frontiers in Education

TYPE Original Research
PUBLISHED 18 March 2026
DOI 10.3389/feduc.2026.1745059

OPEN ACCESS

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RECEIVED 12 November 2025
REVISED 20 February 2026
ACCEPTED 25 February 2026
PUBLISHED 18 March 2026

CITATION
Yoon I, Ryu J, Kim K and Kim I (2026) What AI–digital competencies should teachers develop throughout their careers?: Designing a career-responsive framework through a Delphi study. *Front. Educ.* 11:1745059. doi: 10.3389/feduc.2026.1745059

What AI–digital competencies should teachers develop throughout their careers?: Designing a career-responsive framework through a Delphi study

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This study develops a career-responsive AI–digital competency framework for in-service teachers in Korea to address the need for competencies that evolve across teachers' professional careers in AI-driven educational environments. Based on national policies, global competency standards, and teacher career-stage theory, an initial set of competencies was developed and validated through a two-round modified Delphi study with 44 trained teachers. Content validity ratio (CVR), consensus, and convergence indices were used to assess item validity, and ANOVA with Scheffé post-hoc tests examined differences in perceived competency importance across career stages. The final framework comprises three dimensions, eight categories, and seventeen competencies supported by 51 behavioral indicators aligned with four career stages: Induction, Development, Mastery, and Leadership. All indicators demonstrated strong content validity (CVR $\geq$ 0.75) and expert consensus. Significant differences were identified in nine competencies, with early-career teachers emphasizing foundational knowledge and ethics, while experienced teachers prioritized curriculum innovation, learning analytics, and digital leadership. The framework provides a structured basis for diagnosing and supporting teachers' AI–digital competency development and offers implications for certification, professional development, and mentoring systems.

KEYWORDS
AI–digital competency, career lifecycle, digital education and training, professional development, teacher education

1 Introduction

Accelerating digital transformation has brought about fundamental changes in the educational landscape. In Korea, the introduction of the AI–Digital Textbook (AIDT) exemplifies the growing role of AI and digital technologies in enhancing the quality and efficiency of classroom instruction (Abad-Segura et al., 2020; Ferrari, 2012). In this context, it has become essential for teachers to acquire AI–digital competencies to effectively adapt to and utilize these evolving digital learning environments (Anthonysamy et al., 2020; Colás-Bravo et al., 2021; De la Calle et al., 2021). Previous studies have focused on defining AI–digital competencies, constructing relevant frameworks, and proposing strategies to support teachers' digital skill development. However, many of these initiatives rely on generalized, one-size-fits-all competency structures that do not adequately reflect the contextual diversity of school settings or the differentiated needs of teachers across career stages. These limitations, in turn, can reduce the relevance and effectiveness of professional development by overlooking the practical demands associated with teachers' dynamic roles.

As a result, teachers' professional development must be understood not as a one-time training effort but as a gradual and systematic process across the teaching career. This calls for diagnostic frameworks and training programs aligned with teachers' roles at each stage of their careers. Accordingly, developing a career-based AI–digital competency framework is essential for enhancing the relevance and impact of professional learning. AI–digital competencies must also be seen not merely as technical skills but as integral to what has been described as sustainable professionalism—the ability of teachers to reflect critically on educational change, act ethically and creatively, and lead innovation in schools (Markauskaite et al., 2023). In this sense, building robust systems to help teachers develop their skills and proactively respond to change is paramount.

Nevertheless, many existing competency frameworks fail to account for the differentiated demands of each career stage and uniformly apply the same criteria to all teachers. To address this gap, this study adopts a career lifecycle perspective to identify how AI–digital competencies vary across the professional trajectory of teachers, thereby refining these competencies into clear and actionable behavioral indicators. The resulting framework aims to support personalized diagnostic tools and professional learning pathways that reflect the needs of teachers at different stages while contributing to the broader sustainability of the education system. Building on this perspective, the proposed framework extends beyond existing AI and digital competency models by explicitly incorporating career-stage differentiation and empirically grounded behavioral indicators derived through expert consensus. While prior frameworks have primarily emphasized generalized competency domains or technological integration, this study advances a developmentally responsive structure that aligns competencies with teachers' evolving professional roles and learning needs. In doing so, the framework provides a more practice-oriented and sustainable approach to AI–digital professional development.

1.1 Sustainable teacher development in AI–digital technologies

The advancement of AI and digital technologies has introduced new opportunities and challenges across all areas of education. Furthermore, competency-based discussions in this domain have recently gained momentum across diverse sociocultural contexts worldwide (Lorenz and Romeike, 2023). In particular, the term "digital competence" has gained attention after the European Commission included it as one of the eight key competencies for lifelong learning in the present information-driven society in 2000 (Vuorikari et al., 2016).

While many previous studies have attempted to define and conceptualize digital competence, it continues to be multifaceted and evolving. Digital competence integrates components such as computer literacy, media literacy, ICT skills, and digital literacy, all shaped by the continuous development of knowledge, information, and technology (Ferrari, 2012). Owing to its layered nature, it is difficult to ascertain a universal definition of digital competence within the academic community (Cartelli, 2010). More recently, research has shifted its focus toward the convergence of digital competence with AI, giving rise to the concept of AI–digital competence and emphasizing the need to understand and apply AI technologies in educational settings.

A review of related studies in school contexts shows that a significant portion of the discourse on AI–digital education has focused on defining and structuring the competencies required of both students and teachers (Shin et al., 2023). One of the most widely recognized frameworks is the Digital Competence Framework for Citizens (DigComp), developed by the European Union. Specifically, its extension to the educational context, DigCompEdu, provides a structured explanation of how teachers can integrate digital technologies into pedagogical practice, with a particular focus on their professional responsibilities. DigCompEdu identifies the following six core areas of teacher digital competence (Basilotta-Gómez-Pablos et al., 2022): Professional Engagement, Digital Resources, Teaching and Learning, Assessment, Empowering Learners, and Facilitating Learners' Digital Competence.

In addition, the Digital Teaching Professional Framework for Teachers, developed by European Training Foundation (2018), outlines a developmental model comprising three stages—exploring, adapting, and leading—across eight core indicators. These include using digital resources for instructional planning, understanding new educational implications, fostering learners' digital skills, developing teaching content, employing tools for assessment and feedback, ensuring accessibility, and promoting self-development. Such developmental perspectives align with theories of teacher professional learning, which view competency growth as an iterative process shaped by experience, reflection, and contextual adaptation. These frameworks have expanded teachers' digital competence from simple technical proficiency to a more integrated, practice-oriented approach to pedagogy. However, in this context, a standard limitation is the lack of explicit attention to AI-specific applications in education.

To address this gap, Lorenz and Romeike (2023) proposed the AI-PACK framework, incorporating the Dagstuhl Triangle—a model that balances technical, sociocultural, and user-centered perspectives. This framework identifies the following four core dimensions of AI-related teacher competencies:

- AI-K: General knowledge for recognizing, understanding, and reflecting on AI phenomena in education;
- AI-PK: Pedagogical knowledge for designing instruction while considering the opportunities, limitations, and risks associated with AI;
- AI-CK: Content knowledge for understanding how AI influences disciplinary knowledge structures; and
- AI-PCK: Integrated pedagogical content knowledge for applying AI tools in subject-specific instruction while evaluating their educational value and impact on learners.

Furthermore, Shin et al. (2023) conceptualized teachers' AI–digital competence in the following five areas, which are aligned with the instructional cycle: Preparation, Design, Implementation, Evaluation, and Professional Development. Such integrated frameworks move beyond the notion of teachers as mere technology users. Instead, they frame AI–digital competence as a dynamic and multidimensional construct that supports pedagogically grounded, context-sensitive, and ethically informed teaching practices. Most importantly, they lay the foundation for rethinking teacher learning as a part of a broader goal, namely sustainable teacher development. In this context, the term "sustainable teacher development" refers to the ongoing enhancement of teachers' professional skills and capabilities to adapt to rapid technological changes, lead innovation, and foster inclusive and equitable educational environments. As noted in recent sustainability-focused literature (Basilotta-Gómez-Pablos et al., 2022), developing digital and AI-related competencies is inseparable from efforts to build long-term capacity in education systems. These efforts emphasize access to training, empowerment, equity, and digital inclusion as central elements of professional learning.

Therefore, teachers' AI–digital competence should be understood as a core pillar of educational sustainability. It enables teachers to enhance the quality and effectiveness of their instruction and contribute meaningfully to the resilience and adaptability of schools in the face of ongoing digital transformation. By embedding AI–digital learning into career-stage-responsive frameworks, educators can engage in professional development responsive to immediate classroom demands and aligned with long-term goals of systemic, ethical, and sustainable change.

Despite the significant contributions of existing AI and digital competency frameworks, many models remain largely conceptual and static, offering limited methodological guidance for translating competency domains into observable and assessable practices. Frameworks such as DigCompEdu and TPACK-based AI extensions primarily define broad areas of competence but rarely provide empirically grounded processes for operationalizing these constructs within teachers' professional development contexts. Building on these theoretical and developmental perspectives, the present study introduces a methodological shift by combining a modified Delphi approach with a developmental structuring process to refine AI–digital competencies into stage-sensitive behavioral indicators. Rather than proposing another conceptual model, this framework emphasizes a systematic and evidence-informed pathway for articulating competencies in ways that support practical diagnosis and implementation in teacher education.

1.2 Career stage of teacher development

In developing a diagnostic framework for teachers' AI–digital competencies, this study adopts a complex and dynamic perspective on teachers' career lifecycle, moving beyond linear, tenure-based categorizations of professional development. Rather than assuming that teachers' career progression follows a fixed and sequential path solely based on their years of service, this approach considers a range of interrelated factors—such as evolving professional roles, contextual responsibilities, instructional challenges, and motivational shifts—that shape teachers' development in nonlinear and fluid ways. This framework is based on a four-stage model, comprising an Induction Stage (0–5 years), a Development Stage (5–15 years), a Mastery Stage (15–25 years), and a Leadership Stage (25 + years)(Kim, 2011). Grounded in developmental professionalism theory, teacher competence is conceptualized not as a fixed set of skills tied solely to years of service but as a dynamic and contextually evolving construct that develops through ongoing professional learning, reflective practice, and adaptive engagement with changing educational environments. From this perspective, professional growth emerges through iterative cycles of experimentation, feedback, and pedagogical refinement, aligning closely with theories of teacher professional learning and adaptive expertise. Rather than assuming a linear progression, developmental professionalism recognizes that teachers' capabilities evolve in response to shifting instructional demands, technological innovations, and sociocultural contexts, thereby providing a theoretical foundation for structuring AI–digital competencies across differentiated career stages.

This theoretical stance informs the present study's decision to conceptualize AI–digital competence as developmentally structured rather than uniformly defined across teachers.

The model was applied not as rigid chronological phases but as flexible developmental contexts reflecting teachers' evolving capacity and readiness for innovation, leadership, and integration of digital technologies.

Earlier teacher development models—such as those proposed by Fuller (1969), Katz (1972)—followed a linear trajectory grounded in tenure, dividing teachers' career progression into successive stages such as survival, consolidation, and maturity. While these models have historical value, they have been widely critiqued for their inability to capture the complexities of teacher identity, professional agency, and diverse teaching contexts. As a result, more recent frameworks adopt nonlinear, cyclical, and context-sensitive models, recognizing that teachers' development may involve revisiting earlier stages, skipping phases, or progressing at varying rates depending on personal, psychological, and institutional factors. For example, Huberman (1989) proposed a developmental model including survival, stabilization, experimentation, self-doubt, serenity, and disengagement stages, arguing that teachers' career progression is rarely linear. On the other hand, Burke et al. (1996) outlined an eight-phase model—including induction, competency building, growth, frustration, stagnation, and retirement—emphasizing the influence of organizational culture and emotional experiences on teachers' career trajectories. These nonlinear and context-sensitive perspectives resonate with teacher professional learning theory and adaptive expertise frameworks, which conceptualize professional growth as an iterative process shaped by reflection, contextual adaptation, and evolving pedagogical challenges rather than as a predetermined chronological sequence.

In the framework mentioned above, each career stage encompasses specific challenges, learning needs, and opportunities for AI–digital integration:

- Induction Stage (0–5 years): At the outset, novice teachers adapt to school life while acquiring essential teaching, classroom management, and administrative skills. They apply theory in practice and receive support in lesson planning and building professional identity (Falloon, 2020). From a situated professional learning perspective, this stage emphasizes scaffolded participation and guided experimentation with AI-supported instructional practices as teachers begin integrating digital tools into authentic classroom contexts (Basilotta-Gómez-Pablos et al., 2022).
- Development Stage (5–15 years): Teachers build professional confidence and autonomy, mastering curriculum design, differentiated instruction, and student engagement strategies. They begin integrating AI tools into personalized learning and use data analytics for instructional decisions (Falloon, 2020). Peer collaboration becomes crucial as AI tools enhance instructional planning and professional discourse (Castañeda et al., 2022). Consistent with adaptive expertise theory, teachers at this stage expand from

routine technology use toward flexible pedagogical experimentation and data-informed instructional decision-making.

- Mastery Stage (15–25 years): Teachers take on leadership roles, contributing to curriculum reforms and professional development. Their advanced digital skills support the design of learning systems using AI for real-time feedback and adaptive instruction (Basilotta-Gómez-Pablos et al., 2022). At this stage, they balance technological integration with human-centered pedagogy (Falloon, 2020). Developmental learning theories suggest that expertise at this stage involves integrating technological innovation with reflective pedagogical judgment rather than merely accumulating technical proficiency.
- Leadership Stage (25 + years): Teachers become key figures in shaping school vision and leading digital transformation. They mentor junior teachers, guide ethical and inclusive AI use, and influence educational policy (Mishra and Koehler, 2006). Their experience enables them to assess the long-term impact of technology and foster empathetic school environments (Zabolotska et al., 2021). From a distributed leadership and professional growth perspective, experienced teachers act as knowledge brokers who support collective learning and ethical AI integration within professional communities.

By recognizing these distinct developmental phases, this comprehensive framework enables differentiated diagnostic tools and targeted support systems that align with teachers' professional growth and practical needs. This career-stage-based model provides a robust foundation for designing behaviorally anchored competency indicators and customized professional development pathways. This ensures that AI–digital competency development is contextually relevant, stage-appropriate, and responsive to the evolving complexities of teaching in the digital era. Such stage-sensitive differentiation reflects a needs-based competency perspective, acknowledging that teachers' professional learning priorities and technological engagement vary according to developmental contexts, instructional roles, and evolving pedagogical demands.

While career lifecycle perspectives highlight the developmental nature of teachers' professional growth, prior research has rarely reconceptualized career stages through the lens of AI–digital transformation. Existing career development models often describe progression in general professional terms without examining how technological change reshapes pedagogical roles and competency expectations over time. The present study extends these perspectives by reframing career stages as dynamic contexts for AI–digital competency evolution, integrating developmental theory with technology-enhanced pedagogical practices. Through this integrative lens, the proposed framework offers a novel perspective that positions career progression not merely as a temporal sequence but as a continuum of evolving AI-mediated professional practices.

1.3 Research questions

The primary purpose of this study is to propose a framework for teachers' AI–digital competencies that considers the distinct stages of career development. In pursuit of this goal, the following three overarching research questions guide the investigation:

> *RQ1:* What career development stages are required for AI–digital competencies?

This question seeks to establish and delineate clear developmental stages in a teacher's career that shape and influence the AI–digital skills needed for effective classroom practice. By identifying these stages, the study aims to provide a foundation for understanding how teachers' AI–digital competencies evolve and how best to support their ongoing growth.

> *RQ2:* What is the framework of AI–digital competencies with behavioral indicators, which represents competency levels?

This research question intends to construct a robust competency structure that includes observable behavioral indicators for each level of AI–digital expertise. It was applied a modified Delphi method to inform systematic revisions and ensure that the final framework aligns with theoretical rigor and practical realities in diverse teaching contexts.

> *RQ3:* How do perceptions of AI-digital competency dimensions differ across the four career stages?

This question explores the possibility that teachers at different career trajectories may prioritize or value certain AI–digital competencies differently. Understanding these variations is critical for tailoring professional development resources and policies to teachers' unique needs at each career stage.

This study developed a preliminary set of AI–digital competencies by analyzing national and international frameworks and reviewing prior research on teachers' career stages. Based on the conceptual foundation, the research employed a modified Delphi method to validate and refine the framework through expert consensus. The modified Delphi technique, which involved iterative rounds of item review and revision, was selected for its ability to reconcile theoretical soundness with on-the-ground applicability in real educational settings.

Accordingly, this study aims to define the core AI–digital competencies required at each teaching profession stage and craft detailed behavioral indicators for competency-based diagnosis and professional support. This research aspires to help teachers identify and pursue training opportunities aligned with their current roles and developmental needs by creating an expert-informed framework, ultimately fostering sustainable professional growth in an AI-integrated educational environment.

2 Methods

2.1 Participants

Focus Group Experts: Initially, 11 in-service teachers were recruited based on their recognized expertise in AI and digital education. As a focus group, they reviewed an early draft of the competency framework derived from an extensive literature review. Their feedback refined the validity and clarity of the proposed competencies, ensuring the framework was aligned with classroom realities.

Delphi Panelists: Subsequently, a separate pool of 44 panelists was recruited for the Delphi process. This group consisted of 26 elementary school teachers and 18 secondary school teachers, who were identified using the following criteria: (1) completion of government-provided AI–digital competency training; (2) enrollment in a Master of Education program specializing in educational technology or AI convergence; and (3) demonstration of substantial interest and experience in AI–digital education.

Participants were provided a stipend of USD 100 for voluntary participation. The panelists were screened based on career stage, subject, school level, and involvement in AI–digital education. Each received a consent form, an information sheet outlining the study's purpose, process, and proposed uses, eight preliminary competency indicators, and related prior research.

Two Delphi rounds were conducted between November and December 2024. Among the 44 teachers, 26 (59 percent) taught at the elementary level and 18 (41 percent) at the secondary level. In terms of career duration, 1 participant (2 percent) had fewer than 5 years of experience, 26 (59 percent) had 5–15 years, 14 (31 percent) had 15–25 years, and 3 (8 percent) had more than 25 years. In terms of subject specialization, 26 (59 percent) taught general subjects in elementary schools, followed by 7 (16 percent) who taught ICT, technology, or home economics, 4 (9 percent) taught English, 2 (5 percent) taught mathematics, 4 (9 percent) taught science, and 1 (2 percent) taught music.

To ensure a comprehensive assessment, each participant ($N = 44$) evaluated the perceived importance of the competency indicators across all four teaching career stages—Induction, Development, Mastery, and Leadership—regardless of their own current career stage. Consequently, the mean scores and subsequent statistical analyses for each stage reflect the collective judgment of the entire expert panel, providing a more robust evaluation than responses limited to participants within specific stages.

2.2 Development of the AI–digital competency framework

An initial set of AI–digital competency statements was developed through an exploratory sequential mixed methods approach, which incorporated (1) analysis of key literature related to teachers' AI–digital competencies and career-stage-based digital expertise; (2) examination of existing research on AI–digital competencies and digital teaching expertise; (3) integration of empirical data on AI–digital technologies in teaching and learning; and (4) consultations with in-service teachers and educational technology experts.

To further illustrate the practical application of these competencies in real-world educational settings, illustrative vignettes were integrated into the framework. For instance, in the Foundational and Contextual domain, a teacher might explain the basic principles of AI while facilitating a class discussion on its societal impacts, such as changes in the job market. In the Design and Implementation phase, teachers demonstrate their expertise by reconstructing curricula based on learner data and promptly diagnosing technical issues during AI-integrated activities to maintain a stable learning environment. Finally, in the Assessment and Reflective domain, teachers provide data-driven personalized feedback using AI dashboards while ensuring strict adherence to ethical standards, such as privacy and copyright protection.

Once the literature-based drafting had been concluded, expert discussion was conducted. This expert panel assessed and refined the preliminary competency statements for validity, clarity, and practical applicability, providing recommendations for enhanced contextual relevance. A competency instrument was then designed, wherein the 51 behavioral indicators were rated on a five-point Likert scale (ranging from 1 = Strongly Disagree to 5 = Strongly Agree). Practical examples illustrating classroom applications of each AI–digital competency were included to clarify how each competency could be enacted in practice. Each item included an open-ended question, which allowed the respondents to suggest revisions or provide feedback. In Delphi Round 1, demographic items (e.g., years of teaching experience, subject area, school level, and teaching specialization) were also collected. All questionnaires were distributed and completed online.

2.3 Research process

This study employed the following four-step research process to develop and validate an AI–digital competency framework based on teachers' career stages:

1. Literature Review: An initial draft framework was developed by comprehensively analyzing previous studies on AI–digital competencies and teachers' professional development across career stages.
2. Expert Consultation: A focus group of 11 in-service teachers and experts examined the framework's clarity, feasibility, and career-stage relevance. Based on their feedback, revisions and refinements were made to improve the framework.
3. A Two-Round Delphi Survey: A two-round Delphi survey was conducted with 44 in-service teachers. In Round 1, consensus, convergence, and Content Validity Ratio (CVR) levels were calculated to assess item validity. Items were revised accordingly and re-evaluated in Round 2, confirming 51 finalized behavioral indicators.
4. Competency Career-stage Analysis: Based on the Delphi survey responses, each competency's perceived importance was analyzed by career stage. In addition, ANOVA and Scheffé *post-hoc* tests were conducted to identify statistically significant differences across stages, confirming the teachers' differentiated competency needs across their professional journey.

An overview of the research process has been presented in Figure 1.

2.4 Data analysis

This study employed a modified Delphi method to identify the core AI–digital competencies needed for elementary and secondary teachers to effectively integrate AI into their instruction in Korea. The Delphi technique, a systematic and iterative communication process designed to build consensus among experts in uncertain knowledge or judgment, is commonly used in education and educational technology to formulate competencies and standards (Slade and Prinsloo, 2013).

To address Research Question 1 (RQ1) "What are the career development stages required for AI-digital competencies?" It was employed a comprehensive thematic analysis of existing national and international frameworks and relevant research literature. Through iterative content analysis, it was identified recurring themes and distinct characteristics defining each career stage. These analyses formed a structured foundation, enabling the clear delineation of the career development stages that would inform subsequent stages of the Delphi validation.

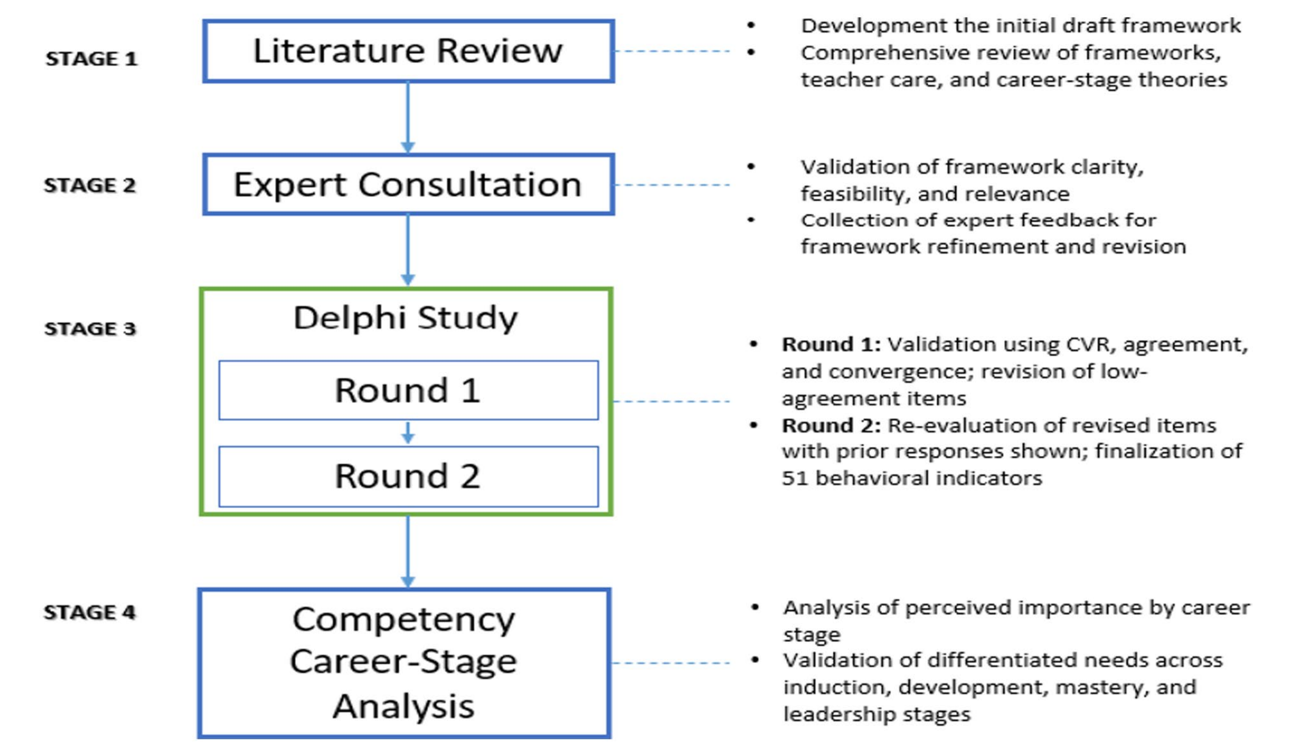

FIGURE 1
Research process overview.

The data analysis followed a rigorous two-round modified Delphi approach. To ensure high validity, this study established a consensus threshold based on a Content Validity Ratio (CVR) of 0.75 or higher, which is significantly more stringent than the minimum requirement of 0.29 for a panel of 44 experts (Lawshe, 1975; Ayre and Scally, 2014). Additionally, items were evaluated based on a convergence index to determine whether further rounds were necessary. For items that met the statistical threshold but received qualitative suggestions, a thematic analysis of open-ended responses was performed. These items were then refined by consolidating expert feedback to improve field applicability and clarity. The iterative integration of these quantitative metrics and qualitative refinements ensured that the final competency framework was both statistically validated and practically relevant.

Finally, to explicitly address Research Question 3 (RQ3) "How do perceptions of AI–digital competency dimensions differ across the four career stages?" It was conducted a one-way Analysis of Variance (ANOVA) to statistically examine variations in competency importance ratings across different teacher career stages. Before performing the ANOVA, the fundamental assumptions for parametric testing, normality and homogeneity of variance, were verified. The normality assumption was satisfied as each career stage was evaluated by the full sample ($N = 44$), and the homogeneity of variance was confirmed through Levene's test. Additionally, the Scheffé *post-hoc* test was selected for group comparisons to ensure a conservative and rigorous interpretation of the significant differences.

Finally, to explicitly address Research Question 3 (RQ3) "What differences, if any, exist in the perceived importance of AI-digital competencies across various teaching career stages?" a one-way Analysis of Variance (ANOVA) was conducted to statistically examine variations in competency importance ratings across different teacher career stages. Panelists' competency ratings collected from the second Delphi round served as dependent variables, while the distinct career stages (induction, development, mastery, and leadership) constituted independent grouping factors. Following the ANOVA, a Scheffé *post-hoc* test was applied to identify specific differences in perceived competency importance among these career stages. The Scheffé test was specifically selected to supplement the omnibus ANOVA results by identifying exact pair-wise differences, while maintaining high robustness against the study's unequal sample sizes and variance differences. This analytical step enabled detailed comparisons, clarifying which career stages significantly differed, thus directly addressing RQ3. The application of ANOVA followed by the Scheffé *post-hoc* analysis enhanced the understanding of career-stage-specific competency priorities, enabling tailored and context-sensitive professional development recommendations.

3 Results

3.1 Career stages for AI–digital competency

To address Research Question 1 (RQ1) "What are the career development stages required for AI-digital competencies?" it was necessary to clearly define and delineate the distinct stages of a teacher's professional trajectory. Clarifying these stages provides an essential foundation for understanding and structuring AI-digital competencies, as teachers' professional needs and roles evolve significantly throughout their careers. The career-stage definitions described in this section form the critical groundwork for developing and accessing a responsive and relevant competency framework.

Following the development of the preliminary draft, a focus group interview (FGI) was conducted with a panel of 11 experts. This FGI served a dual purpose: first, to evaluate the draft for clarity, validity, and contextual relevance, and second, to gather expert insights on differentiated AI–digital competency needs across distinct stages of the teaching career. The key findings from the FGI, categorized by career stage, have been summarized as follows:

- Induction Stage (0–5 years): Teachers at this early stage had limited familiarity with core instructional practices and insufficient awareness of digital ethics. As such, competencies in privacy protection, copyright awareness, lesson planning, and reflective practice were identified as essential. These competencies are closely aligned with the dimensions of Apply and Analyze AI–Digital Teaching Practices and Evaluate and Create Professional Growth in AI–Digital Education.
- Development Stage (5–15 years): With increased instructional experience, teachers in this stage actively reflect and seek more structured approaches to integrating AI and EdTech tools. Accordingly, competencies related to instructional design, lesson implementation, and learning assessment were emphasized—falling within the scope of Apply and Analyze AI–Digital Teaching Practices.
- Mastery Stage (15–25 years): Teachers at this level often serve as mentors and instructional leaders. Herein, the key competencies included conducting classroom-based research and supporting novice teachers, highlighting the growing importance of the Create Professional Growth in AI–Digital Education dimension.
- Leadership Stage (25 + years): The seasoned educators in this group strongly desired to extend their accumulated instructional experience into educational research and systemic leadership. However, in this regard, they also noted institutional and practical challenges. As a result, practice-based research and the balanced integration of competencies across all three dimensions emerged as critical needs.

Based on these findings, the competency framework was refined and structured in alignment with the AI–Digital Competency Framework proposed by Shin et al. (2023). It includes the following core elements: (1) Understanding of AI and Digital Technologies; (2) Educational Application of AI and Digital Technologies, including lesson planning, instructional implementation, and assessment practices; (3) Professional Development through AI and Digital Integration; and (4) Ethical Use of AI and Digital Technologies, such as personal data protection and copyright awareness.

Each sub-competency is supported by concrete behavioral indicators that help teachers identify, evaluate, and enhance their AI–digital teaching capabilities. This framework is designed to guide teachers in meaningfully and responsibly integrating AI into their educational practices across various career stages. Three behavioral indicators were developed for each of the 17 competencies, resulting in a comprehensive 51 behavioral indicators. Each item was carefully designed to reflect observable teaching behaviors closely aligned with authentic classroom practice.

3.2 AI–digital competency framework

Building upon the career-stage definitions established in Section 3.1, the next logical step is to address Research Question 2 (RQ2) "What is the framework of AI-digital competencies with behavioral indicators showing teachers' competency levels, and how is expert consensus used to refine and validate this framework?" This section thus outlines the comprehensive AI-digital competency framework, including detailed behavioral indicators, as refined and validated through iterative expert input obtained during the modified Delphi process. This collaborative refinement ensured that the resulting competencies would be theoretically rigorous and practically applicable within diverse educational contexts and aligned precisely with teachers' developmental stages.

3.2.1 Delphi rounds and consensus levels

Of the 51 initial competency statements presented to the Delphi panel, the majority reached a stable consensus in the first round of review. Those that did not achieve consensus were, in turn, refined based on panel feedback, including adjustments for clarity, improved alignment with teachers' practical contexts, or incorporation of additional examples. As a result of these modifications, several statements achieved 100 percent agreement by the second round. In contrast, others showed improved or stabilized IQR, indicating heightened consensus across the panel (see Table 1). Introducing new statements and deleting a few items with persistent disagreement further sharpened the framework, ensuring each competency addressed a genuinely recognized need.

Overall, the Delphi process significantly enhanced both clarity and consensus. Most items demonstrated reduced IQR alongside increased agreement percentages, suggesting convergent perspectives among experts from different career stages and instructional contexts. Key revisions, including wording refinements and the strategic removal or addition of certain statements, yielded competencies that blend rigor with real-world applicability.

Building on Delphi's feedback, the research team iterated on the AI–digital competencies multiple times. The principal investigator initially drafted 51 statements and then organized two formal review rounds (which were conducted by the expert panel), followed by amendments and validation by co-investigators and participating teachers. This cyclical review, feedback, and revision process improved the practicality of the framework and ensured theoretical robustness. Consequently, the final set of competencies accurately reflected the dynamic requirements of AI–digital education in diverse school environments.

3.2.2 Final framework structure

The finalized AI–Digital Competency Framework was organized into the following three dimensions, each capturing a distinct aspect of AI–digital pedagogy

- Understand AI–Digital Technologies, encompassing teachers' capacity to grasp foundational concepts, mechanisms, and pedagogical implications of AI and digital tools and apply them meaningfully in classrooms
- Apply and Analyze AI–Digital Teaching Practices, covering skills required to integrate AI technologies across instructional design, delivery, and assessment—each represented by distinct competency categories
- Evaluate and Create Professional Growth in AI–Digital Education, including competencies related to ethical and responsible technology use, data privacy, copyright compliance, and continuous professional development

TABLE 1 Perceived importance of AI–digital competencies across career stages.

Competencies	Career-stage mean (sd)				
	Induction	Development	Mastery	Leadership	Total
1.A.1	4.59 (0.58)	4.79 (0.51)	4.64 (0.65)	4.64 (0.65)	4.66 (0.60)
1.B.1	4.70 (0.51)	4.84 (0.43)	4.84 (0.43)	4.55 (0.59)	4.73 (0.51)
1.B.2	4.70 (0.63)	4.81 (0.59)	4.77 (0.60)	4.36 (0.72)	4.66 (0.66)
1.C.1	4.95 (0.21)	4.98 (0.15)	4.89 (0.39)	4.70 (0.55)	4.88 (0.38)
2.A.1	4.66 (0.64)	4.81 (0.59)	4.70 (0.67)	4.27 (0.82)	4.61 (0.71)
2.A.2	4.66 (0.71)	4.79 (0.67)	4.70 (0.73)	4.34 (0.81)	4.62 (0.75)
2.A.3	4.57 (0.62)	4.77 (0.57)	4.68 (0.60)	4.20 (0.73)	4.55 (0.67)
2.A.4	4.59 (0.58)	4.77 (0.48)	4.80 (0.46)	4.25 (0.65)	4.60 (0.59)
2.B.1	4.86 (0.41)	4.88 (0.39)	4.86 (0.41)	4.55 (0.63)	4.79 (0.49)
2.B.2	4.27 (0.76)	4.35 (0.72)	4.23 (0.71)	3.86 (0.82)	4.18 (0.77)
2.C.1	4.66 (0.64)	4.71 (0.59)	4.66 (0.64)	4.32 (0.77)	4.59 (0.68)
2.C.2	4.68 (0.71)	4.79 (0.67)	4.70 (0.70)	4.52 (0.85)	4.67 (0.74)
2.C.3	4.66 (0.71)	4.79 (0.67)	4.73 (0.59)	4.48 (0.73)	4.66 (0.68)
3.A.1	4.61 (0.58)	4.77 (0.53)	4.61 (0.62)	4.41 (0.6)	4.60 (0.61)
3.A.2	4.39 (0.78)	4.65 (0.57)	4.48 (0.66)	4.11 (0.81)	4.41 (0.74)
3.B.1	4.95 (0.21)	4.93 (0.26)	4.89 (0.32)	4.89 (0.32)	4.91 (0.28)
3.B.2	4.98 (0.15)	4.93 (0.26)	4.89 (0.39)	4.82 (0.58)	4.90 (0.38)

Furthermore, the AI–digital competency framework for teachers was organized into the following four hierarchical levels:

- o Dimensions represent broad domains of professional competence;
- o Categories cluster related competencies into thematically coherent subdomains;
- o Competencies define the specific skills required for effective AI–digital integration;
- o Behavioral Indicators describe observable actions that demonstrate proficiency and facilitate assessment and reflection.

Within these dimensions, eight categories delineate the logical groupings of competencies. Table 2 presents the results from Rounds 1 and 2 of the Delphi study, including mean, consensus, convergence and CVR for each behavioral indicator. Items that did not meet the consensus thresholds in Round 1 and 2 were revised or added based on expert feedback, as indicated in the Amended Competency column. In Round 1, which initially included 47 items, 3 items were deleted, and 7 new items were added, resulting in 51 items. In Round 2, most items showed improved consensus, convergence and CVR, indicating stronger agreement. The items were systematically organized by dimension, category, competency, and behavioral indicator, with detailed results shown by the item number.

4 Dimensions and categories

• Dimension 1: Understand AI–Digital Technologies

- Category 1.A: Foundational Knowledge
- Category 1.B: Contextual Awareness
- Category 1.C: Ethical Awareness

These categories emphasize recognizing fundamental AI–digital concepts, understanding technology's broader societal and educational implications, and upholding high ethical standards.

• Dimension 2: Apply and Analyze AI–Digital Teaching Practices

- Category 2.A: Design
- Category 2.B: Implementation
- Category 2.C: Assessment

These categories focus on applying and critically evaluating AI–digital resources from curriculum development to classroom-level tool usage. Teachers learn to design AI-based materials, implement instructional technologies, troubleshoot technical issues, and analyze assessment data for improved learning outcomes.

•Dimension 3: Evaluate and Create Professional Growth in AI–Digital Education

- Category 3.A: Reflective and Inquiry Practices
- Category 3.B: Ethical and Legal Responsibilities

These categories target higher-order competencies by emphasizing reflective practice, action research, and the responsible management of ethical and legal obligations. Teachers can cultivate a sustainable, forward-looking professional identity by leveraging these categories, contributing to an ethically sound and legally compliant educational culture.

4.1 Behavioral indicators

In total, 17 competency statements were defined across the 8 categories, each elaborated by 51 behavioral indicators. This granular level of detail helps teachers understand successful integration in

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TABLE 2 Comparative analysis of expert consensus and content validity (CVR) across Delphi Rounds 1 and 2 (refer to Appendix 1 in Supplementary material for full behavioral indicators).

Dimension	Category	Competency	Behavioral indicator (Appendix 1 in Supplementary material)	Item no.	Round 1					Round 2			
					Mean	Consensus	Convergence	CVR		Mean	Consensus	Convergence	CVR
1	A	1	1.A.1.1	1	4.65	0.80	0.50	0.96		4.77	1.00	0.00	0.95
			1.A.1.2	2	4.52	0.80	0.50	0.78		4.61	0.80	0.50	0.86
			1.A.1.3	3	4.26	0.75	0.50	0.61		4.24	0.75	0.50	0.68
	B	1	1.B.1.1	4	4.48	0.80	0.50	0.74		4.68	0.80	0.50	1.00
			1.B.1.2	5	4.63	0.80	0.50	0.83		4.39	0.80	0.50	0.68
			1.B.1.3	6					Added	4.86	1.00	0.00	1.00
		2	1.B.2.1	7	4.59	0.80	0.50	0.83		4.27	0.80	0.50	0.59
			1.B.2.2	8	4.67	0.80	0.50	0.91		4.70	0.85	0.38	0.91
			1.B.2.3	9					Added	4.75	0.85	0.38	1.00
	C	1	1.C.1.1	10	4.70	0.95	0.13	0.87		4.91	1.00	0.00	1.00
			1.C.1.2	11	4.67	0.95	0.13	0.83		4.83	1.00	0.00	1.00
			1.C.1.3	12					Added	4.66	0.85	0.38	0.82

(Continued)

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TABLE 2 (Continued)

Dimension	Category	Competency	Behavioral indicator (Appendix 1 in Supplementary material)	Item no.	Round 1					Round 2			
					Mean	Consensus	Convergence	CVR		Mean	Consensus	Convergence	CVR
2	A	1	2.A.1.1	13	4.46	0.80	0.50	0.74		4.58	0.80	0.50	0.82
			2.A.1.2	14	4.72	1.00	0.00	0.87		4.91	1.00	0.00	0.95
			2.A.1.3	15	4.76	1.00	0.00	0.96		4.82	1.00	0.00	0.91
		2	2.A.2.1	16	4.70	0.80	0.50	0.91		4.80	1.00	0.00	0.95
			2.A.2.3	17	4.50	0.80	0.50	0.83		4.70	0.80	0.50	0.95
			2.A.2.3	18	4.70	0.95	0.13	0.91		4.84	1.00	0.00	0.95
		3	2.A.3.1	19	4.61	0.80	0.50	0.87		4.41	0.80	0.50	0.68
			2.A.3.2	20	4.43	0.80	0.50	0.74		4.82	1.00	0.00	1.00
			2.A.3.3	21					Added	4.57	0.80	0.50	0.91
		4	2.A.4.1	22	4.35	0.78	0.50	0.74		4.61	0.80	0.50	0.91
			2.A.4.2	23	4.46	0.80	0.50	0.78		4.77	1.00	0.00	0.95
			2.A.4.3	24	4.39	0.80	0.50	0.70		4.77	1.00	0.00	1.00
	B	1	2.B.1.1	25	4.72	0.95	0.13	0.91		4.91	1.00	0.00	1.00
			2.B.1.2	26	4.76	1.00	0.00	0.87		4.82	1.00	0.00	0.95
			2.B.1.3	27					Added	4.77	1.00	0.00	0.95
		2	2.B.2.1	28	4.00	0.50	1.00	0.30		3.93	0.74	0.53	0.41
			2.B.2.2	29	4.00	0.50	1.00	0.35		4.02	0.56	0.88	0.50
			2.B.2.3	30	4.15	0.69	0.63	0.52		3.91	0.56	0.88	0.36
	C	1	2.C.1.1	31	4.59	0.80	0.50	0.87		4.66	0.80	0.50	0.91
			2.C.1.2	32	4.57	0.80	0.50	0.87		4.68	0.80	0.50	1.00
			2.C.1.3	33	4.54	0.80	0.50	0.78		4.68	0.80	0.50	0.95
		2	2.C.2.1	34	4.50	0.80	0.50	0.70		4.77	1.00	0.00	0.95
			2.C.2.2	35	4.61	0.80	0.50	0.74		4.82	1.00	0.00	0.95
			2.C.2.3	36	4.65	0.80	0.50	0.91		4.77	1.00	0.00	0.91
		3	2.C.3.1	37	4.65	0.80	0.50	0.91		4.58	0.80	0.50	0.82
			2.C.3.2	38	4.59	0.80	0.50	0.83		4.77	0.97	0.07	1.00
			2.C.3.3	39					Added	4.75	0.84	0.39	1.00

(Continued)

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TABLE 2 (Continued)

Dimension	Category	Competency	Behavioral indicator (Appendix 1 in Supplementary material)	Item no.	Round 1					Round 2			
					Mean	Consensus	Convergence	CVR		Mean	Consensus	Convergence	CVR
3	A	1	3.A.1.1	40	4.15	0.56	1.00	0.43		4.23	0.75	0.50	0.64
			3.A.1.2	41	4.63	0.80	0.50	0.91		4.70	1.00	0.00	0.82
			3.A.1.3	42	4.54	0.80	0.50	0.74		4.55	0.80	0.50	0.68
		2	3.A.2.1	43	4.43	0.75	0.50	0.91		4.52	0.80	0.50	1.00
			3.A.2.2	44	4.24	0.69	0.63	0.52		4.05	0.75	0.50	0.59
			3.A.2.3	45					Added	4.20	0.75	0.50	0.64
		–			4.72	0.95	0.13	0.91	Deleted				
		–			4.63	0.80	0.50	0.87	Deleted				
		–			4.59	0.80	0.50	0.78	Deleted				
	B	1	3.B.1.1	46	4.65	0.80	0.50	0.91		4.86	1.00	0.00	1.00
			3.B.1.2	47	4.74	1.00	0.00	0.91		4.59	0.80	0.50	0.91
			3.B.1.3	48					Added	4.91	1.00	0.00	1.00
		2	3.B.2.1	49	4.70	1.00	0.00	0.83		4.84	1.00	0.00	0.95
			3.B.2.2	50	4.70	1.00	0.00	0.83		4.77	1.00	0.00	0.86
			3.B.2.3	51	4.76	1.00	0.00	0.87		4.86	1.00	0.00	0.95

practice and aids administrators or mentors in providing targeted feedback and support. A comprehensive list of behavioral indicators has been provided in Appendix 1 in Supplementary material.

4.2 Career stages in AI–digital competencies

Having established a validated AI-digital competency framework in Section 3.2, the next step is to address Research Question 3 (RQ3) "How do perceptions of AI–digital competency dimensions differ across the four career stages?" This section explores explicitly how competencies and their perceived importance differ across the identified career stages. Clarifying these distinctions is crucial for providing tailored professional development support and guiding meaningful policy interventions that reflect the evolving professional needs of teachers at each career stage. The findings presented here offer valuable insights into the practical significance and prioritization of competencies as teachers advance through their careers.

Table 1 presents the perceived importance of 17 AI–digital competencies across four teaching career stages. Competencies were generally rated highly across all stages, with the Development stage showing the highest overall ratings. Several competencies, such as competencies 4, 9, 16, and 17, received consistently high scores, whereas a noticeable decline in ratings was observed in the Leadership stage for some items, in particular, competencies 5, 7, and 10.

To examine differences in AI-digital competency scores across career stages, a one-way analysis of variance (ANOVA) was conducted. Significant differences were found in nine competency indicators. 1.B.2 showed a statistically significant difference among groups, $F(3, 40) = 4.53$, $p < 0.05$, $\eta^2 = 0.074$. Additionally, significant group differences were observed in 1.C.1, $F(3, 40) = 5.08$, $p < 0.05$, $\eta^2 = 0.082$; 2.A.1, $F(3, 40) = 5.18$, $p < 0.05$, $\eta^2 = 0.083$; 2.A.2, $F(3, 40) = 3.13$, $p < 0.05$, $\eta^2 = 0.052$; 2.A.3, $F(3, 40) = 6.64$, $p < 0.001$, $\eta^2 = 0.104$; and 2.A.4, $F(3, 40) = 9.13$, $p < 0.001$, $\eta^2 = 0.138$; 2.B.1, $F(3, 40) = 5.27$, $p < 0.05$, $\eta^2 = 0.085$; 2.B.2, $F(3, 40) = 3.57$, $p < 0.05$, $\eta^2 = 0.059$; 2.C.1, $F(3, 40) = 3.31$, $p < 0.05$, $\eta^2 = 0.055$; and 3.A.2, $F(3, 40) = 4.29$, $p < 0.05$, $\eta^2 = 0.070$.

A Scheffé *post-hoc* test was conducted following the ANOVA for each competency to further explore group differences. This analysis identified significant differences in the perceived importance of several AI–digital competencies across teaching career stages. In terms of Competency 1.B.2, the Development [Mean Difference (MD) = 0.45; $p = 0.014$] and Mastery (MD = 0.41; $p = 0.031$) groups rated it significantly higher than the Leadership group. With respect to Competency 1.C.1, significant differences were found between the Induction and Leadership (MD = 0.25; $p = 0.017$) and the Development and Leadership (MD = 0.27; $p = 0.008$) groups. Competency 2.A.1 showed differences between the Development and Leadership (MD = 0.54; $p = 0.004$) and the Mastery and Leadership (MD = 0.43; $p = 0.036$) groups. In Competency 2.A.2, the Development group scored significantly higher than the Leadership group (MD = 0.45; $p = 0.046$). Competency 2.A.3 had the strongest differences, with the Development (MD = 0.56; $p < 0.001$) and Mastery (MD = 0.48; $p = 0.007$) groups scoring higher than the Leadership group. Competency 2.A.4 showed differences between the Induction (MD = 0.34; $p = 0.041$), Development (MD = 0.52; $p < 0.001$), and Mastery (MD = 0.55; $p < 0.001$) groups compared to the Leadership group. Similar patterns appeared in Competency 2.B.1, whereby the Induction (MD = 0.32; $p = 0.020$), Development (MD = 0.34; $p = 0.012$), and Mastery (MD = 0.32; $p = 0.020$) groups rated it higher than the Leadership group. Competency 2.B.2 revealed a significant difference between the Development and Leadership (MD = 0.49; $p = 0.032$) groups, whereas Competency 3.A.2 showed a difference between the Development and Leadership (MD = 0.54; $p = 0.008$) groups. These results suggest that teachers in the Development and Mastery stages consistently perceived certain competencies—especially those related to instructional application and classroom practice—as more important than teachers in the Leadership stage.

Table 3 shows significant *post-hoc* comparisons of AI–digital competencies across teaching career stages.

Figure 2 compares how teachers at different career stages perceive the importance of 17 AI–digital competencies. The Development and Mastery stages consistently show high ratings across most competencies. In contrast, the Leadership stage demonstrates more fluctuation and lower ratings for certain competencies, particularly competencies 5, 7, 10, and 15. Competencies 16 and 17 were rated highly across all stages.

5 Discussion

5.1 Defining career stages of teacher expertise

The first research question asked, "What career-development stages are required for AI-digital competencies?" Four stages—Induction (0–5 years), Development (5–15 years), Mastery (15–25 years), and Leadership (25 + years)—were delineated through triangulation of national policy documents, international competency

TABLE 3 Significant *post-hoc* comparisons of AI–digital competencies across teaching career stages.

Competency	Comparisons in four stages
Competency 1.B.2	Development > Leadership
	Mastery > Leadership
Competency 1.C.1	Induction > Development
	Development > Leadership
Competency 2.A.1	Development > Leadership
	Mastery > Leadership
Competency 2.A.2	Development > Leadership
Competency 2.A.3	Development > Leadership
	Mastery > Leadership
Competency 2.A.4	Induction > Development
	Development > Leadership
	Mastery > Leadership
Competency 2.B.1	Induction > Development
	Development > Leadership
	Mastery > Leadership
Competency 2.B.2	Development > Leadership
Competency 3.A.2	Development > Leadership

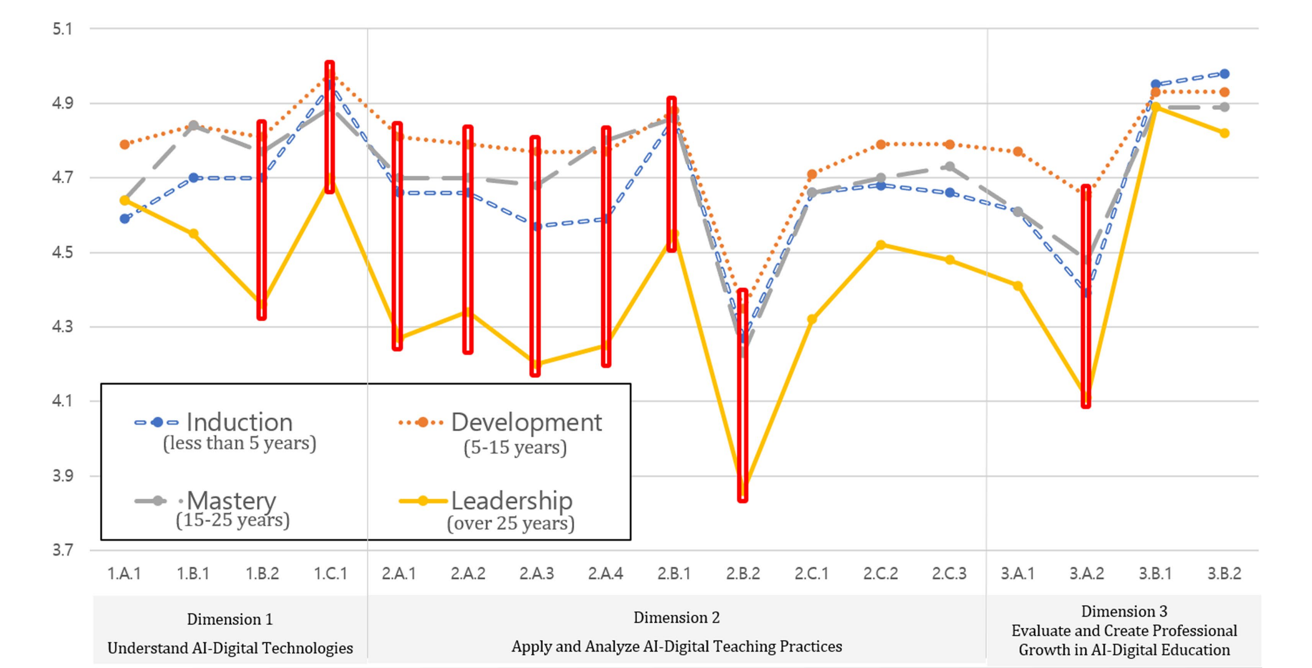

FIGURE 2
Perceived importance of 17 AI–digital competencies by career stage.

frameworks, and expert testimony. This staged model confirms that a single, static list of digital skills is insufficient. Teachers' digital needs expand as their professional roles evolve early-career teachers require foundational technical knowledge and ethical orientation, whereas mid- and late-career teachers benefit most from advanced integration skills, curricular leadership, and mentoring capacity. By mapping competencies to clearly bounded career periods, ministries and professional-development providers gain a scaffold for sequenced learning trajectories that respect teachers' changing responsibilities.

5.2 Validating a hierarchical competency framework (RQ2)

Addressing RQ2, "What validated framework of AI-digital competencies and behavioral indicators emerges from expert consensus?" It was refined a 3-dimension, 8-category, 17-competency framework across two Delphi rounds. All statements achieved Content Validity Ratios of 0.75 or higher, indicating strong consensus among panelists. The hierarchical design—dimension, category, competency—signals that competencies are practiced in clusters of related skills rather than in isolation. Policymakers and professional-development designers can therefore treat each category as a coherent module for assessment or training. The layered architecture also clarifies progression: teachers first consolidate conceptual understanding within a dimension before branching into specialized categories and observable indicators.

A stage-wise analysis further illuminated the framework's relevance. Teachers in the Development and Mastery stages assigned the highest importance to "curriculum reconstruction" (2.A.1), "personalized learning design" (2.A.2), "AI-based assessment planning" (2.A.3), and "technical problem-solving" (2.B.2). These patterns reflect mid-career motivation to translate technology into concrete pedagogical innovation as teachers gain confidence and instructional control.

Although the validated framework was derived primarily from teacher education contexts, its career-stage-responsive structure suggests potential applicability beyond pre-service preparation. Because AI–digital competence is conceptualized as a developmental trajectory rather than a fixed training outcome, the framework may be extended to in-service teachers and educational leaders who engage with technology integration at different levels of responsibility. Early-career in-service teachers may use the framework to guide structured professional learning, whereas experienced teachers and school leaders may apply it to mentoring, instructional leadership, and school-level digital transformation initiatives.

However, extending the framework to broader professional roles would require contextual adaptation. Leadership-oriented indicators may need to be expanded to reflect organizational decision-making, policy alignment, and distributed leadership practices that were not the primary focus of the present study. Future research should therefore examine how the framework functions across diverse professional contexts to further evaluate its scalability and practical relevance.

5.3 Comparing perceived importance across career stages (RQ3)

To answer RQ3, "Do perceived priorities for AI-digital competencies differ by career stage?" This study was conducted a one-way ANOVA followed by a Scheffé *post-hoc* test. Significant effects emerged for nine of the 17 competencies ($p < 0.05$). Novice teachers valued foundational knowledge and digital-ethics safeguards most highly, while teachers in the Mastery and Leadership stages prioritized curriculum redesign, advanced analytics, and school-wide digital leadership. Induction-stage teachers expressed the lowest confidence in competencies requiring analytical or design-oriented thinking—such as AI-based assessment planning and data-driven feedback—highlighting the practical challenges novices encounter when moving from conceptual understanding to classroom enactment. Conversely, some senior teachers rated certain AI-digital competencies lower, not from lack of interest but because entrenched instructional routines and limited leadership-focused training can hinder tool adoption (Basilotta-Gómez-Pablos et al., 2022; Mishra and Koehler, 2006).

5.4 Practical implications for policy and professional development

Recent scholarship calls for AI literacy to expand into full AI competency that integrates attitudes, ethics, and reflection (Chiu and Sanusi, 2024) and warns that preservice teachers often lack confidence without practice-based training (Kayaalp et al., 2025). The present framework speaks directly to these challenges. It suggests that Induction-stage teachers need targeted support in basic AI knowledge and digital-ethics decision-making. Development-stage teachers benefit most from design-centric learning, assessment, and analytics, while senior teachers require leadership-oriented opportunities that merge mentoring with policy alignment (Basilotta-Gómez-Pablos et al., 2022; Kim et al., 2023). Effective delivery methods should mix case discussions, workshops, action research, professional learning communities, and policy forums; multilayered training mapped to Bloom's taxonomy can bridge reflective thinking and classroom practice (Kayaalp et al., 2025).

Beyond preservice teacher education, the findings also suggest that the framework can be extended to in-service professional learning and school-level leadership development. Because the framework conceptualizes AI–digital competence as a developmental continuum, it enables differentiated professional-development pathways aligned with evolving teacher roles rather than uniform training structures. For example, mid-career teachers may engage in curriculum redesign and data-informed instructional innovation, whereas experienced educators and school leaders may utilize the framework to guide mentoring systems, collaborative decision-making, and digital transformation initiatives at the institutional level.

From a policy perspective, the hierarchical structure of dimensions, categories, and behavioral indicators provides a practical foundation for designing modular training systems that respond to varying expertise levels. Ministries of education and professional-development providers may adopt the framework to align national teacher-training policies with career-stage-responsive standards and sustainable teacher development strategies. Rather than implementing one-size-fits-all programs, policymakers can use the framework to prioritize ethical AI integration, inclusive digital pedagogy, and long-term capacity building across the education system.

However, extending the framework beyond teacher education contexts requires contextual adaptation. Leadership-oriented competencies—such as organizational decision-making, ethical governance of AI, and system-level innovation—may need to be further articulated to address the responsibilities of school leaders and advanced practitioners. Future research should therefore examine how the framework functions across diverse professional roles and institutional contexts to ensure scalability and contextual relevance.

5.5 Limitations

Although the Delphi panel captured diverse expertise, it was limited to Korean in-service teachers, which may constrain transferability. Importance ratings were self-reported, raising potential response bias. To further solidify the structural validity of the proposed framework, future research should transition from expert-based consensus to large-scale empirical testing. Specifically, conducting Confirmatory Factor Analysis with a broader sample of in-service teachers will be essential to verify whether the identified dimensions and behavioral indicators maintain their statistical integrity in diverse educational settings. This subsequent validation phase will refine the framework into a more robust, standardized assessment tool, bridging the gap between expert-driven design and real-world classroom application. Future studies should replicate the framework in other cultural contexts, triangulate the behavioral indicators through classroom observation, and conduct longitudinal research on the impact of stage-aligned professional learning on teacher and student outcomes. Rapid advances in AI technology also mean the framework will need periodic updates to remain current.

6 Conclusion

This study presents a theoretically grounded and practice-sensitive AI-digital competency framework that positions teachers for proactive leadership in AI-enhanced education. By aligning competencies with authentic instructional needs and the Korean national initiative for AI-Digital Textbooks (AIDT), the framework moves professional learning beyond passive adaptation toward sustainable innovation across the teacher career lifecycle.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

IY: Data curation, Investigation, Methodology, Writing – original draft. JR: Conceptualization, Project administration, Supervision, Writing – original draft, Writing – review & editing. KK: Data curation, Methodology, Software, Validation, Visualization, Writing – original draft. IK: Data curation, Methodology, Writing – original draft.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2025S1A5C3A04022456).

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2026.1745059/full#supplementary-material

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