PROCEEDINGS
International Conference on Education
Faculty of Tarbiyah | UIN Syekh Wasil Kediri
E-ISSN: 3025-6828

Volume 4, 2026

Preparing Future-Ready Teachers through Artificial Intelligence Literacy and Sustainability Competencies: A Systematic Literature Review

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Abstract:
The rapid integration of artificial intelligence (AI) into education, alongside global demands for sustainable development, has created an urgent need for teacher education programs to cultivate both AI literacy and sustainability competencies among future teachers. This study aims to systematically review and synthesize existing literature on the integration of AI literacy and sustainability competencies in teacher education. A systematic literature review guided by the PRISMA 2020 Statement was conducted across Scopus, Web of Science, ERIC, ScienceDirect, SpringerLink, Taylor and Francis, and Wiley Online Library, using a structured search string combining terms related to AI literacy, teacher education, and sustainability competencies. Twenty peer-reviewed studies published between 2018 and 2026 met the inclusion criteria and were analyzed through descriptive, thematic, and narrative synthesis. The results indicate a marked increase in AI literacy research following the widespread adoption of generative AI, a comparatively slower growth pattern in sustainability competency research, and very limited integration between the two domains within existing teacher education literature. The review proposes a conceptual framework in which AI literacy strengthens digital pedagogical competence, which in turn supports the development of sustainability competencies necessary for future-ready teachers. These findings offer theoretical grounding for bridging the UNESCO AI Competency Framework for Teachers with the GreenComp Framework and provide practical direction for curriculum design in teacher education institutions.

Keywords: Artificial Intelligence Literacy; Future-Ready Teachers; Sustainability Competencies; Systematic Literature Review; Teacher Education

Introduction

Artificial intelligence has increasingly reshaped the global landscape of education by altering how teaching, learning, and assessment are designed and delivered. Contemporary classrooms are gradually adopting generative and adaptive AI tools that support personalized instruction and administrative efficiency. Evidence from recent studies indicates that structured exposure to AI tools enhances the digital literacy and twenty-first century skills of preservice teachers (Bircan et al., 2025). Generative AI has also been found to strengthen collaborative problem solving and creativity performance among learners engaged in digital content creation (Wei et al., 2025). These developments indicate that AI competence has become an emerging core dimension of teacher preparation programs worldwide. Understanding how preservice teachers develop AI-related competencies has therefore become a pressing concern for teacher education institutions across different national contexts (Ayanwale et al., 2024).

Parallel to the growth of AI in education, global education agendas continue to emphasize the importance of sustainability competencies among future graduates. Education for Sustainable Development has been positioned as a central pillar for equipping learners to address environmental, social, and economic challenges. The GreenComp framework introduced by the European Commission outlines specific competencies that learners and educators are expected to internalize for sustainable practice. Empirical studies conducted in STEM contexts demonstrate that engineering design-based makerspace activities can foster systems thinking skills related to renewable energy understanding (Abdurrahman et al., 2023). Scoping evidence further suggests that teacher education programs remain unevenly prepared to embed sustainability competencies within their curricula (Sperling et al., 2024). This condition indicates that sustainability literacy, much like AI literacy, requires deliberate and systematic curricular attention rather than incidental exposure (Le et al., 2026).

Despite growing interest in both domains, teacher education research has generally treated AI literacy and sustainability competencies as separate lines of inquiry. Studies examining AI-based feedback systems in teacher preparation programs have concentrated primarily on diagnostic reasoning and pedagogical decision making (Bauer et al., 2025). Other investigations centered on reflective competence have relied on structured video annotation without extending their scope toward sustainability-oriented content (Rogge & Herzig, 2025). Similarly, work on digital pedagogy for inclusive education has emphasized teacher self-efficacy and wellbeing while leaving sustainability competencies largely unaddressed (Shi et al., 2025). This pattern of disciplinary separation limits the field's capacity to understand how AI literacy might actively support the cultivation of sustainability-oriented teaching practice. Consequently, a conceptual and empirical bridge between these two competency domains remains largely underdeveloped within the teacher education literature.

A closer examination of recent AI literacy research reveals that training programs tend to produce more consistent gains in foundational knowledge than in applied teaching competencies (Han, 2025). Mixed-methods evidence involving English language learner instruction similarly shows that preservice teachers' AI literacy fluctuates depending on contextual and instructional support (Kushki et al., 2026). Perceived competency studies among English as a foreign language teacher candidates further reveal persistent gaps between AI awareness and confident classroom integration (Karaduman, 2025). These findings imply that AI literacy alone, without deliberate pedagogical and contextual scaffolding, may not automatically translate into sustainability-oriented instructional practice. At the same time, no existing review has systematically synthesized how AI literacy interacts with sustainability competency

frameworks such as GreenComp within teacher education. This absence of integrative synthesis constitutes a substantial gap between the fragmented body of prior research and the integrated competency demands of future-ready teachers.

Addressing this gap requires a systematic and transparent method capable of consolidating dispersed evidence across multiple disciplinary boundaries. A systematic literature review guided by the PRISMA 2020 Statement offers a rigorous pathway for mapping publication trends, theoretical frameworks, and methodological patterns within this emerging field. Recent scoping work on teacher training in the age of AI demonstrates that such systematic approaches can reveal shifts in attitudes and competency development over time (Lademann et al., 2025). Meta-analytic evidence on AI literacy within preservice teacher preparation programs further confirms that systematic synthesis can clarify inconsistent findings across national and disciplinary contexts (Tunjera & Chigona, 2025). Professional development interventions grounded in instructional design frameworks have likewise shown measurable improvement in AI literacy skills among preservice teachers, reinforcing the value of synthesizing intervention-based evidence (Younis, 2024). Building on these precedents, the present review adopts a similarly systematic approach to consolidate evidence connecting AI literacy and sustainability competencies in teacher education.

This study therefore aims to systematically review and synthesize existing literature regarding the integration of artificial intelligence literacy and sustainability competencies in teacher education. The review seeks to identify publication trends, theoretical frameworks, and characteristics of AI literacy and sustainability competencies as discussed across the included studies. It further examines pedagogical approaches for integrating both competency domains and identifies existing research gaps that warrant future investigation. International training program evidence involving blended learning approaches suggests that structured interventions can enhance intelligent capabilities alongside broader competencies for future society, offering an illustrative precedent for such integration (Ahn & Oh, 2024). Interplay studies examining AI literacy, readiness, and acceptance among preservice teachers similarly point toward the value of an integrated competency perspective (Balasa, 2025). Building on these insights, this review proposes a conceptual framework linking AI literacy, digital pedagogical competence, and sustainability competencies, a framework further supported by analysis of readiness-related variables in teacher preparation contexts (Özüdogru & Durak, 2025).

Methods

This study employed a Systematic Literature Review (SLR) design guided by the PRISMA 2020 Statement to ensure transparency, replicability, and methodological rigor throughout the identification, screening, and inclusion of relevant studies. The SLR design was selected because it allows for a structured synthesis of dispersed evidence across two distinct but conceptually related research domains, namely AI literacy and sustainability competencies in teacher education. The review process followed four sequential stages recommended by PRISMA, consisting of identification, screening, eligibility assessment, and final inclusion, each of which was documented to allow full traceability of the selection process.

The literature search was conducted across seven major academic databases, namely Scopus, Web of Science, ERIC, ScienceDirect, SpringerLink, Taylor and Francis, and Wiley Online Library. The search string combined three conceptual clusters using Boolean operators, namely terms related to artificial intelligence literacy, terms related

to teacher education, and terms related to sustainability competencies, expressed as ("Artificial Intelligence Literacy" OR "AI Literacy" OR "Artificial Intelligence Competence") AND ("Teacher Education" OR "Preservice Teacher*" OR "Teacher Training") AND ("Sustainability Competenc*" OR "Education for Sustainable Development" OR GreenComp). This search strategy was designed to capture studies addressing either domain independently as well as studies attempting integration between the two.

Studies were included if they were peer-reviewed journal articles written in English, published between 2020 and 2026, focused on teacher education, and addressed AI literacy and or sustainability competencies through empirical or conceptual approaches. Studies were excluded if they consisted only of conference abstracts, editorials, book reviews, non-English publications, or content unrelated to education. Data extraction focused on author, year, country, research design, participants, AI literacy dimensions, sustainability framework, key findings, and research implications. Data analysis combined descriptive analysis, thematic synthesis, and narrative synthesis, with optional bibliometric mapping. Table 1 presents the inclusion and exclusion criteria applied throughout the screening and eligibility assessment stages.

Table 1 Inclusion and Exclusion Criteria for Study Selection

Criteria Type	Included	Excluded
Publication type	Peer-reviewed journal articles	Conference abstracts, editorials, book reviews
Language	English	Non-English publications
Publication year	2020 to 2026	Outside the specified range
Focus	Teacher education, AI literacy, and or sustainability competencies	Studies unrelated to education
Study type	Empirical or conceptual studies	Studies without clear methodological description

As shown in Table 1, the criteria were designed to balance inclusivity toward the emerging nature of this research area with sufficient rigor to maintain the quality of the synthesized evidence. This structured approach ensured that the twenty studies retained for analysis represented the most relevant and methodologically sound contributions available within the searched databases.

Results and Discussion

Findings

The search and screening process followed the four stages of the PRISMA 2020 framework, beginning with identification across the seven databases and concluding with the final inclusion of twenty studies that met all eligibility criteria. During the identification stage, records were retrieved based on the structured search string, after which duplicate records were removed. The screening stage involved title and abstract review to exclude studies clearly unrelated to teacher education, AI literacy, or sustainability competencies. The eligibility stage involved full-text assessment against the inclusion and exclusion criteria presented in Table 1, resulting in twenty studies retained for final synthesis.

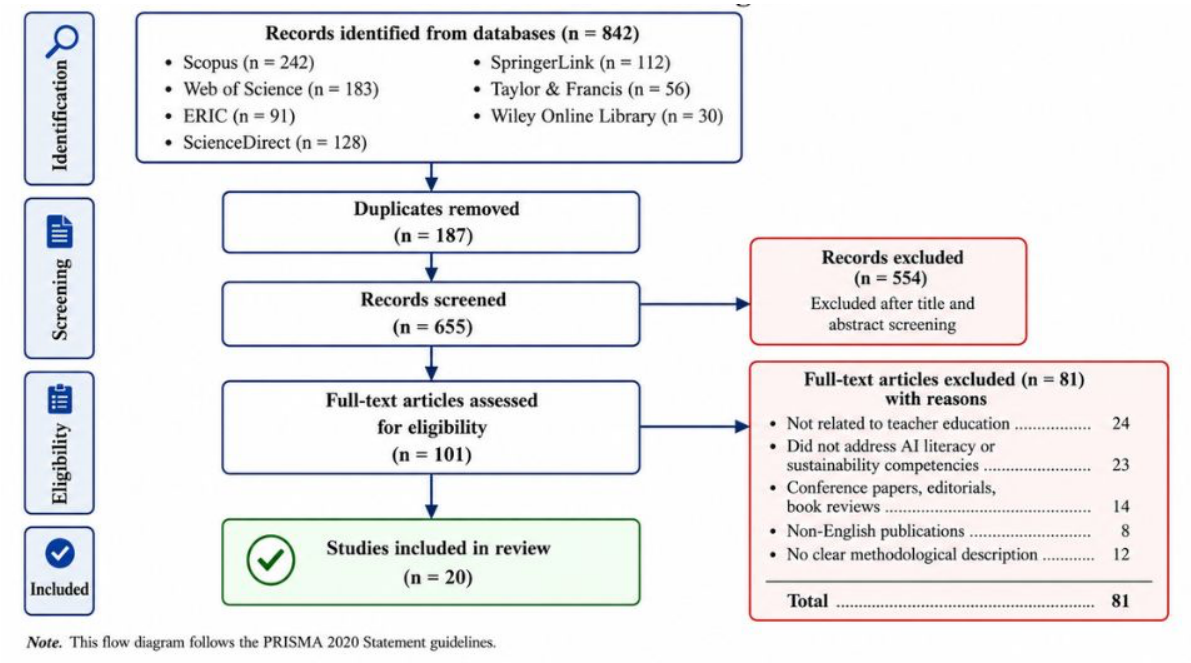


Figure 1 PRISMA 2020 flow diagram of the study selection process

The publication years of the twenty included studies ranged from 2018 to 2026, with a visible concentration of studies published between 2024 and 2026. Table 2 presents the distribution of included studies according to publication year, illustrating the accelerating research interest following the wider adoption of generative AI tools in educational settings.

Table 2 Distribution of Included Studies by Publication Year

Year	Number of Studies	Percentage
2018 to 2020	3	15%
2021 to 2022	4	20%
2023 to 2024	5	25%
2025 to 2026	8	40%

The distribution in Table 2 indicates that publications addressing AI literacy and or sustainability competencies in teacher education have grown steadily, with the largest proportion emerging in the most recent two-year period. This pattern reflects the field's rapid expansion following heightened institutional attention to generative AI in higher education.

Beyond publication trends, the included studies varied considerably in their thematic focus, research design, and geographical context. Table 3 summarizes the characteristics of the twenty included studies, organized according to their primary thematic orientation.

Table 3 Characteristics of Included Studies by Thematic Focus

Thematic Focus	Representative Studies	Predominant Research Design
AI literacy in teacher education	Bircan et al. (2025); Bokan et al. (2025); Bauer et al. (2025); Pu et al. (2021); Samantray et al. (2024)	Quasi-experimental, experimental
Sustainability and ESD competencies	Abdurrahman et al. (2023); Li et al. (2022); Brennan and Molloy (2020); Sidiropoulos (2018); Conradty and Bogner (2022)	Conceptual, quasi-experimental
Digital competence bridging AI and future readiness	Silor and Silor (2025); Bamrungsin and Khampirat (2022); Rogge and Herzig (2025); Shi et al. (2025); Ahn and Oh (2024)	Mixed-methods, quasi-experimental
Generative AI and higher-order competencies	Wei et al. (2025); Song et al. (2025); Meinlschmidt et al. (2025)	Experimental, protocol-based

As shown in Table 3, the majority of included studies addressed AI literacy or sustainability competencies independently, with only a small subset attempting to bridge digital competence with future-readiness constructs. Narrative analysis of these studies revealed that AI literacy was consistently characterized through dimensions of foundational knowledge, self-efficacy, ethical awareness, and readiness for classroom application. Studies focusing on preservice teachers repeatedly reported measurable gains in knowledge and confidence following structured AI-related training, particularly when training incorporated hands-on and collaborative tasks rather than theoretical instruction alone.

In contrast, sustainability competencies were most frequently represented through systems thinking, creative problem solving, and personal engagement with environmental and social issues, typically cultivated through project-based or makerspace-oriented learning activities. None of the twenty included studies measured both AI literacy and sustainability competency outcomes within a single research design, confirming the fragmentation identified during the introduction. This absence of integrated measurement constitutes the central empirical gap addressed by the conceptual framework proposed in this review.

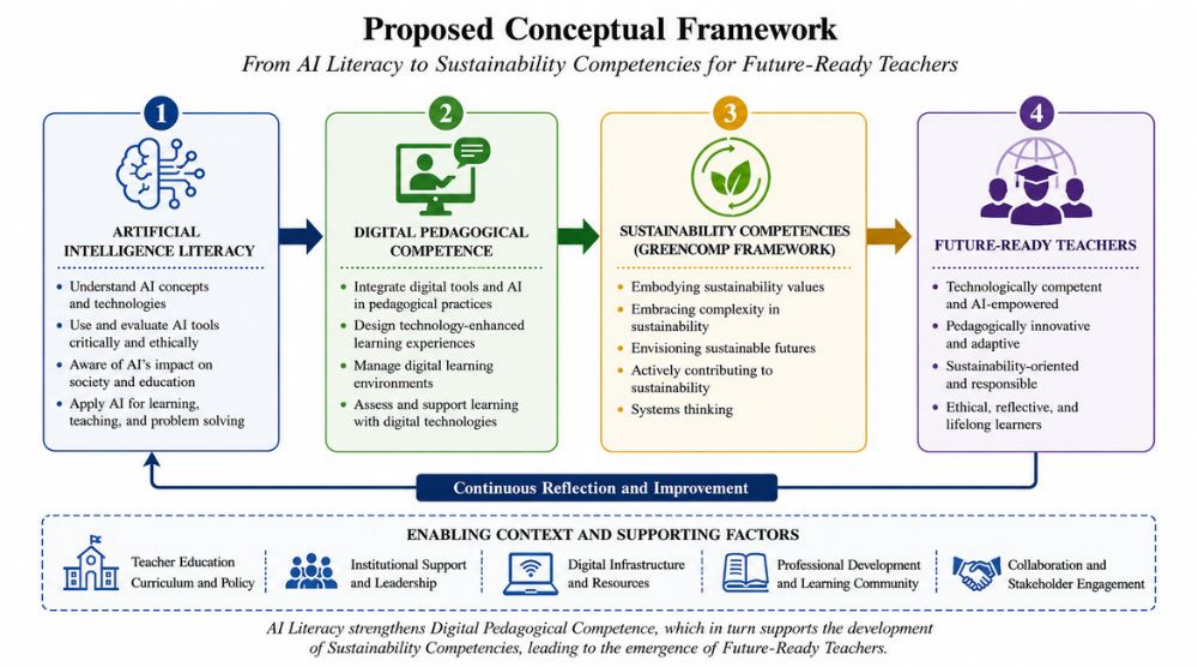


Figure 2 Proposed conceptual framework linking Artificial Intelligence Literacy, Digital Pedagogical Competence, Sustainability Competencies, and Future-Ready Teachers

Discussion

The findings show that publications addressing AI literacy and sustainability competencies in teacher education have expanded markedly since 2023, coinciding with wider public adoption of generative AI tools. This trend emerged gradually, beginning with studies focused narrowly on general digital literacy before extending toward more specific AI competency constructs among preservice teachers. Such a trajectory is consistent with prior scoping work indicating that AI literacy research in teacher education is a relatively young and rapidly evolving field (Sperling et al., 2024). Sustainability competency research follows a comparatively slower and more incremental growth pattern than the acceleration observed in AI literacy studies. Foundational AI literacy training research demonstrates similarly rising interest, as programs targeting physics preservice teachers report measurable knowledge gains following structured input-based training (Abdulayeva et al., 2025). Taken together, this uneven growth pattern confirms that AI literacy has become a fast-moving research frontier while its integration with sustainability competencies remains an emerging rather than established area of inquiry.

The review reveals that theoretical frameworks applied across the included studies are dominated by technology acceptance and self-efficacy oriented models rather than sustainability-specific frameworks. This pattern arose largely because most AI literacy interventions were originally designed to measure confidence, attitude, and readiness rather than environmental or social competency outcomes. Such reliance aligns with training evaluation research showing that AI literacy programs consistently improve self-efficacy and attitudes toward generative AI among teacher education students (Le et al., 2026). Antecedent-based studies similarly emphasize perception, attitude, and machine learning knowledge as key predictors of AI literacy rather than sustainability-related constructs (Laru et al., 2025). Sustainability education research tends to draw on system dynamics and personal context-oriented frameworks that

rarely intersect with technology acceptance theory. This theoretical divergence explains why few studies have attempted to construct an integrated framework connecting AI competency models with sustainability competency structures such as GreenComp.

Across the reviewed studies, AI literacy in teacher education is most frequently conceptualized as a composite of foundational knowledge, self-efficacy, ethical awareness, and readiness for classroom application. This conceptualization developed as researchers moved from simple technical familiarity measures toward multidimensional competency profiles capturing use, detection, ethics, and creation-related skills. Such a multidimensional view corresponds closely with competency profiling research identifying use, detection, ethics, creation, and problem solving as core dimensions of preservice teachers' AI literacy (Ayanwale et al., 2024). Assessment-focused studies extend this conceptualization further by demonstrating that AI literacy also involves the capacity to design effective evaluation tools for language learning contexts (Coşgun, 2025). Other evidence indicates that applied competencies such as problem solving and AI-based teaching practice remain the most difficult dimensions to develop compared to foundational knowledge (Han, 2025). This conceptual pattern suggests that AI literacy in teacher education should be understood as a layered construct in which foundational knowledge precedes, but does not guarantee, competent classroom application.

Sustainability competencies within the reviewed literature are largely represented through systems thinking, creative problem solving, and personal engagement with environmental and social issues. These competencies were typically cultivated through project-based or makerspace-oriented learning activities rather than through direct instructional exposure to AI tools. This pattern is consistent with engineering design-based makerspace research showing that systems thinking skills can be fostered through renewable energy-focused learning units (Abdurrahman et al., 2023). Vocational education research similarly reports that creative thinking teaching methods can strengthen sustainable development ability among higher vocational students (Li et al., 2022). Sustainability competency research rarely incorporates digital or AI-mediated tools as part of its pedagogical design, revealing a persistent methodological separation between the two fields. This separation indicates that sustainability competency development in teacher education has so far progressed largely independent of the digital transformation occurring within AI literacy research.

Only a limited number of studies in this review attempt to combine AI-mediated instruction with sustainability-oriented pedagogical goals within a single learning design. Where such integration occurs, it tends to emerge indirectly through digital pedagogy training that emphasizes inclusive and reflective teaching practice rather than explicit sustainability content. This indirect pattern is evident in professional development research showing that digital pedagogy training improves teacher competence, self-efficacy, and wellbeing in inclusive education settings (Shi et al., 2025). Structured video annotation approaches similarly enhance preservice teachers' reflective competence, offering a pedagogical mechanism that could plausibly be extended toward sustainability-themed reflection (Rogge & Herzig, 2025). Comparable evidence from ICT-integrated pedagogy research demonstrates improved teaching competence in mathematics instruction, suggesting transferability of similar integrated designs to sustainability content areas (Samantray et al., 2024). These findings collectively suggest that direct AI and sustainability integration remains rare, yet existing digital pedagogy models offer a plausible foundation upon which such integration could be deliberately designed.

The synthesis identifies a clear absence of studies that explicitly connect the UNESCO AI Competency Framework for Teachers with the GreenComp sustainability framework. This gap became apparent when comparing intervention designs across the included studies, none of which measured both AI competency and sustainability competency outcomes within the same research design. This observation is consistent with meta-analytic findings noting substantial variability in how AI literacy is measured across preservice teacher preparation programs globally (Tunjera & Chigona, 2025). Readiness-oriented research further shows that variables such as digital citizenship and perceived AI threats influence AI readiness, yet none of these studies extend their scope toward sustainability readiness (Özüdogru & Durak, 2025). Sustainability education studies rarely account for digital or AI-related variables when explaining student learning outcomes, reflecting a comparable blind spot on the opposite side of the field. This bidirectional gap confirms the necessity of a dedicated conceptual framework capable of bridging AI literacy and sustainability competencies within a unified teacher education research agenda.

Building on the identified gaps, this review proposes a conceptual framework in which AI literacy enhances digital pedagogical competence, which subsequently supports the development of sustainability competencies. This framework was constructed by tracing recurring pathways across the included studies, beginning with foundational AI knowledge and progressing toward applied pedagogical and sustainability-related outcomes. Such a progression mirrors training evaluation evidence showing that AI literacy development strengthens attitudes and confidence before translating into broader instructional competencies (Younis, 2024). International blended learning program evidence similarly demonstrates that structured AI-related training can enhance core competencies relevant to future society, supporting the plausibility of a comparable pathway toward sustainability competencies (Ahn & Oh, 2024). Some studies caution that professional communication and protocol-based interventions require sustained institutional support before measurable competency gains are observed, indicating that the proposed pathway may not operate uniformly across contexts (Meinlschmidt et al., 2025). Despite this variability, the proposed framework offers a coherent starting point for future empirical validation linking AI literacy, digital pedagogy, and sustainability competencies in teacher education.

The findings carry practical implications for teacher education curriculum design, particularly regarding the need to embed AI literacy and sustainability competencies within a shared instructional structure. This implication emerged from observing that professional development programs achieving the strongest outcomes consistently combined hands-on practice with authentic pedagogical tasks rather than theoretical instruction alone. Such an approach is supported by training design research demonstrating that AI literacy programs relying on institutional cooperation and structured practice yield stronger self-efficacy outcomes among trainee teachers (Reher et al., 2025). Interplay research examining readiness, confidence, and acceptance further suggests that curriculum design should account for contextual variables such as gender, discipline, and connectivity when embedding AI competencies (Balasa, 2025). Evidence on fostering AI literacy through school-based implementation indicates that institutional context and school-level support play an equally decisive role in competency development (Nuangchalerm et al., 2024). These implications suggest that policymakers and teacher education institutions should prioritize contextually

grounded, practice-based curriculum reform that simultaneously cultivates AI literacy and sustainability competencies among future-ready teachers.

Conclusion

This systematic literature review has synthesized existing evidence on the integration of artificial intelligence literacy and sustainability competencies within teacher education. The findings indicate that AI literacy research has grown rapidly and is generally conceptualized as a multidimensional competency encompassing knowledge, self-efficacy, ethics, and applied classroom practice. Sustainability competencies, meanwhile, continue to develop along a separate research trajectory that rarely intersects with AI-mediated instructional approaches. This persistent separation confirms the existence of a substantial gap between two competency domains that are equally essential for preparing future-ready teachers.

Based on this synthesis, the review proposes a conceptual framework in which AI literacy strengthens digital pedagogical competence as a pathway toward sustainability competency development. This framework offers both theoretical and practical value by bridging the UNESCO AI Competency Framework for Teachers with the GreenComp sustainability framework. Future research is encouraged to empirically test this framework through intervention-based studies that simultaneously measure AI literacy and sustainability competency outcomes. Teacher education institutions and policymakers may use these findings as a foundation for designing integrated curricula that prepare teachers to navigate both the technological and sustainability-related demands of contemporary education.

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