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Identifying Empirical Needs For AI-Integrated Sustainable Teacher Education: A Convergent Mixed-Methods Study

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Abstract

The rapid advancement of Generative Artificial Intelligence (GenAI) offers transformative opportunities for teacher education while raising concerns about ethical use, professionalism, and sustainability. This study identified empirical needs for developing an AI-integrated sustainable teacher education framework using a convergent mixed-methods design within Design and Development Research (DDR). Data from literature and document analysis, focus groups, interviews, and surveys were integrated through methodological triangulation. Five key needs emerged: positioning AI as a human-centered cognitive partner, promoting ethical and evidence-based AI use, integrating AI Literacy and Sustainability Literacy, establishing pedagogical guidance for AI-supported learning, and strengthening teacher agency and responsible decision-making. These findings were translated into evidence-based design requirements, providing a foundation for developing responsible and sustainable AI-integrated teacher education.

Keyword: Artificial Intelligence Literacy; Sustainability Literacy; Teacher Education; and Generative Artificial Intelligence.

INTRODUCTION

The rapid advancement of Generative Artificial Intelligence (GenAI) has fundamentally transformed educational practices and redefined expectations of teacher professionalism. Unlike earlier educational technologies that primarily supported information access and digital content delivery, Generative AI functions as an intelligent cognitive partner capable of generating instructional materials, designing assessments, providing personalized feedback, and facilitating creative problem-solving. Consequently, teachers are increasingly expected not only

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to operate digital technologies but also to collaborate critically, ethically, and pedagogically with Artificial Intelligence (AI). This transformation has shifted the focus of teacher competence from conventional digital literacy toward Artificial Intelligence Literacy, which encompasses conceptual understanding, critical evaluation, ethical reasoning, and responsible educational decision-making (UNESCO, 2024; Holmes et al., 2022; Zhai et al., 2024).

Simultaneously, teacher education is expected to contribute to achieving the Sustainable Development Goals (SDGs) by preparing educators capable of addressing increasingly complex environmental, social, economic, and technological challenges. Education for Sustainable Development (ESD) emphasizes that teachers should develop systems thinking, futures thinking, values-based reasoning, collaboration, and action competence to enable learners to participate actively in sustainable societal transformation (UNESCO, 2020; European Commission, 2022). Consequently, technological innovation and sustainability should no longer be treated as separate educational agendas but as mutually reinforcing dimensions of teacher professional competence.

Recent international competency frameworks have attempted to respond to these educational transformations. The UNESCO AI Competency Framework for Teachers emphasizes Human-Centered AI, ethical AI utilization, and responsible professional practice. DigCompEdu provides guidance for teachers' digital competence development, while GreenComp and the OECD Learning Compass 2030 promote sustainability competencies and transformative learning. Despite their significant contributions, these frameworks primarily address AI competence and sustainability competence independently. AI-oriented frameworks pay limited attention to sustainability values, whereas sustainability-oriented frameworks rarely incorporate Generative AI as an integral pedagogical component. Consequently, an important conceptual gap remains regarding how AI Literacy and Sustainability Literacy should be integrated within teacher education.

This conceptual separation is increasingly reflected in educational practice. Teachers are rapidly adopting Generative AI to improve instructional efficiency, whereas sustainability education frequently remains confined to curriculum content rather than becoming a guiding pedagogical principle. As a result, AI is often implemented without systematic guidance regarding ethical reasoning, evidence-based evaluation, or sustainability considerations. Likewise, sustainability education is rarely supported by AI as a cognitive partner capable of facilitating systems thinking, problem analysis, and informed decision-making. These conditions suggest that technological advancement alone is insufficient to prepare teachers for future educational challenges without an accompanying sustainability-oriented perspective.

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Previous studies have predominantly examined AI Literacy, digital competence, or Sustainability Literacy as separate constructs. Although these studies provide valuable insights into teacher competencies, relatively little empirical evidence exists regarding stakeholders' needs for integrating these competencies into a coherent teacher education framework. Within the Design and Development Research (DDR) paradigm, comprehensive needs analysis constitutes the essential first stage for establishing empirically grounded design requirements prior to framework development. However, studies employing mixed-methods approaches to identify integrated competency requirements remain limited.

Therefore, this study aims to identify the empirical needs underlying the development of an AI-integrated sustainable teacher education framework through a mixed-methods approach. Specifically, the study seeks to synthesize evidence obtained from literature mapping, document analysis, focus group discussions, interviews, and questionnaire surveys to formulate design requirements for future framework development. The findings are expected to contribute theoretically by extending the integration of AI Literacy and Sustainability Literacy, methodologically by demonstrating the role of mixed-methods needs analysis within Design and Development Research, and practically by providing evidence-based guidance for future teacher education programs.

METHOD

2.1 Research Design

This study employed Design and Development Research (DDR) as the overarching methodological approach to establish an empirical foundation for developing an AI-integrated sustainable teacher education framework. DDR is a systematic research methodology designed to generate educational innovations through iterative phases comprising needs analysis, design, development, validation, implementation, and evaluation (Richey & Klein, 2007; Ellis & Levy, 2010). Unlike conventional educational research that primarily aims to explain or evaluate existing phenomena, DDR seeks to produce practical and theoretically grounded educational solutions that address authentic problems.

The present article reports only the first phase of the DDR process, namely the needs analysis phase. This phase aims to identify stakeholders' needs, analyze contextual problems, and formulate evidence-based design requirements that will guide the subsequent development of the framework. Conducting a comprehensive needs analysis before framework development is essential because educational innovations should emerge from empirical evidence rather than theoretical assumptions alone (Plomp, 2013).

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To achieve a holistic understanding of stakeholders' perspectives, this study adopted a convergent mixed-methods design (Creswell & Plano Clark, 2018). Qualitative and quantitative data were collected during the same research phase, analyzed independently, and subsequently integrated through methodological triangulation. This approach enabled the researchers to compare, validate, and synthesize findings from multiple data sources, thereby strengthening the credibility of the resulting design requirements.

2.2 Research Context

The study was conducted within the context of teacher education, involving both pre-service teacher preparation and professional development for in-service teachers. This context was selected because teacher education represents a strategic environment for preparing future educators capable of integrating Artificial Intelligence (AI) and sustainability principles into educational practice. Recent developments in Generative AI have created new opportunities for improving instructional planning, learning design, assessment, and feedback. Simultaneously, educational institutions are expected to prepare teachers who can contribute to sustainable development by integrating environmental, social, economic, and ethical perspectives into learning. These parallel developments highlight the necessity of investigating how AI Literacy and Sustainability Literacy can be integrated within teacher education.

2.3 Participants

Purposive sampling was employed to recruit participants who possessed direct experience relevant to teacher education, AI utilization, and sustainability-oriented learning (Merriam & Tisdell, 2016). The sampling strategy prioritized information-rich participants capable of providing comprehensive insights into the competencies required for future teacher education. Three stakeholder groups participated in this study: a) Teacher educators, who contributed perspectives on curriculum design, teacher preparation, and institutional policy; b) In-service teachers, who shared practical experiences regarding classroom implementation, AI utilization, and sustainability-oriented teaching practices; c) Pre-service teachers, who represented prospective educators currently developing professional competencies within teacher education programs. The inclusion of these three participant groups enabled the study to capture complementary perspectives across different stages of teacher professional development, thereby enhancing the comprehensiveness of the needs analysis.

2.4 Data Collection

Needs analysis was conducted using five complementary data sources to obtain comprehensive empirical evidence and strengthen methodological triangulation. Each data collection method addressed a distinct analytical objective while collectively contributing to the

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formulation of design requirements.

Table 1. Data Collection Methods and Analytical Purposes

Data Source	Purpose	Expected Output
Literature Mapping	Identify recent developments, research trends, and conceptual gaps	Research trends and research gaps
Document Analysis	Analyze international competency frameworks and policy documents	Competency mapping and conceptual synthesis
Focus Group Discussions	Explore collective perceptions regarding AI and sustainability integration	Pedagogical needs
Semi-structured Interviews	Investigate participants' experiences and expectations	User needs
Questionnaire Survey	Validate qualitative findings through broader participant responses	Quantitative confirmation

2.5 Data Analysis

Qualitative data obtained from literature mapping, document analysis, FGDs, and interviews were analyzed using reflexive thematic analysis following the six-phase procedure proposed by Braun and Clarke (2021): familiarization with the data, initial coding, theme generation, theme review, theme definition, and report production. This analytical approach enabled the identification of recurring themes representing participants' needs, implementation challenges, and expectations for future teacher education. Quantitative questionnaire data were analyzed using descriptive statistics, including frequencies, percentages, means, and standard deviations. Because the purpose of the quantitative component was to support needs

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identification rather than hypothesis testing, descriptive analysis was considered appropriate for summarizing participants' perceptions and confirming qualitative findings.

RESULTS AND DISCUSSION

3.1 Repositioning AI as a Human-Centered Cognitive Partner

The convergence of evidence across all data sources consistently demonstrated that the future role of Artificial Intelligence (AI) in teacher education should be understood as a cognitive partner rather than an autonomous instructional agent. Participants did not perceive Generative AI as a substitute for teachers' professional expertise; instead, they emphasized its potential to augment teachers' cognitive processes, instructional creativity, and pedagogical decision-making. This finding emerged consistently from literature mapping, document analysis, focus group discussions, interviews, and questionnaire responses, indicating that Human-Centered AI represents a fundamental requirement for future teacher education.

The literature mapping revealed a growing shift in educational research from technology-centered perspectives toward Human-Centered AI approaches. Recent studies argue that the educational value of Generative AI lies not in replacing teachers but in strengthening human intelligence through collaborative interaction, critical reasoning, and reflective practice (Holmes et al., 2022; UNESCO, 2024). Similarly, contemporary discussions on AI in education emphasize that teachers should retain responsibility for interpreting AI-generated outputs, making pedagogical judgments, and ensuring that instructional decisions remain aligned with educational goals and learners' needs.

This perspective was further reinforced through the analysis of international competency frameworks. The UNESCO AI Competency Framework for Teachers identifies Human-Centered AI as a foundational principle, emphasizing that AI systems should support teachers' professional agency, ethical responsibility, and informed decision-making rather than automate educational authority (UNESCO, 2024). However, the document analysis also revealed that while these frameworks provide valuable guidance on AI competencies, they offer limited direction regarding the integration of Human-Centered AI with sustainability-oriented teacher education.

Evidence from the focus group discussions confirmed these conceptual findings. Participants acknowledged that Generative AI had become increasingly useful for preparing lesson plans, generating instructional resources, designing assessments, and facilitating classroom innovation. Nevertheless, participants consistently rejected the notion that AI should determine instructional decisions. Instead, they emphasized that AI should function as an intellectual partner that broadens teachers' perspectives while leaving professional judgment

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entirely under human control.

The interview findings provided further insight into this perspective. In-service teachers described AI as a valuable assistant capable of increasing instructional efficiency; however, they expressed concerns regarding the reliability and contextual appropriateness of AI-generated information. Teacher educators similarly argued that future teachers must develop the ability to critically evaluate AI outputs rather than accept them uncritically. Pre-service teachers also viewed AI primarily as a learning companion that supports idea generation and academic productivity, while recognizing the importance of maintaining independent thinking and professional responsibility.

These qualitative findings were supported by the questionnaire results, which demonstrated strong agreement among participants that AI should enhance rather than replace teachers' professional roles. Respondents consistently emphasized the importance of maintaining teacher autonomy, critical reflection, and pedagogical responsibility when integrating AI into educational practice. This convergence between qualitative and quantitative findings strengthens the credibility of Human-Centered AI as a central empirical need identified in this study.

Collectively, these findings indicate that the future integration of AI within teacher education should move beyond technological adoption toward collaborative human-AI interaction. Rather than positioning AI as an autonomous educational actor, participants consistently envisioned AI as a cognitive partner that expands teachers' professional capabilities while preserving human responsibility for educational, ethical, and pedagogical decisions. Accordingly, the first empirical need identified in this study is the establishment of Human-Centered AI Partnership as the philosophical foundation for developing an AI-integrated sustainable teacher education framework.

3.2 Advancing Ethical and Evidence-Based AI Utilization

Beyond positioning AI as a cognitive partner, the convergence of findings revealed a second fundamental empirical need: the integration of ethical and evidence-based AI utilization within teacher education. Across all data sources, participants consistently emphasized that the educational value of Generative AI depends not only on its technological capabilities but also on teachers' ability to critically evaluate AI-generated information, recognize its limitations, and make informed pedagogical decisions. Consequently, AI competence should be understood as an ethical professional competency rather than merely a technical skill.

The literature mapping demonstrated that recent studies increasingly highlight ethical AI

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literacy as an essential dimension of teacher competence. While Generative AI offers unprecedented opportunities for instructional innovation, concerns regarding hallucinated information, algorithmic bias, data privacy, copyright, and academic integrity have become central issues in educational research (Holmes et al., 2022; UNESCO, 2024; Zhai et al., 2024). These studies consistently argue that teachers should not become passive consumers of AI-generated content but should develop the capacity to verify information, evaluate evidence, and exercise professional judgment before integrating AI outputs into teaching and learning.

The document analysis reinforced these findings. International frameworks, particularly the UNESCO AI Competency Framework for Teachers, emphasize responsible AI use, transparency, accountability, and human oversight as fundamental principles for educational practice (UNESCO, 2024). Similarly, digital competence frameworks acknowledge that teachers should critically evaluate digital resources rather than rely on technological outputs uncritically. Nevertheless, the analysis indicated that these frameworks provide limited pedagogical guidance regarding how ethical AI decision-making should be cultivated within teacher education programs.

Evidence from the focus group discussions further illustrated this concern. Participants acknowledged that AI-generated instructional materials could substantially reduce preparation time and improve lesson planning. However, they simultaneously expressed reservations regarding the factual accuracy, contextual relevance, and educational appropriateness of AI-generated responses. Participants repeatedly emphasized that teachers must verify AI outputs using reliable academic and professional sources before applying them in classroom practice.

Interview findings deepened this understanding. Teacher educators argued that AI should support professional reasoning rather than replace reflective educational judgment. Several participants highlighted the importance of cultivating habits of source verification, critical questioning, and evidence-based instructional planning among future teachers. In-service teachers similarly reported that although AI frequently produced useful instructional ideas, these ideas often required substantial modification to align with curriculum objectives, learner characteristics, and classroom contexts. Pre-service teachers also recognized that excessive dependence on AI could reduce opportunities to develop independent critical thinking if not accompanied by appropriate ethical guidance.

The questionnaire results confirmed these qualitative findings. Most respondents strongly agreed that future teacher education should explicitly include competencies related to verifying AI-generated information, evaluating source credibility, recognizing algorithmic limitations, and applying ethical principles when utilizing AI in educational contexts. Participants

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also agreed that teachers should remain fully responsible for instructional decisions regardless of the recommendations generated by AI systems.

Taken together, these findings demonstrate that effective AI integration requires more than technological proficiency. Teachers must develop the capacity to evaluate, interpret, and responsibly apply AI-generated information within authentic educational settings. Therefore, the second empirical need identified in this study is the establishment of ethical and evidence-based AI utilization as a core component of future teacher education. This need highlights that responsible AI integration depends on strengthening teachers' critical judgment, professional ethics, and evidence-informed decision-making rather than simply expanding technological skills.

3.3 Integrating AI Literacy and Sustainability Literacy

One of the most significant findings emerging from the convergence of all data sources is the need to integrate Artificial Intelligence (AI) Literacy and Sustainability Literacy into a unified competency framework for teacher education. Rather than viewing these competencies as independent educational domains, participants consistently perceived them as complementary capacities that jointly enable teachers to respond to increasingly complex educational, technological, and societal challenges. This finding represents a critical shift from existing competency models, which generally position AI competence and sustainability competence as separate areas of professional development.

The literature mapping demonstrated that research concerning AI Literacy has expanded rapidly following the emergence of Generative Artificial Intelligence. Contemporary studies increasingly emphasize teachers' abilities to understand AI concepts, critically evaluate AI-generated information, collaborate effectively with intelligent systems, and utilize AI responsibly within educational contexts (Holmes et al., 2022; Zhai et al., 2024). In parallel, studies on Sustainability Literacy continue to stress systems thinking, anticipatory competence, normative reasoning, collaboration, and action competence as essential capabilities for achieving the Sustainable Development Goals (UNESCO, 2020; European Commission, 2022). Although both research streams address competencies required for future education, the literature review revealed that they have largely evolved independently, resulting in limited conceptual integration between technological innovation and sustainability-oriented education.

Document analysis confirmed this conceptual separation. Frameworks such as the UNESCO AI Competency Framework for Teachers primarily focus on AI knowledge, ethical AI utilization, professional engagement, and human-centered educational practice. Conversely,

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GreenComp emphasizes sustainability values, futures thinking, environmental responsibility, and collective action, while DigCompEdu concentrates on teachers' digital competence for effective technology integration. Despite their respective strengths, none of these frameworks explicitly provides guidance on how AI Literacy and Sustainability Literacy should be developed simultaneously as interconnected professional competencies within teacher education. This gap indicates the need for a more integrated conceptual foundation capable of preparing teachers for both digital transformation and sustainable societal development.

The focus group discussions provided further evidence supporting this integration. Participants consistently argued that technological competence alone is insufficient for preparing future teachers. While AI can substantially improve instructional efficiency, participants emphasized that educational innovation should also contribute to broader societal goals, including environmental sustainability, social responsibility, equity, and ethical citizenship. Several participants noted that AI-supported learning activities should not merely improve classroom productivity but should also encourage learners to analyze authentic sustainability issues, evaluate alternative solutions, and make responsible decisions aligned with the Sustainable Development Goals.

Interview findings reinforced this perspective. Teacher educators highlighted that AI should become a pedagogical resource for facilitating inquiry, critical reflection, collaborative learning, and systems thinking rather than merely functioning as an information generator. In-service teachers similarly explained that AI-assisted learning activities become significantly more meaningful when connected to authentic community problems related to environmental conservation, climate change, social justice, or sustainable development. Pre-service teachers also expressed the need for learning experiences that simultaneously develop technological competence and social responsibility, arguing that future teachers should be capable of integrating AI into meaningful learning rather than using technology solely for instructional efficiency.

The questionnaire findings further strengthened these qualitative insights. Respondents expressed strong agreement that teacher education programs should integrate AI Literacy and Sustainability Literacy rather than offering them as separate learning components. Participants consistently perceived sustainability as an essential context within which AI should be applied responsibly, while AI was viewed as a powerful cognitive tool capable of supporting sustainability-oriented learning through information analysis, problem-solving, scenario exploration, and collaborative knowledge construction.

The convergence of evidence across all data sources suggests that AI Literacy and

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Sustainability Literacy represent mutually reinforcing competencies. AI Literacy primarily equips teachers with the knowledge and skills required to collaborate effectively with intelligent technologies, whereas Sustainability Literacy provides the ethical orientation, systems perspective, and societal purpose necessary for responsible educational innovation. AI therefore answers the question of how technology can be utilized, while Sustainability Literacy clarifies why technology should be utilized and toward what educational goals. This complementary relationship indicates that neither competency is sufficient in isolation for preparing teachers to educate learners in an increasingly interconnected and technology-driven world.

From the perspective of Design and Development Research, this integrated competency perspective constitutes one of the most important empirical needs identified in the present study. The findings indicate that future teacher education should no longer organize AI competence and sustainability competence into separate curricular domains. Instead, both competencies should be designed as interconnected learning outcomes that collectively support responsible, ethical, and transformative educational practice.

Accordingly, the third empirical need identified in this study is the integration of AI Literacy and Sustainability Literacy as the conceptual core of an AI-integrated sustainable teacher education framework. This empirical need provides the conceptual bridge between technological innovation and Education for Sustainable Development, establishing the primary foundation for the framework that will be developed in the subsequent phase of the Design and Development Research process.

3.4 Establishing Pedagogical Guidance for AI-Supported Learning

While the integration of AI Literacy and Sustainability Literacy establishes the competency foundation for future teacher education, the convergence of empirical findings further indicates that these competencies require explicit pedagogical guidance to be translated into meaningful classroom practice. Across all data sources, participants consistently emphasized that possessing technological competence alone does not guarantee effective educational implementation. Instead, teachers require structured pedagogical approaches that enable them to integrate Generative Artificial Intelligence (GenAI) into learning while maintaining educational quality, ethical responsibility, and sustainability-oriented objectives.

The literature mapping demonstrated that recent research increasingly recognizes the importance of pedagogical rather than technological integration of AI. Although numerous studies have explored AI applications for lesson planning, assessment, adaptive learning, and feedback generation, fewer studies provide systematic guidance regarding how teachers should

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design AI-supported learning experiences that promote critical thinking, collaboration, creativity, and sustainability-oriented problem solving (Holmes et al., 2022; Zhai et al., 2024). Existing studies therefore suggest that pedagogical competence remains one of the most significant challenges in implementing AI within educational settings.

Document analysis further confirmed this observation. International competency frameworks acknowledge teachers' responsibility for selecting, adapting, and evaluating digital technologies within learning environments. However, these frameworks generally describe expected competencies without providing comprehensive pedagogical processes that explain how AI should be integrated into authentic teaching practice. Consequently, teachers often receive competency standards but relatively limited instructional guidance for translating these standards into classroom implementation.

Evidence from the focus group discussions revealed that participants frequently experienced uncertainty when attempting to integrate AI into instructional activities. Although teachers recognized the potential of AI for generating learning materials, designing assessments, and facilitating inquiry-based learning, they expressed the need for structured pedagogical guidance that could help determine when AI should be used, how AI-generated outputs should be evaluated, and how students should interact responsibly with AI during learning activities. Participants repeatedly emphasized that pedagogical decisions should continue to be driven by instructional objectives rather than technological capabilities.

Interview findings reinforced these concerns. Teacher educators highlighted that future teachers require practical learning models demonstrating how AI can support student inquiry, collaborative learning, reflective thinking, and authentic problem solving related to sustainability issues. In-service teachers similarly reported that successful AI integration depends on teachers' ability to design meaningful learning experiences rather than simply introducing AI tools into classroom activities. Pre-service teachers also expressed a strong preference for teacher education programs that provide opportunities to practice designing AI-supported lessons, evaluate AI-generated resources, and reflect upon the pedagogical implications of AI-assisted instruction.

Quantitative findings obtained from the questionnaire supported these qualitative perspectives. Participants consistently agreed that teacher education should include practical guidance for lesson planning, instructional implementation, assessment, classroom facilitation, and reflective evaluation involving AI-supported learning. Respondents also emphasized that pedagogical guidance should explicitly connect AI utilization with sustainability-related learning objectives rather than treating AI as a stand-alone technological resource.

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The convergence of these findings suggests that the effectiveness of AI integration depends less on technological sophistication than on the quality of pedagogical design. AI should therefore function as a pedagogical resource embedded within meaningful learning experiences that promote inquiry, critical reflection, collaboration, ethical reasoning, and sustainability-oriented action. This perspective aligns with contemporary constructivist approaches, which position technology as a tool for supporting knowledge construction rather than directing learning itself.

From the perspective of Design and Development Research, these findings indicate that future framework development should extend beyond competency identification to include explicit pedagogical guidance that assists teachers in operationalizing AI-supported learning. Such guidance is essential for ensuring that AI Literacy and Sustainability Literacy are translated into observable teaching practices rather than remaining abstract competency statements.

Accordingly, the fourth empirical need identified in this study is the establishment of pedagogical guidance for AI-supported learning. This empirical need emphasizes that future teacher education should provide structured instructional processes through which teachers can integrate Artificial Intelligence responsibly, ethically, and purposefully in support of meaningful and sustainability-oriented learning experiences.

3.5 Strengthening Teacher Agency in the Era of Generative AI

The final empirical need identified through the convergence of all data sources concerns the strengthening of teacher agency as the defining characteristic of future teacher professionalism. Although Generative Artificial Intelligence (GenAI) has significantly expanded teachers' access to knowledge, instructional resources, and decision-support systems, participants consistently emphasized that professional responsibility should remain firmly under human control. Across literature mapping, document analysis, focus group discussions, interviews, and questionnaire findings, teacher agency emerged as the central principle ensuring that AI functions as an educational partner rather than an autonomous decision-maker.

The literature mapping demonstrated an increasing international concern regarding the implications of AI for teacher autonomy and professional identity. Recent scholarship argues that while AI systems can automate routine instructional tasks and provide valuable recommendations, educational decision-making requires contextual understanding, ethical sensitivity, empathy, and professional judgment that cannot be delegated entirely to intelligent technologies (Holmes et al., 2022; UNESCO, 2024). Consequently, contemporary discussions increasingly position teachers as reflective professionals who critically evaluate AI-generated

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recommendations rather than simply implementing them.

Document analysis reinforced this perspective. International frameworks consistently emphasize that teachers remain accountable for instructional planning, assessment, classroom interaction, and learner development, even when AI technologies are integrated into educational practice. Human oversight, professional accountability, and ethical responsibility are repeatedly identified as essential principles of AI-supported education. Nevertheless, existing frameworks provide limited guidance regarding how teacher agency should be systematically strengthened throughout teacher education programs.

Evidence from the focus group discussions further highlighted this issue. Participants acknowledged that AI has become increasingly capable of generating lesson plans, learning materials, assessment items, and personalized instructional suggestions. However, they expressed concern that excessive dependence on AI could gradually weaken teachers' critical reflection, creativity, and instructional independence if AI outputs were accepted without professional evaluation. Participants therefore argued that future teachers should be prepared to engage in continuous reflection before adopting AI-generated recommendations within classroom practice.

Interview findings provided deeper insight into the meaning of teacher agency in the context of AI-supported education. Teacher educators consistently emphasized that professional expertise involves interpreting educational contexts, understanding learners' diverse needs, making ethical judgments, and adapting instructional strategies beyond what AI systems can accomplish. In-service teachers similarly reported that effective AI integration depends on their capacity to modify AI-generated content according to curriculum standards, classroom realities, and students' individual characteristics. Pre-service teachers also expressed the importance of developing confidence to question AI-generated information, defend professional decisions, and maintain independent pedagogical reasoning despite the increasing sophistication of AI technologies.

The questionnaire findings confirmed these qualitative perspectives. Respondents overwhelmingly agreed that teachers should retain full responsibility for educational decision-making regardless of AI recommendations. Participants also emphasized that future teacher education should explicitly cultivate reflective thinking, professional autonomy, ethical responsibility, and adaptive decision-making as essential competencies for the AI era. These findings demonstrate that technological advancement should reinforce rather than diminish teachers' professional authority.

The convergence of all evidence indicates that teacher agency represents the integrative

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dimension connecting Human-Centered AI, ethical AI utilization, integrated competencies, and pedagogical implementation. Human-centered educational innovation cannot be achieved unless teachers possess the confidence and professional capacity to make informed instructional decisions independently of technological recommendations. Consequently, AI-supported education should be conceptualized as a partnership in which AI contributes analytical capabilities while teachers retain authority over pedagogical, ethical, and contextual decisions.

From the perspective of Design and Development Research, strengthening teacher agency constitutes the final empirical foundation for framework development. Future teacher education should therefore be designed not merely to improve AI proficiency but also to cultivate reflective practitioners capable of balancing technological innovation with educational values, professional ethics, and learner-centered decision-making.

Accordingly, the fifth empirical need identified in this study is the strengthening of teacher agency and responsible professional decision-making. This empirical need establishes teachers as the central actors within AI-supported education, ensuring that technological advancement remains aligned with human values, educational purposes, and sustainable development.

3.6 Translating Empirical Needs into Design Requirements

The primary objective of the needs analysis phase within Design and Development Research (DDR) is not merely to identify stakeholders' needs but to transform empirical evidence into actionable design requirements that can guide the development of educational innovations (Richey & Klein, 2007; Plomp, 2013). Accordingly, the five empirical needs identified in this study were synthesized into a set of design requirements that will serve as the conceptual foundation for the subsequent development of the AI-integrated sustainable teacher education framework.

The translation process was conducted through an iterative synthesis of convergent findings obtained from literature mapping, document analysis, focus group discussions, interviews, and questionnaire surveys. Rather than representing isolated stakeholder expectations, each design requirement reflects consistent evidence emerging across multiple qualitative and quantitative data sources. Consequently, the resulting design requirements represent empirically grounded specifications for framework development rather than normative recommendations based solely on theoretical assumptions.

The synthesis revealed that each empirical need contributes a distinct design implication. The first empirical need, which repositions AI as a Human-Centered cognitive partner, indicates that the future framework should explicitly establish human authority over AI-supported

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educational processes. The second empirical need emphasizes that ethical reasoning and evidence-based judgment should become integral components of all AI-assisted learning activities. The third empirical need demonstrates that AI Literacy and Sustainability Literacy should not be developed independently but should function as interconnected professional competencies. The fourth empirical need indicates that competency development requires explicit pedagogical guidance that assists teachers in implementing AI-supported learning within authentic educational contexts. Finally, the fifth empirical need highlights the importance of strengthening teacher agency so that professional responsibility remains under human control despite increasing technological sophistication.

CONCLUSION

This study identified five interrelated needs for developing AI-integrated sustainable teacher education: Human-Centered AI, ethical and evidence-based AI use, integration of AI Literacy and Sustainability Literacy, pedagogical guidance, and strengthened teacher agency. These findings provide evidence-based design requirements for developing a responsible and sustainability-oriented teacher education framework. As this study represents only the needs analysis phase of Design and Development Research, future research should translate these requirements into design principles, develop and validate the proposed framework, and evaluate its effectiveness across diverse educational contexts.

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