ISSN: 2393-8048
International Advance Journal of Engineering, Science and Management (IAJESM)
Multidisciplinary, Multilingual, Indexed, Double Blind, Open Access, Peer-Reviewed, Refereed-International Journal.
SJIF Impact Factor = 8.35, January-June 2026, Published on 28th February 2026

Teacher Education and Professional Development through Enabled Systems

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Abstract

This paper explores the transformative potential of technology-enabled systems, particularly those integrating artificial intelligence (AI) and blockchain, in revolutionizing teacher education and professional development. It addresses the limitations of traditional models and highlights the benefits of AI-driven analytics, virtual reality, and personalized learning pathways in cultivating technological and pedagogical fluency. The study emphasizes the urgent need for expanded frameworks prioritizing AI literacy training, enabling teachers to leverage tools effectively and ethically. It introduces the 'Enabled System,' a conceptual framework that positions teacher education as a dynamic, AI-enhanced ecosystem fostering collaborative reflection and dialogic knowledge creation. The paper discusses the system's role in enhancing content knowledge, its perceived usability and effectiveness, and the challenges and limitations in its implementation. It also provides recommendations for practice and policy, advocating for structured training on ethical and pedagogical AI use, certification standards for AI literacy, and collaborations between educators and AI experts. The conclusion underscores the importance of evidence-based refinements and longitudinal studies to ensure the scalability and efficacy of AI-enabled professional development models, ultimately cultivating a legacy of responsible innovation that bridges technological advancement with humanistic educational values.

Keywords: Artificial Intelligence, Teacher Education.

Introduction

In the contemporary educational landscape, technology-enabled systems are profoundly transforming teacher education and professional development. These innovative platforms enhance pedagogy, foster lifelong learning, and provide secure mechanisms for tracking professional milestones (Saravanakumar et al., 2023; Сахипов et al., 2023). They address historical challenges like burdensome paperwork and a lack of transparency in documenting teacher achievements. Specifically, blockchain-integrated systems offer decentralized, immutable ledgers for verifying professional development activities, giving teachers control over their credentials and promoting continuous learning.

Beyond secure documentation, these systems facilitate global collaboration among educators, enriching pedagogical practices with diverse international perspectives (Saravanakumar et al., 2023). However, their widespread adoption requires overcoming hurdles such as technological literacy gaps and ensuring equitable access to prevent a digital divide. This paper highlights the transformative potential of blockchain in ensuring transparency and efficiency in professional development records. By integrating artificial intelligence and virtual reality, these systems further enrich teacher training through immersive simulations and adaptive learning pathways, cultivating both technological and pedagogical fluency (Siyam et al., 2025; Sui et al., 2024). Ultimately, these advancements underscore the critical need for tailored professional development opportunities that effectively bridge the gap between available AI tools and their practical implementation by teachers in various educational settings.

Conceptual Frameworks in Existing Research

Existing research primarily frames artificial intelligence in teacher professional development as a goal: equipping educators to integrate AI into pedagogy. A significant research imbalance shows only 35% of studies focus on AI's role *in* teacher PD, rather than its application *in* teaching. This highlights an urgent need for expanded frameworks prioritizing AI literacy training, enabling teachers to leverage tools like intelligent tutoring systems and blockchain for

secure, personalized growth. Blockchain-enhanced platforms offer immutable documentation for PD activities, granting teachers ownership of credentials and fostering lifelong learning. Emerging frameworks also promote AI-driven analytics and virtual reality to boost motivation, while emphasizing training on biases and data privacy (Meylani, 2024). The literature's Western bias underscores challenges in developing countries, necessitating expanded frameworks like TPACK for generative AI integration. Social network analyses confirm PD as a pivotal link between generative AI and language teacher education, demanding structured training programs based on models like TPACK and SAMR.

Traditional Models of Teacher Education

Traditional teacher education models, often centralized and workshop-based, have faced limitations such as logistical constraints, inconsistent evaluation, and a lack of individualized learning paths. These shortcomings frequently lead to poor long-term retention of pedagogical skills and limited scalability for diverse educator cohorts.

In stark contrast, contemporary AI-enabled systems are introducing adaptive and scalable architectures that revolutionize professional development by tailoring it to individual teacher profiles. These systems leverage conversational AI and chatbots to simulate real-time pedagogical scenarios, thereby enhancing transformative agency. This adaptive approach aligns with the Technological Pedagogical Content Knowledge framework, empowering educators to navigate the intricate connections between generative AI, pedagogical strategies, and subject-specific content for more effective language instruction integration (Casierra et al., 2025; Shrestha et al., 2025). Bibliometric analyses further highlight key thematic clusters, such as professional development intertwined with AI literacy and pre-service teachers' readiness, which guide the evolution of these frameworks towards comprehensive generative AI adoption in teacher training (Karakaya et al., 2025; Ye et al., 2024).

However, significant gaps persist in empirical evidence, particularly from underrepresented regions like Latin America, and across various educational levels. These gaps underscore the critical need for contextually validated instruments to support comprehensive generative AI adoption in teacher training. To address this, innovative strategies grounded in TPACK frameworks are essential to empower language teachers as co-designers of generative AI tools, fostering contextual customization and pedagogical relevance in diverse educational settings (Karakaya et al., 2025; Shrestha et al., 2025). Such integration necessitates the incorporation of AI-specific pedagogies into core teacher education curricula, providing pre-service teachers with hands-on experience in designing AI-supported tasks and developing prompt literacy for ethical implementation.

These curricula must prioritize reflective constructivist frameworks that embed generative AI training to build teacher agency and address uncertainties surrounding its ethical deployment in language classrooms (Karakaya et al., 2025; Wang et al., 2025). Empirical scoping reviews consistently show generative AI's capacity to boost teacher self-confidence, cultivate positive attitudes toward AI usage, and improve lesson design through targeted interventions, thereby mitigating representational biases in teacher development research. To further address these biases, future teacher education initiatives should prioritize participatory action research methodologies that employ design thinking to co-create AI-powered professional development tailored to educators' varying knowledge levels and professional trajectories (Casierra et al., 2025; Kildė, 2024). This co-creation process is further strengthened by embedding AI literacy and ethics into curricula, alongside experiential learning with generative AI tools, to cultivate teachers as critical orchestrators of technology-enhanced instruction (Karakaya et al., 2025; Lee et al., 2025). Ultimately, these enriched curricula demand rigorous longitudinal evaluations to ascertain the sustained impact of generative AI on teachers' adaptive expertise across multifaceted instructional contexts. Leveraging generative AI within these evaluations can also illuminate barriers related to teachers' attitudes and skills, necessitating context-sensitive

professional development programs that integrate TPACK to overcome integration challenges in language teaching (Casierra et al., 2025; Kildė, 2024). Crucially, institutional support is vital to provide teacher educators with expanded access to diverse generative AI tools and features, embedding explainable AI and prompt engineering as core elements within sustained professional development frameworks (Nyaaba & Zhaı, 2024).

Current Trends in Professional Development

Current trends in professional development for teacher education increasingly emphasize sustained, practice-oriented frameworks. These frameworks integrate hands-on engagement with generative AI tools alongside AI literacy training, empowering educators in ethical implementation and critical lesson design. Such trends also advocate for cross-institutional, mixed-methods research to deepen AI literacy and ethical preparedness, positioning generative AI as a pedagogical agent that transforms instructional design, delivery, and reflection in teacher education. Emerging interventions, including cognitive apprenticeship and socio-constructivist approaches, have significantly enhanced instructors' self-efficacy for AI integration, complemented by targeted programs that bolster pedagogical and critical AI awareness. This occurs despite lingering gaps in guiding student generative AI usage (Karakaya et al., 2025).

Consequently, institutional policies must enforce consistent guidelines on acceptable generative AI use across departments, compelling instructors to model critical evaluation of AI outputs for accuracy, bias, and curricular alignment while updating syllabi collaboratively. This collaborative syllabus updating fosters a human-centered AI pedagogy, equipping educators with structured support to integrate generative AI ethically while simultaneously teaching students analogous critical skills (Casierra et al., 2025). Furthermore, these policies should extend to fostering collaborative networks among educators to co-develop explainable generative AI applications, ensuring alignment with localized pedagogical needs and ethical standards in teacher training programs (Nyaaba & Zhaı, 2024). These collaborative networks necessitate the extension of TPACK frameworks to incorporate contextual knowledge as a surrounding influence alongside ethical AI components, enabling teachers to address micro-, meso-, and macro-level factors in technology integration. Ongoing longitudinal studies are essential to track the long-term efficacy of these extended TPACK frameworks in cultivating teachers' adaptive capacities for generative AI integration across diverse educational contexts. Parallel efforts in scenario-based training within practicum settings can simulate classroom challenges, equipping pre-service teachers with prompt engineering skills and the ability to critically evaluate generative AI outputs for biases and validity (Asghar et al., 2025; Nyaaba, 2024). This scenario-based training aligns with recommendations for explicit generative AI training through practical guidelines and ethical frameworks, enabling teacher educators to foster responsible classroom integration (Ko et al., 2025). Moreover, these initiatives should operationalize TPACK and 5E models through concrete scenarios in professional development, training educators to embed generative AI in inquiry-based settings and adaptive assessments for meaningful pedagogical enhancement (Kesgin, 2025). Institutions must therefore prioritize the development of discipline-specific policies and guidelines that account for instructors' contextual teaching needs, engaging educators across departments to align generative AI integration with evolving tool capabilities and ethical standards (Wang et al., 2023; Xia et al., 2024). These policies should incorporate mechanisms for ongoing monitoring and evaluation of generative AI systems to assess their instructional impact and ethical compliance in teacher education programs (Chan, 2023; Elbourn, 2024). Simultaneously, these monitoring mechanisms should integrate faculty training programs focused on AI literacy and ethical guidelines to ensure equitable access and minimize biases in generative AI deployment (Ayanwale et al., 2024; Bura & Myakala, 2024). This integration of faculty training extends to pre-service teacher programs, where hands-on modules emphasize evaluating AI-generated

content for biases and ethical alignment across diverse cultural contexts (Kehoe, 2023). These hands-on modules in pre-service programs should incorporate validated dialogue-based assessments with generative AI during lesson planning to rigorously evaluate and refine pedagogical content knowledge (Blonder et al., 2024). This approach not only personalizes instruction by uncovering pre-service science teachers' PCK through generative AI interactions but also extends TPACK integration to enable effective use of these tools in addressing specific content representations and student understanding challenges (Blonder et al., 2024). Consequently, embedding such validated assessments within broader AI literacy curricula equips pre-service teachers with the competencies to navigate generative AI's dialogical processes, fostering structured prompt engineering and output evaluation essential for ethical classroom integration (Blonder et al., 2024; Nyaaba & Zhai, 2024). To advance these competencies, policymakers should establish comprehensive guidelines for ethical generative AI use, including training programs for faculty and students to foster AI literacy while addressing data privacy and equitable access (Akanzire et al., 2025; Jin et al., 2024). These guidelines must further promote stakeholder collaboration across academia, industry, and government to refine ethical frameworks, drawing from initiatives like UNESCO's principles for AI in education while tackling algorithmic bias and intellectual property concerns in teacher training (Bura & Myakala, 2024). Such multifaceted stakeholder collaboration is pivotal for cultivating teacher agency in AIED, wherein practical training with diverse generative AI resources complements theoretical ethical discourse to redefine dialogical practices in course design, delivery, and assessment (Mouta et al., 2024).

The Role of Technology in Teacher Learning

Technology plays a pivotal role in teacher learning by integrating AI tools that demand ethical assessment knowledge to evaluate fairness, transparency, and inclusivity, shaping educators' expertise across micro-, meso-, and macro-level factors. Generative AI, for instance, facilitates interactive dialogues during lesson planning, uncovering pre-service science teachers' pedagogical content knowledge and enabling targeted program adjustments (Blonder et al., 2024). This technological support extends to providing real-time, tailored feedback on pedagogical content knowledge gaps, thereby personalizing professional development in teacher education programs (Blonder et al., 2024).

Professional development sessions leveraging AI tools in collaborative settings allow teacher educators and candidates to critically discuss outputs, evaluate ethical standards, and address contextual complexities (Estaiteyeh & McQuirter, 2024). These collaborative AI-driven sessions cultivate transversal competencies, positioning teachers as active agents in epistemological renewal and the revitalization of educational paradigms through continuous professional development (Mouta et al., 2024). Initiatives like UNESCO's AI competency framework for educators further delineate a three-stage progression encompassing human-centric approaches, AI ethics, pedagogical incorporation, and professional growth, systematically bolstering these transversal competencies (Mouta et al., 2024). This progression empowers educators to cultivate shared epistemic agency through collective professional development, reinforcing ethical AIED practices within interdependent structural contexts (Mouta et al., 2024).

Conceptual Framework: The Enabled System

The Enabled system conceptualizes teacher education as a dynamic, AI-enhanced ecosystem that fosters collaborative reflection and dialogic knowledge creation, positioning technology as a catalyst for co-constructed professional agency within socially situated learning environments. This framework delineates ten developmental areas across micro, meso, and macro levels, driving up-to-date teacher professionalization by integrating AI literacy into curricula and professionalism conceptions to promote equitable AIED practices (Rütti-Joy et al., 2024).

At its core, the Enabled system positions generative AI as a synergistic mediator, enhancing content knowledge acquisition for pre-service teachers by efficiently synthesizing materials and delivering personalized learning support through real-time feedback and interactive engagement (Blonder et al., 2024; Nyaaba, 2024). This mediation aligns teacher professional vision with competency frameworks by supporting knowledge-based reasoning in AI-enhanced environments, thereby bridging cultural contexts in design processes (Tammets & Ley, 2023). By embedding ethical stewardship, the Enabled system empowers teacher educators to navigate AI-mediated landscapes as responsible agents, harmonizing technological integration with pedagogical and ethical imperatives at institutional levels. This harmonization manifests through research-teacher partnerships that combine teachers' pedagogical and content knowledge with AI-enhanced tool designs, modeling interactions within professional vision frameworks to advance adaptive teaching practices (Tammets & Ley, 2023). Such partnerships exemplify the AI-TPACK model's extension of Technological Pedagogical Content Knowledge, enabling educators to select AI tools that align content, pedagogy, and ethical awareness for transformative instructional design (Huynh et al., 2025).

Within this extended AI-TPACK paradigm, the Enabled system advocates for institutionalized teacher education structures that proactively intertwine AI literacy and ethical knowledge across individual, organizational, and societal scales through coherent, adaptable strategies (Rütti-Joy et al., 2024). This strategic coherence is operationalized through researcher-teacher partnerships that embed AIED solution design into professional learning cycles, promoting multifaceted competencies for professional vision development. These partnerships further leverage theory-informed dashboards to monitor student engagement and learning gaps, enabling instantaneous methodological adjustments that refine educators' predictive capabilities in AI-supported classrooms (Tammets & Ley, 2023). Consequently, these refined predictive capabilities underpin the Enabled system's emphasis on sustained teacher professional development, where AI-enhanced tools progressively deepen educators' insights into student problem-solving strategies and adaptive instructional responses.

Defining the Enabled System

The Enabled System defines teacher education as a dynamic, AI-enhanced ecosystem that cultivates collaborative reflection and dialogic knowledge creation. It positions technology as a catalyst for co-constructed professional agency within socially situated learning environments (Xerri, 2025). This framework delineates ten developmental areas across micro, meso, and macro levels, driving contemporary teacher professionalization by integrating AI literacy into curricula and professionalism, thereby promoting equitable AIED practices.

At its core, the Enabled System leverages generative AI as a synergistic mediator. This enhances content knowledge acquisition for pre-service teachers by efficiently synthesizing materials and providing personalized learning support through real-time feedback and interactive engagement. This mediation aligns teacher professional vision with competency frameworks by supporting knowledge-based reasoning in AI-enhanced environments, bridging cultural contexts in design processes (Tammets & Ley, 2023). By embedding ethical stewardship, the Enabled System empowers teacher educators to navigate AI-mediated landscapes as responsible agents, harmonizing technological integration with pedagogical and ethical imperatives at institutional levels.

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Continuous professional development initiatives reinforce this stewardship, cultivating profound AI literacy and ethical knowledge as intertwined pillars of teacher educator professionalism to ensure high-quality AI integration (Rütti-Joy et al., 2024). This necessitates teacher educators developing AI-specific technological, pedagogical, and ethical knowledge, addressing research gaps by creating scales grounded in extended TPACK frameworks for responsible AI tool integration (Çelik, 2022; Ren & Wu, 2025). This approach prioritizes authentic pedagogy and AI-specific characteristics in evaluating teacher educators' competencies (Eyal, 2025), establishing robust metrics for assessing AI-TPACK competencies and facilitating targeted professional development that models responsible AI integration for pre-service teachers (Eyal, 2025; Ren & Wu, 2025). This targeted development aligns with recommendations to embed AI courses across teacher training curricula, enhancing pre-service teachers' competencies in applying AI tools effectively (Han, 2025).

Enhancement of Content Knowledge

The Enabled System significantly enhances content knowledge in language teacher education by aligning AI tools with pedagogical imperatives through structured protocols that guide reflection on language choices and theory-practice connections. These protocols operationalize the core domains of the TPACK framework—content, pedagogy, and technology—by facilitating educators' integration of generative AI to interrogate linguistic nuances and bridge theoretical constructs with practical classroom enactments (Casierra et al., 2025). This integration is evident in micro-teaching simulations where pre-service teachers utilize NLP-driven feedback to refine diagnostic reasoning and articulate teaching judgments, thereby applying situated content knowledge in authentic language pedagogy contexts.

Furthermore, these simulations incorporate reflective journaling phases that prompt pre-service teachers to evaluate their linguistic performance against professional benchmarks, cultivating metacognitive strategies crucial for sustained content mastery in technology-enhanced language instruction (Wiboolyasarin, 2023). The development of these metacognitive strategies extends to mobile learning affordances, such as interactive video tools and voice recording platforms, which enable pre-service teachers to engage in asynchronous pronunciation practice and peer-mediated content analysis during practicum placements. These mobile learning affordances, in turn, synergize with generative AI-supported collaborative lesson planning to foster pre-service teachers' cognitive engagement and professional knowledge construction during STEM-focused practicum activities (Kılıçkaya & Kic-Drgas, 2025).

This cognitive engagement manifests in pre-service teachers' refined Pedagogical Content Knowledge levels, as evidenced by their structured interactions with Generative AI during lesson planning and iterative prompt engineering within training frameworks (Blonder et al., 2024). These refined PCK levels are further substantiated by structured observations during teaching phases, where peers and mentors assess GenAI's impact on lesson delivery and classroom dynamics, fostering critical thinking and iterative skill refinement (Kılıçkaya & Kic-Drgas, 2025). GenAI's capacity to act as a peer tutor underpins this iterative skill refinement, enabling pre-service teachers to self-direct TPACK development even amidst resource

constraints in teacher training programs. This self-directed TPACK development is bolstered by GenAI's role in personalizing initial teacher education programs through assessments of pre-service teachers' PCK derived from their interactions, leading to tailored instructional pathways that address individual pedagogical gaps in language teaching practicum.

These tailored instructional pathways converge with social cognitive theory by leveraging GenAI-mediated informal digital learning practices to mitigate technical difficulties in technology integration, thereby elevating pre-service teachers' commitment to English as a Foreign Language pedagogy (Guan et al., 2024). This heightened commitment is paralleled by GenAI's facilitation of personalized support in pre-service science teacher programs, where dialogue analysis uncovers PCK gaps to inform tailored lesson planning and confidence-building in classroom management pedagogies (Blonder et al., 2024). Such personalized support extends to EFL contexts by deploying GenAI as a conversational partner that simulates authentic language interactions, thereby enhancing pre-service teachers' oral proficiency and cultural responsiveness in diverse classroom settings (Guan et al., 2024).

Moreover, this enhancement of oral proficiency through GenAI-simulated interactions underpins pre-service teachers' development of a code of practice for ethical AI integration in lesson planning, derived from reflective discussions on its impacts during practicum teaching phases. This code of practice, informed by structured observations of GenAI-integrated lessons, emphasizes real-time data safeguarding and student engagement metrics to ensure ethical deployment across diverse practicum environments. Building upon this ethical foundation, GenAI serves as a peer tutor that outperforms human pre-service teachers in objective TPACK performance, thereby augmenting content knowledge integration within diverse practicum settings. This augmentation is evidenced by GenAI's capacity to deliver 24/7 self-directed support as a peer tutor within the Zone of Proximal Development, surpassing human counterparts in fostering objective TPACK proficiency for pre-service teachers.

Consequently, GenAI's superiority as a TPACK peer tutor fosters pre-service teachers' subjective experiences and psychological engagement, such as perceptions and attitudes toward AI-mediated interactions, thereby enriching the affective dimensions of content knowledge development in teacher education programs (Çelık et al., 2023). This affective enrichment aligns with GenAI's pivotal role in synthesizing content efficiently and supporting personalized learning experiences, reducing reliance on static materials and enabling pre-service teachers to supplement subject-specific content mastery in resource-constrained environments. This supplementation empowers pre-service teachers to engage in dialogue with GenAI during lesson planning, uncovering and refining their PCK through prompt engineering and critical evaluation of AI-generated feedback. This PCK refinement through GenAI dialogue during lesson planning aligns with empirical findings that generative AI significantly enhances pre-service teachers' access to diverse teaching resources and cultural contexts, thereby broadening their content knowledge horizons and addressing resource deficits in teacher education (Nyaaba et al., 2024). Consequently, these broadened horizons through GenAI interactions reveal pre-service teachers' PCK levels via interactive dialogues during lesson planning, enabling personalized adjustments to teacher preparation programs. These interactions provide insights into pre-service teachers' knowledge and skills, enabling personalized learning experiences and targeted program adjustments. Specifically, this approach leverages critical interpretation of knowledge components within GenAI dialogues to personalize pre-service science teachers' preparation programs, ultimately enhancing their readiness for future roles as educators (Blonder et al., 2024).

Perceived Usability and Effectiveness of the Enabled System

Pre-service teachers perceive the Enabled system as highly usable due to its seamless integration of GenAI as a learning buddy, which extends their pedagogical perspectives through access to diverse educational paradigms and real-time interactive feedback beyond

conventional resources. This perceived usability is corroborated by pre-service teachers' universally positive attitudes toward GenAI, transcending demographic differences and facilitating barrier-free integration into teacher preparation programs. This barrier-free integration is further evidenced by GenAI's structured support in refining lesson objectives and generating adaptable lesson plans that incorporate pedagogical best practices, thereby enhancing pre-service teachers' instructional efficacy during practicum phases (Nyaaba et al., 2024). This instructional efficacy is amplified by GenAI's structured dialogues that critically interpret pre-service teachers' pedagogical content knowledge, enabling personalized adjustments to science education preparation programs. Such personalized adjustments through GenAI dialogue analysis equip pre-service science teachers with enhanced pedagogical content knowledge, ultimately preparing them more effectively for their future roles as science educators (Blonder et al., 2024). This preparation extends to science lesson planning, where pre-service teachers leverage ChatGPT to integrate interactive activities that foster personalized learning and classroom management in large-scale settings (Lee & Zhai, 2024). This integration of ChatGPT into science lesson planning elicits balanced perspectives from pre-service teachers on its merits for teaching and learning, while highlighting the imperative for professional development programs to address integration challenges such as ethical deployment and technical impediments (Lee & Zhai, 2024).

Challenges and Limitations

Despite the affordances of generative AI, pre-service teachers face significant challenges fully utilizing its advanced functions in science lesson planning. Their plans often receive lower scores for maximizing GenAI's potential compared to traditional instructional strategies. These rubric scores underscore the necessity for targeted professional development initiatives that equip pre-service teachers with AI literacy to discern suitable GenAI content and mitigate over-dependence (Al-Ali & Miles, 2025; Lee & Zhai, 2024). Moreover, pre-service teachers frequently need to substantially revise GenAI-generated lesson components to achieve pedagogical coherence, conceptual rigor, and curriculum alignment, emphasizing the importance of teacher-led interventions during professional development (Choi, 2025).

To bridge the gap between self-reported competence and practical performance, GenAI employs a two-stage evaluation method. This involves recording and scrutinizing pre-service teachers' dialogues during science lesson planning for manifestations of Pedagogical Content Knowledge. This mechanism uncovers PCK deficiencies, providing reflective evidence for professional growth and tailored identity formation, particularly for second-career educators (Blonder et al., 2024).

Future research should prioritize longitudinal studies employing the Enabled System's GenAI dialogues to track PCK evolution across diverse pre-service teacher cohorts, informing scalable professional development frameworks for AI-integrated science education. These frameworks must also incorporate comparative analyses across institutional contexts to delineate contextual variables' mediating influences on GenAI efficacy (Kılıçkaya & Kic-Drgas, 2025). Furthermore, pre-service teachers express concerns regarding the accuracy and trustworthiness of GenAI outputs, necessitating targeted professional development to foster confidence in their integration.

Consequently, professional development must emphasize scaffolding interventions that train pre-service teachers to critically evaluate GenAI outputs as starting points, fostering responsible integration in science lesson planning. This responsible integration is supported by the imperative for teacher educators to deliver explicit training in generative AI, encompassing practical guidelines and ethical frameworks to cultivate effective classroom practices. By embedding these ethical frameworks within ongoing teacher education curricula, the Enabled System equips pre-service teachers with competencies to harness GenAI effectively, addressing persistent gaps in evaluating and developing their pedagogical content knowledge (Blonder et

al., 2024; Huynh et al., 2025). Embedding theory-driven noticing frameworks into the Enabled System's GenAI prompts operationalizes scalable support for pre-service teachers' reflective skills, balancing open-ended dialogue with reliable guidance to refine their classroom observation competencies (Bastian et al., 2025). This operationalization aligns with action research paradigms that systematically develop and assess interventions for practical problem-solving in teacher education, enhancing the Enabled System's capacity to foster sustained professional growth.

Discussion

The Enabled System's integration of Generative AI into teacher education exemplifies a paradigm shift towards hybrid human-AI professional development models. Here, structured dialogues amplify pre-service teachers' Pedagogical Content Knowledge and cultivate metacognitive awareness, crucial for lifelong pedagogical adaptation. This hybrid model transcends conventional professional development by leveraging GenAI's iterative feedback loops to simulate real-time classroom contingencies, empowering pre-service teachers to anticipate and adapt to dynamic instructional challenges in science education.

This simulation extends to ethical deliberation, where GenAI prompts pre-service teachers to navigate dilemmas such as algorithmic biases and data privacy in lesson design, instilling human-centered oversight critical for equitable science instruction (Kehoe, 2023). Such oversight is operationalized through curriculum modules that train pre-service teachers to evaluate GenAI-generated content for inclusivity and to cross-reference it with authoritative sources, ensuring unbiased lesson materials respectful of diverse backgrounds. This evaluative training fosters pre-service teachers' PCK by facilitating interactive GenAI dialogues that reveal deficiencies in content-pedagogy integration during science lesson planning, thereby enabling personalized professional development adjustments. Consequently, these adjustments harness GenAI's capacity for scalable, personalized support in teacher noticing skills, enabling pre-service teachers to process classroom situations through sustained reflective dialogues anytime and anywhere (Bastian et al., 2025).

The ubiquity of reflective support via the Enabled System aligns with Diffusion of Innovations principles, enabling proactive tailoring of instructional strategies to pre-service teachers' varying adoption stages of GenAI technologies in science education ("September 2024 Full Issue," 2024). By aligning professional development pacing with early adopters' enthusiasm and laggards' apprehensions, the Enabled System accelerates GenAI diffusion across pre-service teacher cohorts, fostering widespread adoption of AI-enhanced pedagogical practices in science education (Blonder et al., 2024; Cooper et al., 2025). Empirical explorations of pre-service teachers' perceptions further underscore the Enabled System's potential to address competencies and preparedness for AI-driven tools in inquiry-based science learning, thereby advancing ethical integration within teacher preparation paradigms (Cooper et al., 2025). This ethical integration is paramount given pre-service teachers' growing reliance on GenAI for reflective feedback, assessment strategies, and lesson preparation, despite its unofficial status in many programs, signaling an urgent need for formal incorporation into teacher education curricula.

Formal incorporation necessitates structured AI literacy training that emphasizes prompt engineering and evaluative judgment to equip pre-service teachers with the competencies required for responsible GenAI adoption in pedagogical practices (Bui et al., 2025). Such training provides pre-service teachers with the evaluative judgment to critically assess GenAI-generated annotations for accuracy, relevance, and pedagogical alignment, thereby enhancing their capacity for equitable science instruction. This evaluative capacity is amplified through GenAI-facilitated interactive dialogues that uncover pre-service science teachers' PCK during lesson planning, effectively bridging theoretical insights with practical application. These dialogues, by revealing nuanced gaps in pre-service teachers' understanding of content-

pedagogy integration, enable targeted program adjustments that foster personalized learning experiences in science education (Blonder et al., 2024).

Implications for Teacher Education Policy

Teacher education programs must integrate structured training on the ethical and pedagogical use of generative AI tools into practicum and coursework. This includes scenario-based learning to prepare pre-service teachers for real-world classroom challenges (Asghar et al., 2025). This policy shift requires empirical studies to outline practical implementation steps, such as prompt engineering training and critical evaluation of GenAI outputs for biases, to maximize benefits within teacher education curricula (Nyaaba, 2024). Furthermore, operationalizing frameworks like TPACK through GenAI-driven scenarios in professional development ensures pre-service teachers integrate AI as a pedagogical resource in inquiry-based science instruction, aligning policy with predictive trends in AI education research (Blonder et al., 2024; Kesgin, 2025).

Policymakers should prioritize certification standards for AI literacy in teacher preparation, utilizing predictive modeling to anticipate generative AI adoption trajectories in science education curricula. These standards should emphasize mindset-oriented professional development that fosters reflective ethical reasoning alongside technical proficiency in GenAI tools, ensuring sustainable teacher competencies for responsible AI integration (Huynh et al., 2025). Institutions must also promote collaborations between pre-service teachers, experienced educators, and AI experts to drive innovation in AI education policy, guaranteeing equitable access to resources across socioeconomic and geographical divides (Ayanwale et al., 2024). Such collaborations can leverage ethical scenarios and narrative-based training to contextualize AIED technologies within ecosystemic factors, fostering teacher agency in addressing ethical dilemmas associated with generative AI deployment (Mouta et al., 2024).

To operationalize this agency, national policies should mandate ongoing professional development programs that equip in-service teachers with skills to craft effective prompts, evaluate AI outputs for relevance and bias, and foster ethical AI literacy encompassing data privacy and algorithmic implications (Ayanwale et al., 2024; Bura & Myakala, 2024; Karakaya et al., 2025). These programs should integrate predictive foresight from bibliometric analyses to anticipate evolving trajectories in AI adoption, guiding the formulation of adaptive certification standards that balance innovation with ethical governance in teacher education (Kesgin, 2025).

Recommendations for Practice

Teacher education programs should establish dedicated GenAI professional development modules that embed AI literacy, ethics training, and experiential learning opportunities to foster critical prompt engineering skills among pre-service educators (Blonder et al., 2024; Rütti-Joy et al., 2024; Walter, 2024). These modules should prioritize embedding AI-specific pedagogies into core curricula, providing pre-service teachers with practical experience in AI-supported tasks and structured prompt literacy development to ensure effective classroom application (Karakaya et al., 2025). Collaborative peer-review sessions within these modules can simulate real-time AI integration challenges, enabling pre-service teachers to refine prompt strategies through shared critique and iterative refinement (Huynh et al., 2025). Moreover, these sessions should incorporate real-time simulations of GenAI interactions in diverse classroom contexts to cultivate adaptive decision-making skills essential for ethical deployment (Huynh et al., 2025).

Institutions should further integrate interdisciplinary workshops that pair AI developers with teacher educators to co-design context-specific ethical guidelines (Mouta et al., 2023, 2024; Rütti-Joy et al., 2024), ensuring alignment with human-centric approaches and data sovereignty principles in AIED deployment ("Guidance for Generative AI in Education and Research," 2023; Rütti-Joy et al., 2024). This co-design process should extend to pilot implementations in

teacher education practicums, where pre-service educators test GenAI tools under supervised conditions to validate ethical guidelines against emergent classroom dynamics. Findings from these pilots can inform scalable frameworks for institutional support, expanding access to GenAI tools and integrating explainable GenAI with prompt engineering into continuous professional development programs (Nyaaba & Zhai, 2024). This integration enables teacher educators to address the unique complexities across teacher educators, candidates, and school-level implementations, tailoring AI training to varying backgrounds and grade spans for comprehensive professionalism (Estaiteyeh & McQuirter, 2024). Ultimately, these tailored AI training initiatives within the Enabled system cultivate future-ready educators equipped with equitable competencies to navigate evolving technological landscapes responsibly (Daher, 2025). By embedding longitudinal assessment mechanisms within these initiatives, teacher education programs can track the sustained development of AI competencies, ensuring alignment with evolving professional standards and learner-centered outcomes (Han, 2025). This longitudinal tracking, informed by comprehensive frameworks for AI competencies, positions teacher education programs to proactively address curriculum gaps in ethical AI implementation and pedagogical integration (Daher, 2025; Mahala & Chauhan, 2025).

Conclusion

In conclusion, the strategic integration of generative AI within teacher education frameworks, such as the Enabled system, promises transformative advancements in professional development by aligning ethical AI competencies with curriculum innovations like digital media literacy modules (Blonder et al., 2024; Estaiteyeh & McQuirter, 2024). This synergy enhances teacher agency in ethical AI deployment and equips educators to foster inclusive learning environments through transparent decision-making processes and periodic audits. Future research should prioritize longitudinal studies and cross-cultural evaluations to refine these AI-enabled professional development models, ensuring their scalability across diverse educational contexts while mitigating unintended barriers to pedagogical innovation (Karakaya et al., 2025; Mouta et al., 2024). Such empirical validations will be instrumental in benchmarking the Enabled system's efficacy against global benchmarks for AI-driven teacher agency, thereby informing scalable policy adaptations for equitable professional growth worldwide (Daher, 2025; Mouta et al., 2024).

By prioritizing these evidence-based refinements, teacher education programs can harness generative AI literacy within professional development to empower educators in guiding ethical GenAI use among students (Brandão et al., 2024). This commitment to ethical stewardship will ultimately elevate teacher education through the Enabled system, cultivating a legacy of responsible innovation that bridges technological advancement with humanistic educational values (Mouta et al., 2024). Institutions adopting the Enabled system must therefore commit to iterative ethical audits and interdisciplinary policy dialogues to sustain this balance, fostering resilient teacher education ecosystems responsive to AI's dynamic societal impacts. These resilient ecosystems will further benefit from empirical investigations into context-specific teacher needs, particularly in developing regions, to bridge persistent gaps in AI integration through action research and sophisticated statistical analyses. These action-oriented methodologies will empower teacher educators to co-develop adaptive training paradigms that prioritize transversal competencies, safeguarding professional agency amid AIED's ethical complexities.

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