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ENHANCING SCIENCE TEACHERS' TECHNOLOGICAL PEDAGOGICAL CONTENT KNOWLEDGE THROUGH AI-MEDIATED PERSONALIZED FEEDBACK: A CROSS-COUNTRY STUDY IN NIGERIA AND GHANA

Emmanuel Ikechukwu Nnamonu[1], Innocent Ezeorah Ezeaku[2], Pamela Amarachi Ndukwe-Ani[3]
1 Department of Biology, Federal College of Education, Eha-Amufu, Enugu State, Nigeria
2 Department of Agricultural Science Education, Federal College of Education, Eha-Amufu, Enugu State, Nigeria
3 Alvan Ikoku Federal University of Education, Owerri, Imo State
nnamonue@gmail.com; +234(0)8064855635

ABSTRACT
This review synthesizes evidence on the potential of AI-mediated personalized feedback to enhance SCIENCE TEACHERS' Technological Pedagogical Content Knowledge (TPACK) in Nigeria and Ghana. Drawing on recent studies of intelligent tutoring systems, generative AI, and adaptive feedback, it examines their contributions to teachers' content, pedagogical, and technological competencies through AI-TPACK and related theoretical frameworks. The review further analyzes contextual factors, including digital infrastructure, linguistic diversity, and ethical considerations, that shape AI adoption in West African education. Although innovations such as Kwame for Science, *educator-focused GPT platforms, and U-Lesson demonstrate considerable promise, empirical evidence remains limited. The review concludes that realizing AI's transformative potential requires rigorous, culturally responsive, comparative research and the co-development of localized, ethically grounded AI tools to inform scalable biology teacher education and policy in West Africa.*

Keywords: Technological Pedagogical Content Knowledge (TPACK), SCIENCE TEACHERS, Artificial Intelligence (AI), Personalized Feedback**,** Cross-Country Study

Introduction
The Technological Pedagogical Content Knowledge (TPACK) framework has long been held as central to preparing teachers to integrate technology effectively into their subject teaching. TPACK emphasizes that teachers need intersecting knowledge of technology, pedagogy, and content to design effective learning activities. As education systems adopt new technologies especially artificial intelligence (AI) researchers have begun to expand TPACK to include AI-specific competencies (Vijayatheepan, 2024, Yue et al., 2024). Yang et al. (2025) describe an AI-TPACK model that explicitly incorporates AI tools into the TPACK framework.

Similarly, Asamoah & Amarteifio, (2025) proposes a TPACKEA model, adding "Ethics" and "Accomplishment" dimensions to TPACK to foreground ethical use of technology and reflective practice. These extended models underline that modern teacher preparation must address AI literacy and responsible use of technology alongside traditional pedagogical and content

knowledge. In short, equipping SCIENCE TEACHERS for the 21st century requires updating TPACK to account for intelligent tools and their ethical implications.

A key way AI can support teacher development is through AI-mediated personalized feedback**.** The term refers to feedback and guidance delivered to teachers (or students) by AI-driven systems, tailored to the individual's performance. In practice, an AI-mediated feedback tool might analyze a teacher's lesson plan, classroom interaction, or student work, and then generate customized recommendations. For instance, a recent Stanford study used an AI tool ("M-Powering Teachers") that analyzed classroom dialogue transcripts and provided each instructor with specific feedback on their questioning and acknowledgement of students. The automated feedback led teachers to improve their use of "uptake" (responding to student ideas), which in turn increased student assignment completion and satisfaction. Such AI-powered feedback systems show that timely, data-driven guidance can enhance teachers' pedagogical skills without requiring an expert observer in every classroom. In the context of TPACK, personalized feedback tools can help teachers reflect on and grow their technological and pedagogical content knowledge for example, by suggesting how to incorporate a simulation or how to pose more effective questions in a lesson (Ayeni et al., 2024, Zhou & Peng, 2025).

In both Nigeria and Ghana, governments recognize the importance of digital skills for teachers, but significant infrastructure and capacity gaps remain. Nigeria's National Policy on Education (2013) officially calls for ICT training in teacher education, yet on-the-ground realities are uneven. Some urban schools have seen ICT upgrades, but many rural and semi-urban schools still lack reliable electricity, internet, and computers. A recent literature review of Nigerian in-service teachers found that while many teachers have basic digital skills, "significant deficiencies" exist in the advanced competencies needed for digital pedagogy. Major barriers include inadequate training and limited access to technology, especially in rural regions. Focused interventions such as comprehensive digital literacy programs, greater investment in educational technology, and integration of technology into teacher education curricula are urgently needed to build teachers' TPACK. In practice, this means Nigerian SCIENCE TEACHERS may not yet have had opportunities to learn how to use, say, data-logging software or AI tools in class, even though policy encourages it (Belo & Ajao, 2024).

Ghana faces parallel challenges. A survey of Ghana's Northern Region during the COVID-19 school closures found that while most schools had electricity and ICT labs for administrative use, classrooms themselves were frequently offline and poorly equipped. Teachers possessed content and pedagogical knowledge, but lacked technical ICT skills to deliver effective online learning. Likewise, studies of pre-service teachers report that trainee educators have strong theoretical understanding of digital concepts but "significant gaps exist in their practical training". Ghana's digital divide remains acute: students in low-income or rural communities still face serious barriers to accessing devices and connectivity. Despite supportive policies, many Ghanaian SCIENCE TEACHERS today may have limited experience with classroom technologies or AI tools, especially outside major cities (Yidana, 2018, Soma et al., 2021, Adomako et al., 2022).

Nigeria's internet penetration is low (around 40% of population) and even lower in remote areas, while Ghana's is higher but still uneven. These disparities mean that AI-empowered learning tools will reach some teachers and students far more easily than others, potentially widening existing inequalities. Language is another critical factor: Ghana is home to 70+ languages and Nigeria over 500, yet English dominates formal schooling. AI tools and feedback systems typically operate in English or a few major languages, which may limit their accessibility in diverse classrooms. Without localization, AI systems risk excluding non-English–speaking teachers or misinterpreting cultural contexts. Moreover, ethical issues are paramount. UNESCO's global guidance on AI in education emphasizes protecting user data and ensuring tools are age-appropriate and equitable. In Nigeria and Ghana, safeguards are only just being developed. For example, Ghana is collaborating with the UN to create local AI policies and ethical frameworks, highlighting the need for "enhanced AI literacy, infrastructure, and policy frameworks" in education. In short, any AI-mediated TPACK initiative must consider data privacy, algorithmic bias, and cultural relevance issues underscored by UNESCO for all education systems UNESCO (2023).

Several pioneering AI-driven educational tools illustrate the region's potential. One notable case is Kwame for Science**, a** bilingual (English/French) question-answering app developed by Ghanaian researchers. It uses a Sentence-BERT model to answer West African secondary students' Integrated Science (including biology) questions, drawing on past exam content. Kwame for Science returns explanatory paragraphs and related exam questions with confidence scores, and it is reportedly the first such AI tutor for science deployed in West Africa. Kwame AI Inc., the Ghanaian company behind this, has likewise created *Adesua*, an AI teaching assistant for science education, and *SuaCode*, an AI tutoring app for coding. Another example is *Brilla AI*, which competed in Ghana's national science and math quiz. These initiatives show local innovators applying AI to support students and by extension teachers (e.g., teachers can use Kwame's answers to generate lesson explanations). However, such tools are still novel; most African schools do not yet have AI tutors or feedback systems in daily use. The literature on AI in African education is sparse, and almost all documented cases remain small-scale or pilot projects (Boateng et al., 2022).

The intersection of TPACK and AI in West African teacher education is underexplored. Existing studies in Ghana and Nigeria focus mainly on general ICT readiness or policy analysis, not on AI-mediated pedagogy. Few have examined how AI-powered feedback might specifically enhance science teachers' TPACK. For example, Ghana's new computing curriculum has prompted research on teacher preparedness, but nothing yet on AI feedback in biology teaching. Likewise, Nigeria's education sector is only now grappling with AI (e.g., reports of AI-generated exam content), but there is dearth of literature to address AI tools for teacher professional development there. These gaps suggest an urgent need for research. Future studies should investigate how AI feedback systems (properly localized and ethically designed) can strengthen SCIENCE TEACHERS' technological-pedagogical content knowledge in West African classrooms. Such work would extend the global TPACK literature into the African context and inform policy on teacher training in an AI-rich world ((Birma et al., 2025, Uzodinma et al., 2025).

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Conceptualizing AI-Mediated Personalized Feedback Within the TPACK Framework

The Technological Pedagogical Content Knowledge (TPACK) framework remains one of the most widely adopted models for understanding teachers' effective integration of technology into teaching and learning. It posits that effective instruction results from the interaction among Content Knowledge (CK), Pedagogical Knowledge (PK)**,** and Technological Knowledge (TK), together with their intersecting domains Pedagogical Content Knowledge (PCK)**,** Technological Content Knowledge (TCK)**,** Technological Pedagogical Knowledge (TPK)**,** and the integrated TPACK construct. Rather than treating these domains as discrete competencies, TPACK emphasizes their dynamic interplay in supporting meaningful technology-enhanced instruction. Empirical evidence continues to affirm its relevance across educational contexts. For example, Datsa and Annin (2023) found that rural South African life science teachers demonstrated strong CK and PK but comparatively weak TK and TPK, highlighting the need to contextualize TPACK within local socio-economic and technological realities. Consequently, strengthening SCIENCE TEACHERS' competencies in Nigeria and Ghana requires simultaneous development of disciplinary, pedagogical, and technological knowledge supported by enabling institutional conditions (Datsa & Annin, 2023; Mekheimer, 2025).

Recognizing the limitations of the original framework in the era of artificial intelligence (AI), recent scholarship has proposed AI-enhanced extensions of TPACK. Ning et al. (2024) introduced the AI-TPACK framework, which incorporates AI-Technological Knowledge (AI-TK) alongside AI-related pedagogical and content intersections **(**AI-TCK, AI-TPK**,** and AI-TPACK**)**. Their factor-analytic validation demonstrated that teachers' competence in AI-supported instruction depends on the integration of technological, pedagogical, and disciplinary knowledge rather than isolated competencies. Similarly, Mekheimer (2025) proposed the Intelligent-TPACK framework, explicitly incorporating ethical knowledge to address concerns relating to algorithmic bias, transparency, accountability, and data privacy. Together, these extensions suggest that effective AI integration requires teachers to combine technological competence with ethical reasoning, critical evaluation of AI-generated outputs, and informed pedagogical decision-making (Datsa & Annin, 2023). A further advancement is the TPACKEA framework, which extends TPACK by incorporating Ethics (E) and Accomplishment (A) as essential dimensions of teacher competence. According to Asamoah and Amarteifio (2025), TPACKEA recognizes that responsible technology use, professional integrity, and teachers' sense of achievement significantly influence successful technology integration. Ethical competence ensures responsible AI use, while accomplishment reflects professional confidence, growth, and instructional effectiveness. By integrating these dimensions, TPACKEA broadens teacher competence beyond technical skills to encompass reflective practice, lifelong learning, and professional fulfillment. Evidence indicates that teachers who combine technological competence with ethical practice demonstrate higher instructional efficacy and improved student learning outcomes (Asamoah & Amarteifio, 2025).

Within these expanded frameworks, AI-mediated personalized feedback has the potential to strengthen every dimension of TPACK. AI systems can enhance Content Knowledge (CK) by

identifying misconceptions and conceptual gaps, Pedagogical Knowledge (PK) by recommending differentiated instructional strategies and formative assessment practices, and Technological Knowledge (TK) by improving teachers' competence in interpreting and applying AI-generated insights. AI-powered tutoring systems, intelligent virtual laboratories, conversational agents, and learning analytics can further strengthen Pedagogical Content Knowledge (PCK) and Technological Pedagogical Knowledge (TPK) by providing evidence-based feedback that informs instructional planning and classroom decision-making. Research also indicates that technological competence and pedagogical application of AI develop synergistically rather than independently, reinforcing the integrated nature of teacher knowledge envisioned by AI-TPACK (Datsa & Annin, 2023). Beyond the traditional TPACK domains, AI-mediated personalized feedback also engages the ethical and accomplishment dimensions proposed in contemporary frameworks. Teachers must critically evaluate issues relating to data privacy, fairness, transparency, and algorithmic bias when interpreting AI-generated recommendations, consistent with the ethical emphasis of Intelligent-TPACK (Mekheimer, 2025). At the same time, personalized AI feedback can strengthen teachers' professional confidence by validating effective instructional practices, identifying areas for improvement, and supporting continuous professional growth. Evidence from AI-supported educational interventions suggests that intelligent tutoring systems can improve student outcomes while enhancing teachers' perceptions of instructional effectiveness and professional accomplishment. However, inadequate training, weak institutional support, and poorly designed AI systems may undermine these benefits. Consequently, AI-mediated feedback should be implemented within robust ethical frameworks that promote responsible AI use alongside sustained professional development (Shittu et al., 2024; Xiao et al., 2025).

AI-mediated personalized feedback necessitates an expanded conception of TPACK in which AI serves as an intelligent instructional partner supporting continuous, data-driven, and reflective teaching. Effective AI integration depends not only on technological proficiency but also on ethical competence, professional judgment, and reflective practice. For SCIENCE TEACHERS in Nigeria and Ghana, this underscores the need for professional development programmes that integrate AI literacy with disciplinary expertise, pedagogical competence, and ethical awareness. Accordingly, the expanded TPACK–AI–Ethics–Accomplishment perspective provides a robust theoretical foundation for examining how AI-mediated personalized feedback can strengthen SCIENCE TEACHERS' professional competence in the proposed cross-country study involving Nigeria and Ghana (Eyal, 2025; Oved & Alt, 2025).

Mapping AI-Enhanced Feedback Models in Biology Education

Recent advances in artificial intelligence (AI) have accelerated the development of AI-enhanced feedback systems that support personalized learning, formative assessment, and teacher professional development. While much of the literature has focused on student learning outcomes, emerging evidence indicates that AI also has considerable potential to strengthen teachers' pedagogical competence, instructional decision-making, and technology integration. Within Africa, these developments have increasingly emphasized culturally responsive AI applications tailored to local educational contexts (Boateng et al., 2022; Boateng et al., 2023).

A notable example is Kwame for Science, a Sentence-BERT–based AI teaching assistant designed for Integrated Science education in West Africa. Developed for resource-constrained environments, the system provides scaffolder question-and-answer support using culturally relevant content. Its initial deployment across 11 countries achieved a top-three response accuracy of approximately 87.5%, while a subsequent implementation involving 750 users across 32 countries maintained comparable performance and demonstrated the system's scalability and usability (Boateng et al., 2022; Boateng et al., 2023). These findings underscore the feasibility of localized AI-powered instructional support within diverse African educational settings. Another significant innovation is Ghana's 21st Century Teacher Educator GPT, a generative AI platform developed to support pre-service teacher education. Built on Retrieval-Augmented Generation (RAG) architecture, the platform integrates Ghana's teacher education curriculum and supports multiple indigenous languages, including Twi, Dagaare, and Mampruli. Its culturally responsive design and emphasis on minimizing algorithmic bias exemplify the "glocalization" of AI by adapting global technologies to local pedagogical, linguistic, and cultural contexts (Nyaaba, 2025).

Evidence from Nigeria further demonstrates the growing relevance of intelligent tutoring systems (ITS) in biology education. Studies involving university biology lecturers reported moderate adoption of platforms such as BioTutor**,** ALEKS, and Smart Sparrow, with the latter two identified as the most accessible and useful for instructional purposes. However, inadequate infrastructure, limited institutional support, and insufficient professional training continue to constrain effective implementation, highlighting the need for sustained investment in digital capacity and teacher development (Anyanwu et al., 2025; Nnanna-Ohuonu, 2025). The growing role of generative AI in teacher education is further illustrated by a survey of 167 Ghanaian pre-service teachers, who reported using AI applications as learning companions and instructional assistants for lesson planning and resource development. Although respondents expressed confidence in AI's pedagogical value, they also identified concerns regarding the accuracy and reliability of AI-generated content, reinforcing the importance of developing teachers' critical AI literacy alongside technical competence (Nyaaba et al., 2024).

Collectively, these initiatives demonstrate the expanding potential of AI-enhanced feedback for biology education while highlighting several common implementation priorities, including cultural localization, teacher capacity building, adequate technological infrastructure, and ethical AI deployment (Onyebuchi et al., 2023). Nevertheless, existing research remains predominantly learner-centred, with relatively little attention devoted to AI-mediated feedback systems designed specifically to enhance teachers' pedagogical competence and Technological Pedagogical Content Knowledge (TPACK). Moreover, the available African studies remain largely exploratory and provide limited evidence regarding the long-term effects of AI-enhanced feedback on SCIENCE TEACHERS' instructional practice and professional knowledge (Abe & Kasumu, 2025).

Nyaaba (2025) observed that although localized innovations such as Kwame for Science and the 21st Century Teacher Educator GPT demonstrate the feasibility of culturally responsive AI applications, empirical evidence regarding their influence on teachers' professional knowledge,

instructional decision-making, and reflective practice remains limited. Addressing these gaps is particularly important for biology education, where effective teaching depends on the integration of disciplinary expertise, inquiry-based pedagogy, and educational technology. Consequently, the present cross-country study seeks to map AI-enhanced feedback models in biology education and examine their contribution to the development of SCIENCE TEACHERS' TPACK in Nigeria and Ghana.

Evaluating Effects on TPACK Domains: Insights from Existing Literature

Emerging evidence suggests that AI-mediated personalized feedback can significantly enhance teachers' Technological Pedagogical Content Knowledge (TPACK) by strengthening both its core and integrated domains. Although much of the literature has focused on student outcomes, growing research indicates that AI-supported instructional systems improve teachers' disciplinary knowledge, pedagogical decision-making, technological competence, and overall instructional effectiveness (Armin et al., 2024; Arifuddin et al., 2025).

Regarding Content Knowledge (CK), AI-enhanced feedback supports teachers by identifying misconceptions, providing immediate explanations, and facilitating evidence-based refinement of subject knowledge. For example, teachers using Kwame for Science reported that AI-generated explanations improved lesson content and conceptual understanding, demonstrating the platform's value as a continuous professional learning resource (Boateng et al., 2022). Similarly, AI-mediated feedback strengthens Pedagogical Knowledge (PK) by supporting lesson planning, formative assessment, and reflective teaching. Lee and Perret (2022) found that AI-focused professional development improved teachers' use of formative assessment and AI-informed instructional strategies, while Ghana's 21st Century Teacher Educator GPT supports pedagogical planning through curriculum-aligned lesson structures and assessment prompts (Nyaaba, 2025).

Evidence also indicates substantial gains in Technological Knowledge (TK) through sustained engagement with AI-supported instructional tools. Nigerian studies involving biology lecturers using platforms such as ALEKS and Smart Sparrow reported improved technological confidence and self-efficacy, although inadequate infrastructure and institutional support continued to limit effective implementation (Asiyanbola et al., 2025). Beyond individual knowledge domains, AI-mediated feedback appears particularly valuable in strengthening the integrated dimensions of Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK)**,** and Pedagogical Content Knowledge (PCK). For instance, AI-supported virtual laboratories in South Africa enhanced teachers' ability to integrate technology with inquiry-based pedagogy and science content, resulting in measurable improvements in TPK and PCK (Aumann et al., 2024). Likewise, the AI-TPACK framework empirically demonstrates that technological and pedagogical competencies develop synergistically within AI-supported teaching environments (Ning et al., 2024; Agadagba & Ekwevugbe, 2025; Ajibike, 2025).

Despite these advances, evidence from Africa consistently reveals that teachers possess stronger CK and PK than TK, TPK, and TCK. Ghanaian teachers, for example, demonstrated comparatively

lower technology-related competencies despite strong disciplinary and pedagogical knowledge (Mensah et al., 2022), while Nigerian SCIENCE TEACHERS similarly reported limited capacity to integrate intelligent technologies because of inadequate exposure and professional training (Elvianasti et al., 2023). These findings underscore technology integration as a persistent challenge within African science education. Methodologically, recent studies have begun adapting validated TPACK instruments to evaluate AI-related competencies. Notably, Nyaaba (2025) combined standardized TPACK measures with qualitative reflections to examine AI-supported teacher development, providing one of the earliest African attempts to assess AI-mediated TPACK comprehensively.

The literature indicates that AI-mediated personalized feedback can enhance CK, PK, TK, and the integrated domains of TPK, TCK, and PCK. However, teacher-centred empirical studies remain scarce within African biology education, and implementation continues to be constrained by infrastructural limitations and inadequate professional development. Consequently, rigorous, context-sensitive investigations are needed to determine how AI-mediated feedback influences SCIENCE TEACHERS' TPACK in Nigeria and Ghana using validated assessment instruments and theoretically grounded intervention designs (Armin et al., 2024; Arifuddin et al., 2025).

Contextual Factors: Digital Infrastructure, Cultural Relevance, and Ethical Considerations
The effectiveness of AI-mediated personalized feedback in biology education depends not only on technological capability but also on contextual factors such as digital infrastructure, cultural relevance, ethical governance, and socioeconomic conditions. In Nigeria and Ghana, these factors significantly influence teachers' access to and effective use of AI-supported professional development (Sarfo et al., 2024).

Digital infrastructure remains a major constraint. AI-supported feedback requires reliable internet connectivity, electricity, digital devices, and technical support, yet access remains uneven across both countries. In Nigeria, broadband penetration reached 41.6% in 2022, although only about 12% of the population had reliable and affordable broadband, with rural communities facing persistent shortages of electricity and digital infrastructure. Ghana has expanded connectivity through initiatives such as the Ghana Investment Fund for Electronic Communications (GIFEC), but disparities persist, with internet access reaching approximately 63% of urban households compared with only 19% of rural households. Consequently, inadequate infrastructure continues to limit teachers' participation in AI-supported teaching and professional learning (Sarfo et al., 2024).

Cultural and linguistic diversity further shapes AI adoption. Although English is the official language of instruction, Nigeria and Ghana are multilingual societies with over 500 and 70 indigenous languages, respectively. AI systems designed exclusively for English-language users risk limiting accessibility and pedagogical relevance. Ghana's 21st Century Teacher Educator GPT addresses this challenge by incorporating indigenous languages such as Twi, Dagaare, and Mampruli alongside culturally contextualized instructional prompts, demonstrating the value of

localized AI design. Comparable large-scale initiatives remain limited in Nigeria, highlighting the need for culturally responsive AI systems that reflect local educational contexts (Nyaaba, 2025; Ohanma et al., 2025).

Ethical governance is equally critical. AI systems may perpetuate algorithmic bias, compromise data privacy, or generate recommendations that inadequately reflect African educational realities if developed from non-African datasets. Although international organizations advocate inclusive and transparent AI, comprehensive frameworks for educational AI governance, data protection, and algorithmic accountability are still evolving in both Nigeria and Ghana despite emerging national AI initiatives (Pasipamire & Muroyiwa, 2024). Embedding ethical principles into AI-mediated feedback is therefore essential to ensure fairness, accountability, and responsible professional practice.

The digital divide further compounds these challenges. In Nigeria, only about 5.7% of public primary schools possess functional computer facilities, while rural communities continue to experience limited electricity access. Similar urban-rural disparities persist in Ghana despite continued investment in digital infrastructure. Although interventions such as solar-powered smart schools and offline learning platforms offer promising alternatives, their high implementation costs constrain large-scale deployment without sustained government commitment and public-private partnerships (Nwegbu et al., 2011).

The successful implementation of AI-mediated personalized feedback requires more than technological innovation. Sustainable adoption depends on investments in digital infrastructure, culturally responsive and multilingual AI systems, robust ethical governance, and targeted support for underserved communities. Addressing these interconnected contextual factors is essential for ensuring that AI effectively strengthens SCIENCE TEACHERS' professional competence and promotes equitable educational development in Nigeria and Ghana (Ohanma et al., 2025; Pasipamire & Muroyiwa, 2024; Sarfo et al., 2024).

Gaps, Challenges, and Future Research Agenda for AI-Mediated TPACK in West African Biology Teacher Education

Despite growing interest in AI applications for education, important conceptual, methodological, and contextual gaps remain regarding the use of AI-mediated personalized feedback to enhance Technological Pedagogical Content Knowledge (TPACK) among SCIENCE TEACHERS in West Africa. Existing studies have largely evaluated system performance, usability, and student outcomes, with limited attention to teachers' professional knowledge development across TPACK domains. Although initiatives such as Kwame for Science and Ghana's 21st Century Teacher Educator GPT demonstrate the feasibility of culturally responsive AI, empirical evidence on their effects on SCIENCE TEACHERS' Content Knowledge (CK)**,** Pedagogical Content Knowledge (PCK), and other discipline-specific competencies remains scarce (Boateng et al., 2023; Nyaaba, 2025).

Methodologically, the literature is dominated by pilot studies, cross-sectional surveys, and self-report measures, providing limited evidence of causal effects or long-term professional development. Few studies employ experimental or longitudinal designs, and AI-specific TPACK assessment instruments remain inadequately adapted and psychometrically validated for African contexts. Although Nyaaba (2025) combined standardized TPACK measures with usability evaluations, the study was confined to Ghana and lacked cross-country comparison. Theoretically, emerging frameworks such as AI-TPACK and TPACKEA remain underutilized in African biology education despite their relevance for examining AI competence, ethics, and professional development.

Empirical validation of these models within teacher education programmes is limited, leaving a gap between theoretical advancement and classroom application (Ning et al., 2024; Asamoah, 2019). Future research should therefore prioritize the design and evaluation of AI-mediated feedback interventions for pre-service and in-service SCIENCE TEACHERS using robust quasi-experimental, experimental, or longitudinal designs. Cross-country comparative studies involving Nigeria and Ghana are equally important for examining how differences in digital infrastructure, educational policy, teacher preparation, language, and institutional capacity influence AI-supported professional development. AI applications should also be localized through indigenous languages, culturally relevant biology examples, and curriculum-aligned content, while future studies should examine ethical issues such as data privacy, algorithmic bias, transparency, and teacher autonomy in line with the TPACKEA framework (Bello, 2014).

Research should extend beyond short-term pilot projects to investigate the sustainability, scalability, and institutionalization of AI-mediated feedback within teacher education systems. Longitudinal evidence on implementation, policy support, organizational readiness, and cost-effectiveness is needed to ensure that AI-supported professional development becomes an enduring component of biology teacher education. Addressing these gaps through rigorous, theory-driven, and context-sensitive research will strengthen the evidence base for AI-enhanced TPACK and inform the development of scalable, ethical, and culturally responsive AI-mediated feedback systems for SCIENCE TEACHERS in Nigeria, Ghana, and the wider West African region (Boateng et al., 2023; Ning et al., 2024; Nyaaba, 2025).

Conclusion

The study has demonstrated that while AI-mediated personalized feedback holds substantial promise for enhancing SCIENCE TEACHERS' Technological Pedagogical Content Knowledge (TPACK) in Nigeria and Ghana, significant work remains. Extended frameworks like AI-TPACK and TPACKEA provide valuable conceptual lenses, and pioneering tools such as Kwame for Science and Educator GPT offer practical proof-points. However, research to date has overlooked biology-specific applications, relied on limited methodologies, and largely failed to validate AI-TPACK constructs in African contexts.

To realize AI's transformative potential, future efforts must rigorously assess AI feedback's impact on CK, PK, TK, and their intersections; co-design localized, ethically grounded AI tools; and implement cross-country comparative studies that account for infrastructural and cultural nuances. By embedding AI-mediated feedback within teacher education policy and practice supported by robust evidence and sustainable model's stakeholders can ensure that the next generation of Nigerian and Ghanaian SCIENCE TEACHERS is not only technologically proficient but pedagogically innovative and ethically informed. Such progress will be essential for preparing educators to meet the challenges and opportunities of 21st-century science teaching in Africa.

Recommendations

Further studies should consider adopting rigorous, culturally adapted evaluation designs implementing quasi-experimental or longitudinal research with psychometrically validated AI-TPACK instruments specifically adapted to Nigerian and Ghanaian contexts to establish causal links between AI-mediated feedback and growth across Content Knowledge**,** Pedagogical Knowledge and Technological Knowledge. Secondly, researchers should partner with biology educators in both Nigeria and Ghana to co-develop AI feedback platforms that embed local languages, culturally relevant biology examples, and TPACKEA ethics measures, then evaluate these tools comparatively to identify best practices and inform scalable, regionally appropriate teacher-education models.

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