators, but as a tool for augmenting teacher learning in a responsible and meaningful way.

Figure 1.

Thematic map illustrating key application areas and challenges of AI in teacher professional development collated from high-impact literature (2018–2025)



Methodology

This research adopts a conceptual research design underpinned by a systematic literature review and an iterative process of theoretical synthesis. The primary aim is to develop a novel framework, the Adaptive AI-STEAM PD Cycle (A²SPDC), in order to support AI-enhanced professional development for secondary STEAM educators. Although the study does not present empirical data, it lays a foundation for future empirical testing using *Design-Based Research* (DBR).

1. Systematic literature review approach

To ensure methodological transparency and scholarly rigor, this study employed a structured conceptual research design rooted in a systematic review of recent literature. The aim was to synthesize current knowledge at the intersection of artificial intelligence (AI), teacher professional development (PD), and secondary STEAM education, and to use this synthesis to inform the development of a new theoretical model.

Literature review strategy: a targeted review of peer-reviewed publications was conducted to map the landscape of AI applications in teacher PD, particularly within STEAM contexts. The search covered literature published between January 2018 and February 2025 and followed guidance for conceptual research in educational technology (Boote & Beile, 2005).

Four academic databases were consulted: *Scopus*, *Web of Science*, *ERIC*, and *Google Scholar*. The search strategy combined keywords using Boolean operators to capture a wide range of relevant publications. Search strings included: ‘Artificial Intelligence’ OR ‘AI’ OR ‘machine learning’ AND ‘teacher professional development’ OR ‘teacher training’ AND ‘STEAM education’ OR ‘STEM education’ OR ‘TPACK’ OR ‘technological pedagogical content knowledge’ AND ‘secondary education’ OR ‘K-12’.

Inclusion criteria were as follows:

- Peer-reviewed journal articles, book chapters, or systematic reviews;
- Explicit focus on teacher professional development and/or STEAM education;
- Discussion of AI applications or implications for teaching and learning;
- Published in English between 2018 and early 2025.

Studies were excluded if they focused solely on student outcomes, lacked a conceptual or theoretical contribution, or appeared in non-peer-reviewed or grey literature sources.

The search process yielded 743 records. After removing 115 duplicates, the remaining 628 titles and abstracts were screened for relevance. This initial screening reduced the pool to 126 articles, which were then read in full. A final selection of 42 studies was retained for in-depth analysis. These included 12 systematic reviews or meta-analyses, 20 empirical studies, and 10 theoretical or conceptual papers.

All selected studies were coded and thematically analyzed. An inductive-deductive synthesis process revealed four dominant themes, which are presented in the Theoretical Framework section.

2. Conceptual framework development

Drawing on the findings of the literature review, the Adaptive AI-STEAM PD Cycle (A²SPDC) was developed through an iterative conceptual synthesis process. The construction of the framework was guided by both established educational theory and emerging trends in AI integration.

This process involved:

- Deductive alignment of insights with principles from adult learning theory, the TPACK model, and literature on effective professional development;
- Inductive identification of new patterns and pedagogical affordances made possible by AI, such as personalized learning, intelligent feedback loops, and adaptive content delivery;
- Cross-referencing of synthesized themes with contemporary frameworks for AI in education;
- Logic modeling to structure the components of the framework into a coherent and cyclical model.

The resulting A²SPDC framework is designed to support secondary STEAM educators in developing interdisciplinary competencies by embedding AI capabilities into a dynamic, reflective, and personalized professional development cycle.

3. Proposed pathway for empirical validation

Although this article presents a conceptual model, future empirical testing is essential to assess its relevance and effectiveness in real educational settings. To this end, a *Design-Based Research* (DBR) methodology is proposed as a suitable pathway for iterative development and evaluation.

DBR is particularly appropriate for testing educational innovations in complex, authentic environments (Anderson & Shattuck, 2012; McKenney & Reeves, 2018). The following *phases are envisioned* for future studies:

- Co-design of an A²SPDC prototype in collaboration with secondary STEAM educators;
- Pilot implementation of the model in selected school-based professional learning contexts;
- Data collection through mixed methods, including pre- and post-intervention TPACK self-assessments, teacher reflective journals, user interaction logs, and analysis of instructional artifacts;
- Iterative refinement of the framework based on findings, user feedback, and contextual variables.

This approach will support the practical operationalization of the framework while contributing theoretical insights to the fields of AI in education and teacher professional learning.

Results: The adaptive AI-STEAM PD Cycle (A²SPDC) framework

The central outcome of this conceptual investigation is the development of the Adaptive AI-STEAM PD Cycle (A²SPDC) – a theoretically grounded framework for enhancing professional development (PD) of secondary STEAM teachers through artificial intelligence. Designed in response to the limitations of conventional PD models, the A²SPDC incorporates six interrelated, iterative components. These components align directly with the key themes identified in the literature review and collectively support a more personalized, adaptive, and pedagogically meaningful approach to teacher learning in STEAM contexts.

The first phase, Diagnostic AI Assessment, reflects the affordances of Theme 1 by employing AI technologies to construct individualized teacher learning profiles. Going beyond surface-level surveys, this stage integrates diverse forms of data, such as adaptive questionnaires, textual analysis of lesson plans, or teacher performance in simulated instructional scenarios. The outcome is a nuanced understanding of each educator's TPACK strengths, areas for development, beliefs, confidence levels, and professional learning goals.

Building on this foundation, the second phase, Personalized Pathway Generation, operationalizes the personalization potential of AI by creating tailored PD trajectories. Rather than offering static content, AI systems dynamically assemble learning sequences

that address the identified needs of each teacher. This includes targeted micro-learning modules, curated resources, simulation activities, and recommendations for peer collaboration. Importantly, these pathways are adaptive, i.e., they adjust over time in response to the teacher's progress, preferences, and feedback within the system.

The third phase, AI-Powered Practice Environments, is informed by Theme 2, which emphasizes the development of *Technological Pedagogical Content Knowledge* (TPACK) for effective STEAM instruction. This phase provides immersive, low-stakes contexts in which teachers can explore interdisciplinary teaching strategies, experiment with digital tools, and integrate AI into lesson design. Virtual simulations with AI-generated student personas, interactive science labs, and makerspace tools allow teachers to develop both conceptual understanding and applied skills relevant to their STEAM disciplines.

As teachers engage in these practice environments, the fourth phase, Multi-Modal AI Feedback, offers ongoing, formative guidance. Drawing from the insights of Theme 3, feedback is generated through analysis of teacher actions, lesson designs, and performance metrics within the simulated environments. Rather than relying on summative evaluation, AI systems provide timely, specific suggestions aligned with pedagogical principles and TPACK dimensions, helping teachers refine their practice in a supportive, non-judgmental manner.

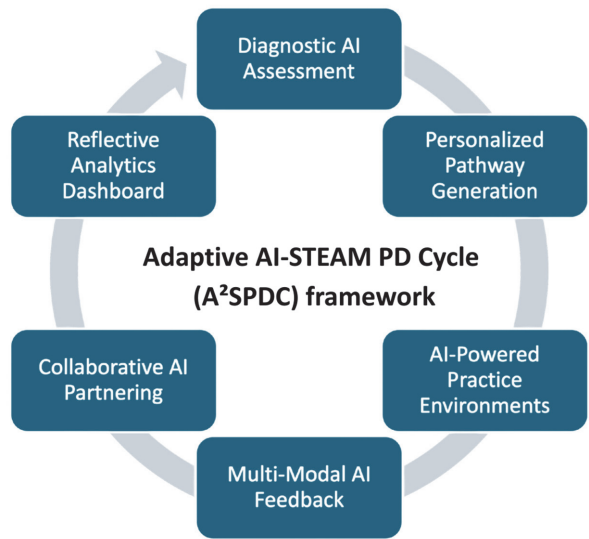
The fifth component, Collaborative AI Partnering, further extends Theme 3 by positioning AI as a co-participant in professional dialogue. Teachers can collaborate with AI tools, such as large language models, to brainstorm project ideas, generate differentiated instructional materials, or plan interdisciplinary units. Additionally, AI can mediate peer review and group collaboration processes, while summarizing discussion points or helping to connect educators with similar interests or complementary strengths. These interactions encourage co-construction of knowledge and foster a sense of shared professional growth.

Figure 2 provides a visual summary of the A²SPDC framework, illustrating how each of the six phases is interlinked, and how they align with the key affordances and challenges of AI-enhanced STEAM professional development.

Finally, the Reflective Analytics Dashboard serves as a central space for teachers to monitor their development, track progress over time, and engage in critical reflection. This phase supports both Themes 3 and 4 by ensuring that teachers can visualize their learning trajectories, analyze changes in specific competencies, and make informed decisions about future goals. Ethical considerations are integral to the design of this component: transparency, teacher agency, and data privacy are prioritized, with feedback presented in formative, non-surveillant ways.

Crucially, the A²SPDC is not linear but cyclical. Insights from the reflection phase inform the next iteration of diagnostic assessment and pathway design, reinforcing continuous professional learning. The structure of the framework also reflects the principles of *Design-Based Research* (DBR), thereby offering a foundation for future empirical testing and iterative refinement in authentic school settings.

Figure 2.
Adaptive AI-STEAM PD Cycle (A²SPDC) – core components and functions



Note. This framework integrates six iterative phases, supported by AI capabilities and grounded in the pedagogical and ethical principles identified in the literature review

By intentionally aligning each component of the A²SPDC with specific theoretical insights and practical needs, the framework offers a comprehensive, forward-looking model of AI-enhanced professional development. It addresses core challenges facing STEAM education and proposes a flexible approach that can be ethically, pedagogically, and contextually responsive.

Addressing implementation challenges

The A²SPDC framework was purposefully designed to address the critical challenges associated with AI-enhanced professional development, as outlined in Theme 4 of the theoretical framework. Central to its design is a firm pedagogical grounding: the framework incorporates principles of adult learning and centers the TPACK model as the core structure guiding teacher growth. By focusing on active learning, reflection, and practical application, the model aims to foster meaningful and sustained pedagogical development.

A key strength of the framework lies in its emphasis on teacher agency. Rather than imposing rigid content or predefined trajectories, A²SPDC offers teachers choices in their learning pathways and activities. This flexibility not only accommodates diverse starting points and preferences but also promotes intrinsic motivation and a sense of ownership over the learning process; these factors have been shown to influence the long-term impact of professional development.

To support readiness and confidence, particularly in areas related to AI literacy, the framework provides scaffolded opportunities for building both conceptual and technical knowledge. AI-powered simulations, targeted modules, and personalized feedback mechanisms are designed to support teachers at varying levels of expertise, ensuring accessible and differentiated entry points into more complex pedagogical and technological domains.

Ethical considerations are embedded in the conceptual structure, though their practical implementation will require further refinement. A²SPDC promotes diagnostic, formative use of AI tools over evaluative or surveillance-based applications. Transparency, data privacy, and bias mitigation are acknowledged as essential design priorities for any future development and deployment of the system. These principles are intended not as afterthoughts but as foundational commitments shaping the responsible integration of AI into professional learning.

While still conceptual, the A²SPDC framework offers a coherent, theoretically informed, and practically oriented approach to rethinking professional development in the era of artificial intelligence. It seeks to unify personalization, collaborative learning, ethical reflection, and pedagogical depth within an adaptive and iterative cycle. In doing so, it contributes not only a structural model for future implementation but also a conceptual lens through which to examine how AI might be harnessed responsibly to advance equity, teacher empowerment, and innovation in STEAM education.

This framework lays the foundation for a structured program of applied research. As outlined in the proposed Design-Based Research (DBR) pathway, future studies should empirically test and refine the model in real-world settings, ensuring that it remains responsive to the practical realities and contextual diversity of schools. Ultimately, A²SPDC aims to contribute to broader social welfare goals by equipping teachers with the tools, knowledge, and confidence to navigate the pedagogical demands of interdisciplinary, technology-rich learning environments.

Discussion

This study has explored how artificial intelligence (AI) can be leveraged to enhance professional development for secondary STEAM educators by proposing a conceptual framework – the Adaptive AI-STEAM PD Cycle (A²SPDC). While the framework synthesizes key insights from recent scholarship and offers an integrated structure for future practice, this discussion critically reflects on its feasibility, potential contributions, and necessary next steps.

The A²SPDC framework responds to longstanding limitations in teacher professional development: limited personalization, lack of contextual relevance, and insufficient support for interdisciplinary pedagogical knowledge (Darling-Hammond et al., 2017; Kennedy, 2016). By aligning specific AI capabilities with adult learning principles and the TPACK framework (Mishra & Koehler, 2006; Ouyang et al., 2022),

A²SPDC proposes a more targeted, iterative, and flexible model for teacher growth. Unlike the traditional PD models, which often offer one-size-fits-all workshops, this framework envisions PD as an adaptive process where the learning content, feedback, and collaboration evolve based on real-time teacher needs (Popova et al., 2022).

However, the implementation of such a system is not without complexity. One critical issue concerns the **scalability and accessibility** of AI-driven PD. For the model to function effectively across educational contexts, it must be supported by robust infrastructure and school-level commitment. Equity of access remains a major concern, particularly in under-resourced schools, where disparities in digital tools and connectivity may hinder participation (Elish, 2019; Reich, 2019).

Another challenge is **teacher readiness and confidence in using AI**, which the literature consistently identifies as a barrier to adoption (Yue et al., 2024; Zhang et al., 2023). Although A²SPDC proposes targeted support to address knowledge gaps in AI-related content and technological skills, building sustained teacher engagement with these tools will require more than technical training. Teachers need time, support, and opportunities for experimentation within a culture that values innovation and learning from failure (Zhang & Chen, 2025).

The **ethical implications** of integrating AI into teacher learning also demand careful consideration. Scholars have warned of the risks related to surveillance, algorithmic bias, and data privacy in AI-based education systems (Selwyn, 2022; Zawacki-Richter et al., 2019; Crompton & Burke, 2023). While the A²SPDC framework emphasizes diagnostic over evaluative use and prioritizes teacher agency, these ideals must be translated into clear design protocols and governance mechanisms. Co-design processes involving teachers and researchers – which is a noted gap in the current AIED development (Holmes et al., 2022; Bond et al., 2018) – will be essential to ensure contextual relevance and ethical integrity.

Despite its conceptual nature, the A²SPDC offers practical value as a **design hypothesis** (Anderson & Shattuck, 2012). It provides a shared vocabulary and architecture for developers, school leaders, and policy-makers seeking to align AI innovations with pedagogical goals. The framework also offers a structure for studying how AI might support interdisciplinary learning approaches central to STEAM education, which is an area that remains underexplored in the literature (Quigley & Herro, 2019; Nguyen et al., 2024).

Future research should prioritize **Design-Based Research (DBR)** to test and refine the model in authentic educational settings. DBR's iterative cycles of analysis, design, implementation, and reflection are particularly well suited to the challenges of developing AI systems that are pedagogically robust and practically usable (McKenney & Reeves, 2018). Longitudinal studies would also be beneficial to evaluate whether AI-enhanced PD contributes to lasting changes in teaching practice and student learning outcomes which represent a current gap in AIED research (Sanusi et al., 2023).

In summary, while the A²SPDC framework does not yet offer empirical evidence of impact, it presents a theoretically grounded and ethically aware model for reimagining teacher professional learning. Its success will depend not only on technological capabilities but also on meaningful teacher engagement, critical design processes, and supportive institutional ecosystems. As educational systems increasingly explore AI's potential, conceptual models, such as A²SPDC, are vital for steering innovation toward equitable and pedagogically sound outcomes.

Conclusions

This article introduces the Adaptive AI-STEAM PD Cycle (A²SPDC) as a conceptual framework for enhancing professional development for secondary STEAM educators through the integration of artificial intelligence. Drawing on recent literature, the framework brings together adaptive personalization, pedagogical support for TPACK, and AI-mediated reflection and collaboration within a cyclical, teacher-centered model.

While the framework remains theoretical, it offers a structured foundation for future empirical exploration. To ensure its relevance and viability, subsequent research should apply iterative, participatory methodologies such as Design-Based Research. This will allow for the framework's refinement in response to practical challenges and contextual diversity.

As educational systems continue to navigate the integration of AI, conceptual models like A²SPDC can help guide innovation toward more equitable, responsive, and pedagogically grounded approaches to teacher learning. Its future development should remain closely tied to classroom realities and collaborative engagement with the educators it seeks to support.

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