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Teaching the teachers: A systematic review of genAI-specific technological pedagogical knowledge (TPK) in teacher education

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ABSTRACT

The increasing prevalence of Generative Artificial Intelligence (GenAI) in education presents significant implications for teacher education and instructional design. This **systematic review** examines the **GenAI-specific Technological Pedagogical Knowledge (TPK)** required by **teacher educators (TEs)** who prepare **post-primary teachers,** addressing a critical but underexplored area in the literature. While tools such as ChatGPT and other GenAI systems offer new possibilities for teaching, learning, and assessment, they also raise complex pedagogical and ethical challenges. These include concerns about data privacy, algorithmic bias, authorship, and accountability, issues that are particularly salient in the context of teacher preparation within higher education institutions (HEIs). TPK for GenAI extends beyond digital competence to encompass pedagogical reasoning, ethical awareness, and AI-augmented instructional design. To explore how these knowledge dimensions are defined and supported, peer-reviewed studies published in English were systematically reviewed across major academic databases. Seventeen studies met the inclusion criteria, focusing explicitly on TEs' engagement with GenAI. The findings highlight persistent challenges in developing GenAI-related TPK, particularly in ethical decision-making, critical AI literacy, and institutional support for professional learning. The review concludes that strengthening TEs' GenAI-specific TPK is essential for preparing future teachers to integrate AI responsibly and effectively. HEIs play a central role in enabling this by fostering coherent strategies, supportive policies, and sustained professional development.

Introduction

The emergence and rapid evolution of Generative Artificial Intelligence (GenAI), a class of Artificial Intelligence (AI) systems capable of producing original content by identifying and applying patterns from large datasets, marks a profound shift in the educational landscape [1–4]. Unlike earlier forms of AI that focused on data-driven personalization and predictive analytics, GenAI, enabled by breakthroughs in deep learning and transformer architecture, has introduced capabilities for producing human-like content, engaging in dialogue, and even simulating pedagogical interactions [5,6]. Since late 2022, the proliferation of accessible GenAI platforms has intensified global discussions about the implications of AI in education [7,8]. These discussions now extend beyond general educational technologies to the specific pedagogical, ethical, and practical considerations that GenAI introduces. As GenAI becomes increasingly integrated into classrooms and institutions, its influence on teaching, learning, and assessment continues to deepen, demanding urgent attention and action across educational ecosystems.

In this rapidly evolving context, teacher education and teacher educators (TEs) hold a pivotal role. TEs are not only responsible for guiding future educators but also for modelling best practices in technology use and pedagogy. Their dual role, teaching about education and simultaneously enacting it, places them at the frontline of navigating the GenAI transition. TEs must understand the affordances, risks, and ethical implications of GenAI, not just for their own practice, but also to adequately prepare teacher candidates for future classrooms shaped by intelligent systems. Consequently, teacher education programmes are increasingly expected to integrate AI literacy, with a particular focus on the pedagogical competencies necessary for effective and responsible GenAI use [9,10]. This task is made more complex by the evolving nature of the technology and the lack of established norms or standards guiding its integration into curriculum and practice [11]. Importantly, this complexity is further compounded by the fact that GenAI is not a singular or uniform technology, but rather an umbrella term encompassing a diverse range of tools, each with distinct affordances, pedagogical potentials, and ethical implications. For example, large language

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models, image-generation platforms, and AI-assisted design tools each demand different forms of technological, pedagogical, and ethical knowledge from educators. Consequently, teachers' and TEs' GenAI-specific Technological Pedagogical Knowledge (TPK), i.e. knowledge of the nature of teaching and learning through the use of GenAI [12], must be viewed as context-dependent and dynamic, requiring sensitivity to the affordances and limitations of specific tools, as well as critical awareness of their ethical and epistemic implications in educational settings.

Despite growing awareness of GenAI's educational potential and risks, there remains a significant gap in understanding how TEs can develop the TPK, necessary to effectively integrate GenAI. The study is a systematic review examining the GenAI-specific TPK required by TEs who prepare post-primary teachers. While the review is organised around GenAI-specific TPK, ethical considerations are treated throughout as an integral rather than separate dimension of this knowledge base. This positioning is consistent with emerging conceptualisations of AI-related teacher knowledge, which increasingly frame pedagogical decision-making, critical evaluation, and ethical reasoning as interdependent in GenAI-mediated educational contexts. Notwithstanding the rapid emergence of research on GenAI in education, there remains a notable absence of systematic synthesis focused specifically on TEs develop and apply TPK in GenAI-mediated contexts. Existing systematic reviews largely concentrate on general AI literacy [13], ethical considerations [14] or classroom-level applications [15], with limited attention to the pedagogical and professional frameworks guiding TEs' engagement with GenAI. To date, no comprehensive review has examined how GenAI reshapes TPK within teacher education or how TEs can prepare future teachers for its ethical and pedagogical integration. This study therefore represents one of the first systematic reviews to conceptualize and synthesise emerging evidence on GenAI-specific TPK for TEs, addressing a critical gap in the literature. By mapping current research trends, challenges, and implications, the review establishes a foundational evidence base to guide curriculum design, professional development, and institutional policy in the era of GenAI. The aim of this paper therefore is to explore and synthesize the existing literature on GenAI-specific TPK as it pertains to TEs who prepare student teachers for the post-primary context. In doing so, it seeks to address the following research question: *What TPK do teacher educators (TEs) require to effectively prepare pre- and in-service post-primary teachers?* The focus on post-primary teachers reflects the increasing likelihood that GenAI tools will be integrated into subject-specialist teaching, advanced assessment practices, and complex disciplinary tasks more prevalent at the post-primary level. Post-primary learners are also more likely to encounter GenAI tools independently, such as through academic writing support, code generation, or subject-specific tutoring applications. Thus, post-primary teachers face more immediate and nuanced challenges related to ethical use, assessment validity, content-specific adaptation, and learner autonomy [16–18]. In addition, focusing on post-primary teachers is vital, as secondary education centres on complex reasoning, knowledge building, and metacognition, skills essential in an AI-saturated world, where GenAI can serve as a key thinking partner for tasks like outlining, critique, and explanation [19].

Identifying the GenAI-specific TPK required by both pre-service and in-service post-primary teachers is therefore foundational. In turn, by understanding these demands on post-primary teachers across diverse disciplines, grade levels, and learning contexts, we can infer the TPK that TEs themselves must possess to adequately prepare and support their students. This reciprocal relationship is critical, as the ability to define GenAI-specific TPK for teachers provides essential insight into the knowledge, skills, and dispositions required of TEs. Without this understanding, the task of equipping TEs with the competencies necessary to lead GenAI integration in teacher education remains fragmented and incomplete.

This exploration is both timely and essential. The increasing sophistication of GenAI raises fundamental questions about the future of educational assessment, the nature of teaching expertise, and the ethical boundaries of technology in learning environments [20,21]. In GenAI-mediated classrooms, the traditional teacher-student dynamic shifts to a more complex teacher-AI-student relationship [22], requiring new forms of interaction, critical evaluation, and co-creation. Yet, many education systems have not clearly defined the AI-related competencies required of teachers, let alone TEs [10]. This lack of clarity leaves TEs underprepared, exacerbating uncertainty and resistance toward GenAI adoption. Moreover, without targeted professional development and institutional support, TEs may struggle to model effective and ethical AI use, thereby limiting the preparedness of future teachers. By synthesizing current research and identifying gaps in the literature, this paper aims to contribute to a growing body of knowledge that can inform policy development, curriculum design, and faculty development initiatives. As GenAI continues to reshape the contours of teaching and learning, the need for empowered, informed, and critically engaged TEs has never been more urgent.

Background and theoretical framework

Technological pedagogical knowledge (TPK) and GenAI

As GenAI becomes increasingly prevalent in teacher education, there is a growing need to explore established frameworks that can support its integration into teaching practice. One such framework is TPACK, which is rooted in Shulman's [23,24] concept of Pedagogical Content Knowledge (PCK), emphasizing how teachers adapt and present subject matter to enhance student understanding. PCK combines an understanding of subject matter (content knowledge) with instructional expertise (pedagogical knowledge) to guide the development of effective teaching approaches tailored to specific content areas. Mishra and Koehler (2006) expanded this concept by introducing Technological Knowledge (TK), resulting in a more holistic model that includes Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and Technological Pedagogical Content Knowledge (TPACK). This integrated framework helps conceptualize the knowledge teachers need to effectively embed technology, such as AI tools, into their teaching practices [12,25]. Please refer to Fig. 1 for an overview of the TPACK framework.

While the TPACK framework [12] has long guided teachers'

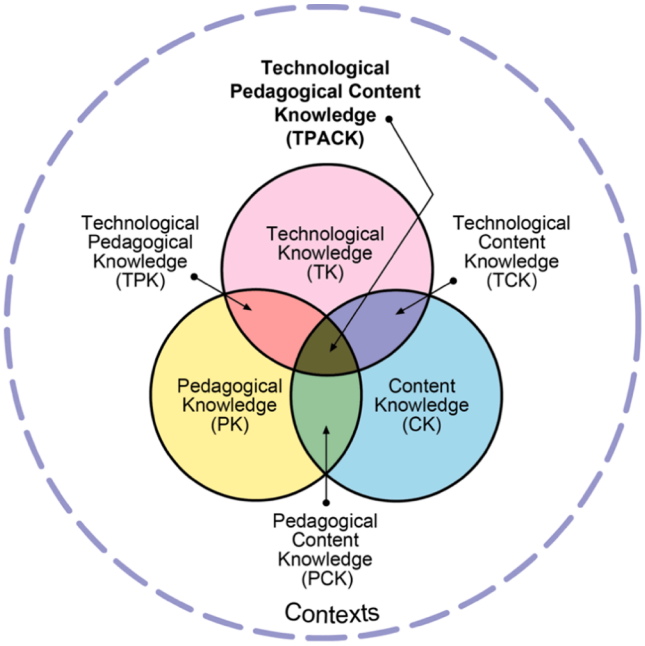


Fig. 1. TPACK Framework (tpack.org).

understanding of the interplay between technology, pedagogy, and content, it does not fully account for the adaptive, autonomous, reflective and ethical dimensions unique to GenAI and required to navigate AI-generated outputs, algorithmic bias, and issues of authorship and accountability. Unlike conventional tools, GenAI systems generate content, feedback, and instructional materials, raising new questions about authorship, bias, accountability, and learner agency. Consequently, there is a growing need to conceptualize GenAI-specific TPK, a knowledge domain that enables TEs to critically and ethically integrate AI-generated outputs into teaching and learning. Framing TPK through this GenAI lens foregrounds the importance of pedagogical judgment, ethical reasoning, and contextual sensitivity in preparing teachers for AI-enhanced classrooms.

Building on the TPACK framework [12], Intelligent-TPACK [1] extends the model by integrating dimensions of ethical reasoning, inclusiveness, and fairness, emphasizing teachers' capacity to align AI tools with pedagogical intent and ethical responsibility. More recently, Contextual Knowledge (XK) [25] has been proposed to incorporate the social, ethical, and long-term implications of AI in education. Complementing these frameworks, the Enabling AI framework [26] situates AI integration within broader institutional and policy contexts, highlighting the need for systemic support, critical literacy, and professional development. Together, these models illustrate the evolving landscape of teacher knowledge in the GenAI era. These models emphasize the subject-specific and ethical dimensions of GenAI integration, highlighting its potential to enhance teaching across disciplines. However, the complexity of these models often exceeds the capacity of existing institutional systems to provide targeted support, resulting in a lack of clear guidance and professional development opportunities for TEs. In addition, despite these conceptual advances, there has been no systematic synthesis examining how these frameworks are being interpreted, adapted, or applied within teacher education to support GenAI integration. This gap underscores the need for a comprehensive review that consolidates emerging evidence on GenAI-specific TPK, providing much-needed clarity and direction for both research and practice in this rapidly evolving field. This study focuses specifically on Technological Pedagogical Knowledge (TPK) as the conceptual core, since it represents the domain where GenAI most directly intersects with instructional design, teacher judgment, and pedagogical decision-making. Within this framing, ethical reasoning is understood as embedded within pedagogical judgment and technology integration, rather than as a separate analytical domain.

Ethical and pedagogical challenges

GenAI presents new opportunities for curriculum innovation and enriched learning by generating diverse, engaging, and high-quality content [20]. It also enhances teaching by offering timely, specific, and constructive feedback, an essential element of effective instruction [27,28]. In broader educational contexts, GenAI supports personalised learning, adaptive e-learning systems, and more authentic assessment processes [29]. However, these possibilities can only be fully realised through the pedagogical expertise and guidance of educators. In particular, TEs, as key agents in preparing future teachers, play a crucial role in ensuring that GenAI tools are integrated in meaningful, ethical, and pedagogically sound ways.

Although there is a generally positive disposition toward GenAI in education, there remains a limited understanding of its technical foundations and operational mechanisms [30]. This gap underscores the importance of developing TEs' TPK, enabling them to model and support the responsible use of GenAI in teaching and learning. The emergence of GenAI underscores a pressing need for ongoing pedagogical reform to ensure that educational practices remain responsive, ethical, and effective [31]. Strengthening TEs' TPK is therefore a foundational step in preparing education systems for the complexities of AI-enhanced teaching and learning.

Institutional responsibility

Higher education institutions (HEIs) commonly offer pedagogical courses and professional development programmes to support university teachers, including those in teacher education [32]. Over recent years, the integration of digital technologies in teaching has been a recurring focus, significantly accelerated by the Covid-19 pandemic [33–35]. In response, many HEIs have updated their professional development offerings to place greater emphasis on digital tools. The advent of GenAI has added urgency and complexity to this shift, sparking debate around both its pedagogical promise and its challenges [36,37]. While institutional responses vary, from cautious experimentation to full-scale implementation, there is little evidence of how teacher education programmes specifically are preparing future educators for this new AI-enhanced reality [38,39]. As TEs play a central role in shaping the digital pedagogical competencies of future teachers, developing their TPK in the context of GenAI becomes essential.

Methodology

Introduction

Though the literature on GenAI reviewed in the previous section is instructive, it provides little guidance on the knowledge demands of GenAI for TEs. This study employs a systematic review to synthesize and evaluate existing research in the field, aiming to enhance understanding of the field, identify key themes and gaps, and propose directions for future research. This section outlines the overall research design adopted to examine what knowledge base TEs need for effective GenAI use and how such knowledge can be cultivated, focusing on a systematic review of empirical evidence.

Research questions and research design

The study sought to investigate the knowledge base required by TEs for effective GenAI use and how this knowledge can be developed across diverse educational contexts. In analyzing the data, the research also drew upon key concepts outlined in the preceding section. The inquiry was structured around the following specific research questions:

1. How does the literature define and describe the specific Technological Pedagogical Knowledge (TPK)that pre- and in-service post-primary teachers require to integrate GenAI meaningfully into their practice?
2. Consequently, what forms of TPK do teacher educators (TEs) require to prepare teachers?
3. How can TEs be supported institutionally and professionally in developing the specific TPK required to integrate GenAI meaningfully into their practice?

Although the review was guided by these pre-established research questions, the thematic synthesis remained open to salient patterns emerging across the included studies. In particular, ethical considerations, including fairness, accountability, transparency, privacy, and responsible use, surfaced repeatedly across studies as a central dimension of how GenAI-specific TPK was conceptualised and enacted. These ethical dimensions were therefore treated analytically as cross-cutting findings that deepened interpretation of the original research questions. To address the above research questions, a systematic and structured approach, aligned with PRISMA guidelines [40], was employed to identify and select relevant research literature. Newman and Gough [41] define systematic reviews as a "family of research approaches that are a form of secondary level analysis (secondary research) that brings together the findings of primary research to answer a research question" (p.4). Prior to the searching, pre-agreed terms were developed. To identify relevant terms, and following the approach of recent systematic

reviews in the field of education [42], a modified version of the PICO framework (Population, Intervention, Comparison, Outcome) was applied. Given that control or comparison groups are less commonly used in educational research [43], including them as a required search criterion would have considerably narrowed the pool of studies eligible for review. It would have also restricted the diversity of methodological and epistemological perspectives informing the analysis. Therefore, a simplified PIO framework was adopted, combining the 'Intervention' and 'Comparison' elements into a single category (See Table 1 below). The PIO framework on the other hand, enabled the inclusion of mixed-methods and exploratory studies that reflected authentic educational contexts and outcomes, rather than excluding valuable evidence on the basis of design. This approach is consistent with methodological guidance recommending adaptations of PICO for non-clinical disciplines, and it has been successfully employed in other education-focused systematic reviews [42,44].

As outlined in Table 1, the population of interest comprised TEs of post-primary teachers as well as in-service and pre-service educators at the post-primary level. This focus was based on the rationale that by identifying the TPK required by pre- and in-service teachers, we can also infer the TPK that TEs need in order to effectively prepare and support them for GenAI integration. Since the public release of large-scale GenAI models such as ChatGPT and related tools, there has been a surge of scholarly interest in exploring their pedagogical potential, ethical implications, and impact on teaching and learning practices. Therefore, this study has considered English-language articles published from 2022 to 2025 to capture the most recent developments, discussions, and emerging trends in the use of GenAI in education.

The final search was conducted in April 2025. Two databases (ERIC and EBSCO) were searched systematically at that time These two databases were selected because they are widely recognized for their comprehensive coverage of education-related research, directly relevant to the intersection of education and emerging technologies such as GenAI. ERIC, in particular, provides authoritative access to educational research literature, while EBSCO offers access to a broad range of multidisciplinary academic journals that include educational technology studies. Other databases, such as Scopus and Web of Science were also considered during the design of the search strategy. However, after preliminary exploration, significant overlap was found between the records retrieved from these databases and those identified through ERIC and EBSCO. To ensure focus, avoid redundancy, and maintain feasibility, we limited the final search to these two databases while ensuring comprehensive coverage of the topic area. To ensure transparency and replicability, the exact search strings used in each database are presented below. Searches were conducted in ERIC and EBSCO using pre-agreed terms reflecting the key concepts of the study, namely *Technological Pedagogical Knowledge (TPK/TPACK), Generative Artificial Intelligence (GenAI), teacher education*, and *ethical, critical, and pedagogical integration*. The search strategy was refined iteratively through pilot searches. The combined master search string used was as follows:

("technological pedagogical knowledge" OR TPK OR TPACK OR "technological pedagogical content knowledge")
AND ("generative AI" OR "artificial intelligence" OR "AI tool*" OR "AI-augmented" OR "machine learning" OR "ChatGPT" OR "large language model*" OR LLM*)
AND ("teacher education" OR "teacher educator*" OR "pre-service teacher*" OR "in-service teacher*" OR "teacher training" OR "education faculty")
AND (ethic* OR "critical literacy" OR "AI literacy" OR "responsible AI" OR "pedagogical integration" OR "instructional design" OR "AI-augmented design" OR "faculty development" OR "professional development")

This search string was applied to the title, abstract, and keyword fields where possible. Truncation symbols (*) were used to capture variations of key terms, and Boolean operators (AND/OR) were employed to combine concept groups. The same logic and terminology were maintained across both databases, with minor syntax adjustments according to each platform's search conventions (e.g., ERIC descriptor terms, EBSCO field tags).

Table 1
The PIO framework of this study.

Component	Description
Population	teacher educators of post-primary teachers; In-service/Pre-service teachers of post-primary school aged children
Intervention	Any study that involved teacher educators engaging with Artificial Intelligence
Outcome	Knowledge, in particular TPK Skills Competencies

Eligibility criteria and screening procedure

The screening process and corresponding eligibility criteria are summarized in Table 2. The following exclusion criteria were applied during the review process. Studies was excluded if (1) the full text was not available; (2) if the sample involved TEs of primary level student teachers; (3) if the study did not address Artificial Intelligence within an Initial Teacher Education (ITE) or Continuing Professional Development (CPD) context, or if it was not situated at the post-primary education level; (4) if the research aims of the study did not include references to professional development; (5) if the study did not gather empirical data; (6) if the study was not peer-reviewed. Studies that fulfilled the inclusion criteria were identified through a careful screening process. The search results were identified and imported into Mendeley Reference Manager, where duplicate entries were subsequently removed. The title/abstracts of all studies were screened by both members of the research team. The full texts of the articles were then screened against the inclusion criteria. Any disagreements between the researchers were addressed and

Table 2
Inclusion/ exclusion criteria.

Criterion	Inclusion	Exclusion
Availability	Full text was available from databases, authors etc	Full text not available
Sample	Teacher educators at post-primary level and in-service/ pre-service teachers of post-primary school aged children	Teacher educators at primary level or third level and in-service/pre-service teachers of primary school aged children
Discipline	Study involved Artificial Intelligence and teacher educators at Initial Teacher Education (ITE), Continuing Professional Development (CPD) and post-primary (PP) level	Study did not involve Artificial Intelligence in an ITE/ CPD setting or was not at the post-primary level
Research aims	Teacher education linked to professional development was included in the study's research aims	Study did not include references to professional development in its research aims
Design	Quantitative and/or qualitative data	Study did not gather empirical data
Reporting	Peer-reviewed papers with a clear methodology	Inadequate reporting of: context, sample characteristics, research quality (e.g. trustworthiness), analytic techniques.
Thesis	Peer-reviewed articles	Theses, reviews and book chapters
Type of AI	GenAI	Non-GenAI
Practice strategies	Teacher Education practices, strategies, implementation	Policy

resolved through collaborative discussion until consensus was reached. This resulted in the identification of 17 full-text studies. The complete inclusion/exclusion criteria can be seen in Table 2. The PRISMA flow is presented in Fig. 2. An overview of studies included in the systematic review is provided in Table 3.

Data extraction

Collaborative data extraction was conducted by the two authors using a standardized coding framework and classification sheet developed from the study's research questions and informed by Miles and Huberman's [45] two-phase analytic model. In the first phase, a vertical (within-case) analysis was performed for each of the 17 studies, guided by a structured classification scheme encompassing study characteristics, conceptualizations of GenAI-specific TPK, educator types, pedagogical enactments, challenges, and institutional or professional supports. This procedure generated detailed analytic summaries of individual studies. To ensure consistency, both researchers independently coded an initial subset of studies and then compared results through pilot coding discussions to refine category definitions and ensure shared understanding. Discrepancies were resolved through consensus, and the finalized framework, as provided in Appendix 1, was subsequently applied to all studies. Ongoing cross-checking and iterative review maintained inter-coder consistency throughout the thematic synthesis.

In the second phase, a horizontal (cross-case) analysis was undertaken to compare and synthesize patterns across cases in relation to the three guiding research questions. Through this cross-case comparison, recurrent themes and contrasts were identified concerning the ethical and critical dimensions of GenAI-TPK, AI-augmented instructional design, and TE professional learning and support. While the coding framework was initially developed in relation to the review's guiding questions and conceptual framing, the analysis also remained sensitive to recurring issues not confined to any single category. Ethical concerns, such as bias, transparency, privacy, authorship, and accountability, emerged consistently across studies and were therefore coded as cross-cutting analytical features rather than isolated topical issues. Their prominence in the findings reflects the frequency and conceptual significance with which they appeared in the included literature. This dual-level analysis facilitated an integrative interpretation of how GenAI-specific TPK is conceptualized, developed, and institutionally scaffolded across diverse educational contexts.

Limitations

This study has several limitations. The primary limitation is the small number of studies included in this review. This reflects the emerging nature of the field, as the integration of GenAI in education is still relatively recent. The low sample size can also be attributed to the strict application of PRISMA guidelines and inclusion criteria, which were necessary to ensure methodological rigour and relevance to the review's objectives. Despite rigorous search efforts, some relevant studies may have been missed due to the omission of certain synonyms during the search process. In addition, the search was confined to the ERIC and EBSCO databases. These databases were chosen for their strong coverage of education and educational technology research, and preliminary exploration indicated substantial overlap with results from Scopus and Web of Science. However, this restriction may have excluded relevant studies from other interdisciplinary or international repositories, such as Scopus, Web of Science, or Google Scholar, thereby potentially limiting the comprehensiveness of the review. Future research could address this by expanding database coverage and refining search terms to capture a broader range of perspectives on GenAI-specific TPK.There is also a risk of publication bias, as studies reporting positive outcomes are more likely to be published than those with negative or null findings. A lack of heterogeneity among the included articles may limit the generalizability of the results, and time lag bias

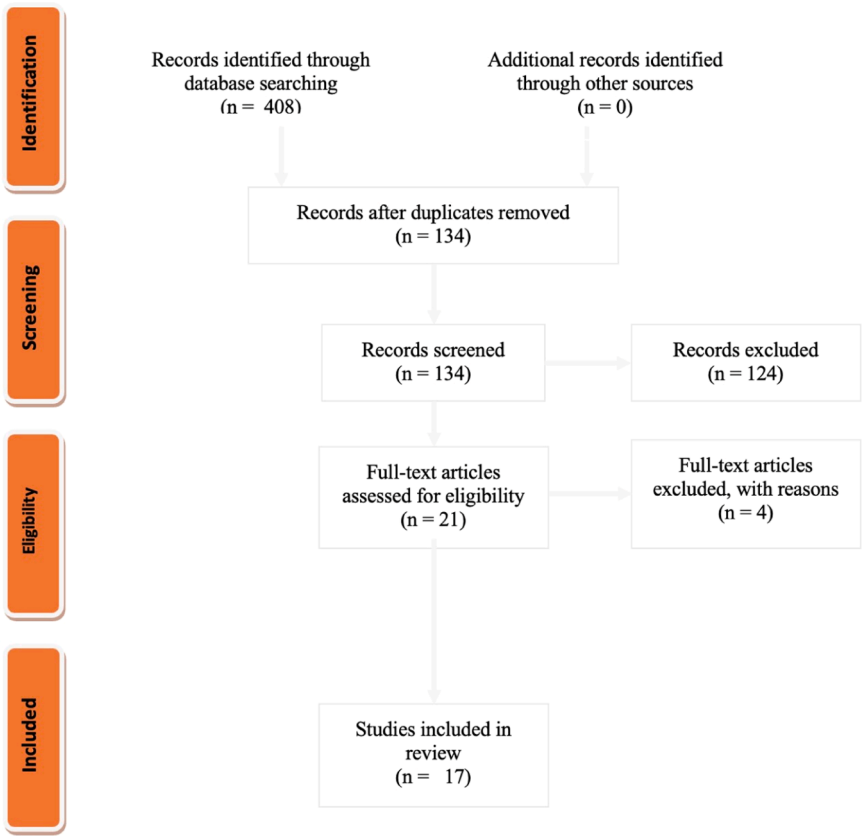


Fig. 2. PRISMA flow diagram.

Table 3
Overview of studies included in the systematic review on Generative AI and educators' Technological Pedagogical Knowledge (TPK).

	Author(s)	Year	Country	Study Type	Sample Characteristics	Key Findings Related to GenAI-Specific TPK
1	Aagaard, Bueie & Hjukse	2022	Norway	Qualitative (case study of course-based professional development)	18 teacher educators + 3 school teachers enrolled in a *Teacher Educator in a Digital Age* master's course	Demonstrated that professional digital competence (PDC), akin to TPK, emerges when teachers collaboratively design and implement technology-integrated projects. Transformative agency, rather than tool use alone, develops teachers' capacity to align pedagogy with digital epistemic change. Though not GenAI-focused, it establishes groundwork for AI-related TPK emphasizing critical, context-sensitive innovation.
2	Barrett & Pack	2023	USA & Hawaii	Quantitative (survey study)	68 educators and 158 university students	Compared perceptions of GenAI (ChatGPT) in the writing process. Teachers and students differed only slightly on acceptable uses. Found widespread uncertainty and need for explicit pedagogical frameworks and PD on integrating GenAI tools ethically and instructionally. Indicates early stage of GenAI-specific TPK development noting teachers lack guidance on how to transform writing pedagogy with AI.
3	Celik	2023	Finland	Quantitative (scale development + structural modeling)	In-service teachers (number not stated; national Finnish sample)	Developed the *Intelligent-TPACK* framework, extending TPACK with an *ethical knowledge* component. Found that technological knowledge enhances understanding of AI's pedagogical affordances, but effective use depends on TPK. Introduces explicit empirical model for *AI-specific TPK*, highlighting ethics as integral to intelligent tool use.
4	Dilek, Baran & Aleman	2025	USA & Uruguay	Qualitative (illustrative case study)	Educators enrolled in online "AI in Education" course	Implemented *critical co-discovery* pedagogy to build teachers' AI literacy. Participants co-constructed understanding of AI concepts, ethics, and classroom use through reflective collaboration. Found that AI literacy grows when pedagogy emphasizes inquiry, reflection, and co-creation - core elements of GenAI-specific TPK empowering teachers to critically shape AI's educational role.
5	Dilling & Herrmann	2024	Germany	Qualitative exploratory study	Pre-service primary and middle-school mathematics teachers	Explored ChatGPT use in constructing mathematical proofs. Interaction analyses showed emergent "instrumental genesis," where teachers developed new schemes to pedagogically use ChatGPT for reasoning. Demonstrates early formation of GenAI-TPK in mathematics with teachers learning to repurpose LLMs as instructional instruments rather than answer generators.
6	Eaton, S. E.	2024	Canada	Qualitative (conceptual essay / reflective analysis)	Discussion drawing on professional and policy contexts; no empirical sample	Highlights tension between cautious policy stances and the need for pre-service teachers to engage directly with GenAI. Advocates hands-on, ethically informed teacher education integrating GenAI for pedagogy. Suggests GenAI-specific TPK requires reframing plagiarism, authorship, and co-creation as part of "postplagiarism" teaching competence.
7	Ghosh, S. S.	2025	India	Quantitative (survey + structural equation modeling)	Pre-service and in-service language teachers using Intelligent Tutoring Systems (ITS)	Demonstrates that GenAI-powered tutoring enhances teachers' instructional design and student assessment literacy. Emphasizes need for training linking AI's adaptive feedback mechanisms to pedagogical strategy, a GenAI-specific TPK combining personalization, data literacy, and feedback design.
8	Guan, L., Zhang, Y., & Gu, M. M.	2025	China (Hong Kong SAR)	Qualitative (interviews, thematic analysis)	24 pre-service K–12 teachers	Emphasized the need to reconceptualize teacher identity and pedagogy for AI collaboration. GenAI-specific TPK involves rethinking teacher roles as facilitators and ethical mediators in AI-integrated classrooms.
9	Kamoun, F., El Ayeb, W., Jabri, I., Sifi, S., & Iqbal, F.	2024	Tunisia & UAE	Quantitative (cross-sectional survey)	855 university students + 145 faculty (engineering & business)	Faculty showed limited readiness to integrate ChatGPT pedagogically; students were more accepting. Calls for training in ethical, critical, and creative use of GenAI in higher education. GenAI-specific TPK involves faculty awareness of conversational AI's affordances for learning dialogue, feedback, and assessment.
10	Kong, S.-C., Cheung, M.-Y. W., & Tsang, O.	2024	Hong Kong, China	Mixed methods (course evaluation: quantitative tests + qualitative reflections)	128 secondary students in AI literacy course	Developed and evaluated an AI Literacy Framework integrating problem-solving and ethics via project-based learning. Demonstrated how metacognitive reflection supports understanding of AI ethics and

(*continued on next page*)

Table 3 (*continued*)

	Author(s)	Year	Country	Study Type	Sample Characteristics	Key Findings Related to GenAI-Specific TPK
						applications, key elements of pedagogical AI knowledge transferable to teacher education.
11	Lee, D., Arnold, M., Srivastava, A., et al.	2024	Australia	Mixed methods (survey + interviews)	30 university educators	Explored educators' perspectives on GenAI (ChatGPT) in higher education. Found inconsistent pedagogical responses and lack of institutional support. Emphasizes professional development to build educators' GenAI-TPK as required for designing assessments, ensuring integrity, and preparing students for AI-rich industries.
12	Mathew, R. & Stefaniak, J. E.	2024	USA	Mixed methods (needs assessment: survey + interviews)	University faculty across disciplines	Identified faculty's knowledge and skill gaps in using GenAI tools for instruction. Found performance gaps in policy awareness, ethics, and instructional integration. Highlights need for targeted PD to build GenAI-specific TPK in course design, adaptive assessment, and AI-supported feedback.
13	Moorhouse, B. L., & Kohnke, L.	2023	Hong Kong, China	Mixed methods (survey + interviews)	604 higher education instructors across disciplines	Explored early adoption of ChatGPT in university teaching. Found educators experimenting with GenAI for lesson planning, content creation, and assessment redesign, but uncertain about pedagogical integration and ethics. Identified need for *pedagogical AI literacy*. Teachers must align GenAI affordances (e.g., feedback, personalization) with learning outcomes. Highlights early stages of GenAI-specific TPK development.
14	Navío-Inglés, M., Tirado-Olivares, S., del Olmo-Muñoz, J., & Guzmán Mora, J.	2025	Spain	Mixed methods (experiment + survey + open-ended questions)	154 pre-service teachers evaluating AI- vs human-written texts	Found pre-service teachers rated ChatGPT-generated texts higher on structure and coherence but lower on emotional expression. Many failed to identify AI-authored work, underscoring limited critical literacy. Demonstrates need for developing GenAI-specific TPK focused on critical evaluation, authorship awareness, and pedagogical use of AI for writing instruction.
15	Nyaaba, M., & Zhai, X.	2024	Ghana	Qualitative (thematic analysis of PD webinar)	307 teacher educators and administrators	Professional development session on GenAI literacy. Participants showed wide variance in awareness and readiness to apply GenAI. Identified gaps in prompt engineering, ethics, and infrastructure. Concluded that GenAI-specific TPK in teacher education should integrate *explainable AI* and *prompt design pedagogy* to enhance innovation and assessment practices.
16	Wang, H., Dang, A., Wu, Z., & Mac, S.	2024	USA	Qualitative content analysis	Policies and teaching resources from top 100 U.S. universities	Mapped institutional approaches to GenAI in higher education. Most universities adopt open-but-cautious stances, emphasizing academic integrity, ethics, and flexible instructor autonomy. Provided frameworks for GenAI pedagogy: aligning tool use with learning objectives, evolving curricula to mitigate misuse, and adopting multifaceted evaluation. Reflects systemic-level development of GenAI-TPK guidance.
17	Warr, M., & Heath, M. K.	2025	USA	Qualitative (critical technology audit)	Audit of LLM feedback on student texts; conceptual analysis	Examined "hidden curriculum" of GenAI, i.e. how LLMs perpetuate bias in automated writing assessment. Found that AI feedback reflected systemic inequities (e.g., lower scores for marginalized identities). Argues GenAI-specific TPK must include *critical technoskepticism*, awareness of algorithmic bias, and reflective pedagogy to mitigate inequitable AI-mediated learning experiences.

between the database search and the publication of newer studies could have led to the exclusion of recent research. This review employed a thematic analysis to identify patterns and conceptual relationships across studies examining GenAI-specific TPK in teacher education. The included research was highly heterogeneous, encompassing varied contexts, methodologies, and theoretical perspectives, most of which were qualitative in nature. As a result, a meta-analysis or quantitative aggregation was not feasible, and no statistical synthesis of effect sizes or trends was conducted. This limits the extent to which generalizable conclusions about the magnitude or direction of specific impacts can be drawn. A further limitation concerns the coding and synthesis process employed in the review. Although a structured coding framework was developed and applied collaboratively by both authors to support consistency and rigour, the thematic analysis remains interpretive in nature and is therefore shaped, to some extent, by researcher judgement. Decisions regarding how studies were coded, grouped, and compared inevitably involved analytical interpretation, and different researchers may have emphasised alternative patterns or relationships within the data. Furthermore, while the coding framework enabled systematic cross-case comparison, the reduction of diverse studies into common categories may have obscured some of the contextual, conceptual, and methodological nuance present in individual studies. This is particularly relevant given the heterogeneity of the included literature in terms of design, theoretical orientation, and educational context. Nevertheless, the thematic approach provided rich interpretive insights into how GenAI-informed TPK is emerging across educational settings.

Findings and discussion

The findings are presented thematically in relation to the review's three guiding research questions. Across the synthesis, however, ethical considerations repeatedly surfaced within and across all themes. For this reason, the discussion begins with the ethical and critical issues that most consistently shaped the pedagogical and professional demands identified across studies.

Ethical and critical dimensions of GenAI-specific TPK

GenAI tools like ChatGPT are increasingly integrated into educational contexts, but their use raises significant ethical and critical concerns, particularly around bias, accountability, and privacy [46,47,21]. Table 4 presents relevant studies examining the ethical and critical dimensions of GenAI use in education, organized by the following subthemes: bias and fairness, accountability and transparency, privacy and data ethics, students' overreliance on GenAI, and the need for ethical literacy. Collectively, they call for a shift from reactive policy-making toward critical, reflective, and equity-centered GenAI education.

One of the primary issues is bias and fairness**.** Since these tools are trained on large-scale datasets that reflect existing societal biases, they can inadvertently produce outputs that are discriminatory or culturally insensitive [48]. This is particularly problematic in subjects such as history or literature, where context and representation are crucial [49, 50]. Another major concern is accountability and transparency**.** The opaque or "black-box" nature of large language models makes it difficult for educators and students to trace or understand how specific outputs are generated [51]. This lack of transparency undermines trust and complicates the ethical use of GenAI, especially in high-stakes tasks like grading or instructional feedback [1,46,25]. In some cases, this may shift responsibility away from educators and encourage a reliance on AI that lacks critical oversight [51]. Issues of privacy and data ethics are also central. AI tools often process user data in ways that are not transparent, leading to concerns about surveillance and data misuse. Many HEIs now advise against inputting identifiable or sensitive data into GenAI tools, advocating instead for anonymized use to protect user privacy [49]. Additionally, students' overreliance on GenAI, such as using it to complete assignments or generate ideas, may negatively affect their cognitive development and ethical engagement with learning tasks [52,26]. To address these challenges, there is a growing emphasis on developing ethical AI literacy among both student teachers and TEs. This involves not only technical understanding of how GenAI tools operate but also the ability to critically reflect on their societal impacts. AI literacy frameworks promote awareness of fairness, accountability, and transparency, enabling more responsible and informed use of these technologies in educational settings [51,17].

Reflecting on these challenges, it becomes clear that the TPK of TEs must evolve to meet the demands of a GenAI-infused educational landscape. TPK is no longer just about knowing how to integrate digital tools into teaching; it now requires a critical and ethical lens to evaluate the broader implications of technology use on learning, identity, and equity. For TEs, this means developing a nuanced understanding of how GenAI technologies function, their potential for both enhancement and harm, and the pedagogical strategies required to mitigate risks. It involves preparing pre-service teachers not only to use GenAI tools effectively but to question them thoughtfully**,** embedding discussions of bias, accountability, and data ethics into initial teacher education. Without this critical TPK, future teachers may either over-rely on GenAI or reject it entirely, missing the opportunity to engage students in meaningful, equitable, and ethically sound learning experiences.

AI-Augmented instructional design

This theme examines how recent studies address AI-augmented instructional design in teacher education, organized under four

Table 4
Summary of key studies on ethical and critical use of GenAI in education.

Subtheme	Authors, Year	Core Findings	Key Implications
Bias and Fairness	Warr & Heath (2025)	Found systemic bias in GenAI scoring/ feedback in teacher education; AI reproduced inequities tied to race and school context.	Conduct AI bias audits, design fairer models, and prepare educators to critically interrogate GenAI outputs.
	Celik (2023)	Ethical fairness and inclusiveness in "Intelligent-TPACK" framework strongly predict teachers' readiness to use AI responsibly.	Integrate fairness, inclusiveness, and ethics into teacher training and AI integration frameworks.
	Dilek, Baran & Aleman (2025)	Critical co-discovery approach exposed AI's role in reinforcing inequities and prompted ethical reflection.	Foster critical AI literacy and challenge deterministic or biased narratives in teacher education.
Accountability and Transparency	Nyaaba & Zhai (2024)	Teacher educators stressed transparency and explainable AI (XAI) as essential for ethical trust and adoption.	Include XAI, prompt engineering and accountability modules in PD; clarify roles/ responsibilities in AI use.
	Celik (2023)	Transparency and accountability identified as core ethical assessment dimensions in AI-pedagogy integration.	Develop tools and rubrics that make AI decision processes interpretable for educators.
	Wang et al. (2024)	University AI policies emphasize transparency, plagiarism control, and accountability, but vary widely.	Institutions should standardize policies and communicate responsibilities clearly to staff and students.
Privacy and Data Ethics	Dilling & Herrmann (2024)	Students raised concerns about data privacy, copyright, and model hallucinations.	Incorporate data-ethics instruction and caution against sharing sensitive info with LLMs.
	Wang et al. (2024)	Data privacy emerged as a top ethical concern in university GenAI policies.	Create clear privacy and data-protection guidelines for educational AI tools.
	Kamoun et al. (2024)	Faculty and students often unaware of privacy implications and over-trust ChatGPT; lack formal training.	Build privacy literacy and informed consent practices in GenAI education.
Students' Overreliance on GenAI	Dilling & Herrmann (2024)	Preservice teachers showed overreliance and misconceptions about LLM accuracy.	Teach critical evaluation and limit unverified use; scaffold human reasoning over automation.
	Kamoun et al. (2024)	Students frequently view GenAI as acceptable for assignments; risk of plagiarism and dependency.	Strengthen academic integrity policies and redesign assessments.
	Nyaaba & Zhai (2024)	Need for prompt-engineering training and innovative assessment to reduce blind reliance.	Promote guided, reflective use and continuous skill development.
Need for Ethical Literacy	Kong, Cheung &	AI-literacy course improved students'	Implement project-based learning and

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Table 4 (*continued*)

Subtheme	Authors, Year	Core Findings	Key Implications
	Tsang (2024)	understanding of ethical principles and reflection on social impact.	reflection to cultivate ethical AI awareness.
	Dilek, Baran & Aleman (2025)	Co-discovery learning built educators' critical and emotional engagement with AI ethics.	Encourage collaborative reflection and dialogue on AI's role in education.
	Celik (2023)	Teachers' ethical competencies equal in importance to tech/ pedagogical skills.	Embed ethics within TPACK frameworks and professional standards.
	Wang et al. (2024)	University policies increasingly include "responsible AI use," though depth varies.	Move beyond compliance to active ethics education and faculty development.

interrelated subthemes (understanding tools, interpreting policy, identity and autonomy, and co-authorship), to highlight how educators are negotiating the pedagogical, ethical, and professional dimensions of integrating GenAI into teaching and learning. Please refer to Table 5 for an overview of core findings and key implications.

As outlined in Table 5, GenAI tools can support personalized learning pathways, facilitate differentiated instruction, and enhance student engagement by providing instant explanations, examples, and feedback [11,1,53,54,49]. However, to harness these benefits effectively, TEs must be able to integrate GenAI purposefully within their specific subject areas. This requires a clear understanding of where such tools meaningfully support learning and where their use may be inappropriate or misaligned with the goals and nuances of the discipline [1,16,55]. In addition, TEs also need the ability to interpret policy documents and critically evaluate appropriate levels of GenAI use in assessment contexts [56,25].

However, these opportunities come with significant instructional tensions. Educators often grapple with balancing the generative affordances of AI against the need to maintain student agency, creativity, and deep engagement with learning [16,57,54]. Pre-service teachers in particular may experience ambivalence, perceiving AI-generated content as potentially undermining their pedagogical identity or autonomy [11,58]. These tensions are further complicated by the emergent phenomenon of co-authorship with AI, which challenges traditional definitions of academic integrity and originality. As such, educators are increasingly called to shift from punitive models of plagiarism toward co-creative pedagogical approaches that acknowledge the realities of AI-assisted learning [51,58]. In more technical domains, such as mathematics, GenAI tools are being explored for their utility in supporting proof-based reasoning. For example, ChatGPT has been used to aid pre-service teachers in constructing geometric proofs. While this has shown promise in guiding learners through complex reasoning tasks, it has also revealed shallow understandings of AI's underlying mechanisms and a tendency to accept outputs uncritically [50].

Together, these insights underscore that while GenAI holds considerable promise for enhancing instructional design, its effective use requires intentional pedagogical planning, critical reflection, and alignment with educational goals. The integration of GenAI into curriculum design demands that TEs develop robust TPK. This includes not only technical proficiency but also the ability to critically assess when and how to use AI tools in pedagogically sound, ethically responsible and discipline-specific ways. TEs must prepare post-primary teachers to navigate issues such as authorship, student agency, and AI bias, while fostering inclusive and reflective practice.

Table 5
Summary of key studies on AI-augmented instructional design in teacher education.

Subtheme	Authors, Year	Core Findings	Key Implications
Understanding Tools	Celik (2023)	Proposed Intelligent-TPACK framework, extending TPACK with ethical dimensions for AI integration. Teachers need both pedagogical and technological knowledge to interpret AI decisions and use tools responsibly.	Teacher education should develop AI-specific pedagogical knowledge, including how AI functions, its limits, and ethical evaluation.
	Dilling & Herrmann (2024)	Examined pre-service teachers using ChatGPT to generate mathematical proofs. Found limited technical understanding and misconceptions about AI operation.	Embed hands-on training on AI's affordances and constraints; emphasize critical evaluation of AI outputs.
	Navío-Inglés et al. (2025)	Compared AI- and human-written texts; pre-service teachers often rated AI higher in structure but failed to identify authorship.	Strengthen AI literacy and capacity to critically assess AI-generated outputs to prevent uncritical acceptance.
	Moorhouse & Kohnke (2024)	Language TEs percieved GenAI reshaping curriculum, instruction, and assessment, yet lacked confidence in tool use.	Provide professional development to build confidence and pedagogical strategies for integrating GenAI tools.
Interpreting Policy	Lee et al. (2024)	Higher education educators expressed uncertainty about GenAI and called for clear institutional policies. Less than a quarter felt equipped for integration.	Universities must clarify AI policies, support staff through training, and align AI use with academic integrity frameworks.
	Mathew & Stefaniak (2024)	Needs assessment revealed gaps in policy awareness, skills, and support for faculty implementing GenAI.	Policy design should connect AI governance, instructional design support, and professional learning.
	Eaton (2024)	Highlighted policy disconnects - teachers in Alberta cautioned not to engage students with GenAI despite global advances.	Encourage proactive, inclusive policy interpretation that views AI use as inevitable and focuses on preparedness, not prohibition.
Identity and Autonomy	Guan et al. (2025)	Pre-service teachers in Hong Kong struggled with changing teacher identity as AI takes on instructional roles. Saw AI as a static tool rather than a collaborator.	Support teachers in redefining professional identity in AI-rich contexts; build agency to engage AI as a pedagogical partner.
	Case, Liu & Mintz (2025)	Language TEs noted that AI-generated instruction can overshadow teachers' voices and	Encourage teacher autonomy and reflective practice to balance AI efficiency with human pedagogical values.

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Table 5 (*continued*)

Subtheme	Authors, Year	Core Findings	Key Implications
		pedagogical creativity.	
	Dilek, Baran & Aleman (2025)	"Critical co-discovery" framework enabled educators to critically negotiate AI's influence on identity, pedagogy, and power.	Embed reflective inquiry and critical AI literacy to preserve teacher agency and voice amid automation.
Co-Authorship	Eaton (2024)	Advocated for reframing plagiarism in a "postplagiarism world," where AI-human co-authorship becomes part of knowledge creation.	Teacher education must redefine authorship and assessment, treating AI as a collaborative partner rather than a threat.
	Navío-Inglés et al. (2025)	Students' inability to distinguish AI from human writing raises questions about authorship, originality, and intellectual agency.	Develop ethical writing frameworks that address AI-assisted authorship and academic responsibility.
	Moorhouse & Kohnke (2024)	TEs foresee AI-generated lesson content blurring boundaries of authorship and intellectual ownership.	Foster transparency and attribution practices when integrating AI-generated materials into teaching.

Professional knowledge gaps

Studies reveal significant professional knowledge gaps among TEs in the integration of GenAI, particularly in aligning AI use with pedagogical goals, fostering critical literacy, and expanding professional development opportunities to support ethical and effective instructional practice. Table 6 provide an overview of core finding and key implications.

Despite the growing presence of GenAI in education, many educators continue to exhibit shallow or superficial understanding of how these tools operate and how to integrate them pedagogically [16,54]. This limits their ability to use GenAI critically and effectively in classroom contexts [50,25,1]. A notable gap exists in TPK [54], particularly in what Celik (2023) describes as 'Intelligent-TPACK,' where educators lack the capacity to align AI tools with sound pedagogical strategies. Traditional frameworks like TPACK may no longer suffice in addressing the complexities of GenAI integration. Mishra et al. (2023) propose an expansion of the model through Contextual Knowledge (XK), which incorporates ethical, societal, and long-term implications of AI in education. Without this dimension, teachers risk using AI in ways that are either overly reliant or dismissive, lacking the critical digital literacy needed to interrogate the socio-political and ethical consequences of GenAI [1,16,52]. Furthermore, ongoing gaps in professional development opportunities have left many educators underprepared to engage with GenAI effectively and ethically [5]. TEs across institutions express an urgent need for practical training, policy clarity, and ethical guidelines to support confident and responsible adoption of GenAI [49,56]. Dilek et al. (2025) advocate for a *critical co-discovery* model that supports the development of reflective, context-sensitive AI literacy, aiming to bridge TPK and ethical reasoning gaps. Addressing these gaps in professional development opportunities is essential to developing reflective practitioners who can lead students in thoughtful, ethical, and pedagogically grounded use of AI.

The presence of these professional knowledge gaps underscores the urgent need to strengthen TEs' TPK. To effectively prepare future teachers, TEs must not only understand how GenAI functions but also be equipped to its ethical, pedagogical, and contextual integration [58].

Table 6
Summary of key studies on professional knowledge gaps in GenAI integration within teacher education.

Subtheme	Study (Authors, Year)	Core Findings / Focus	Key Implications
Alignment with Pedagogical Goals	Celik (2023)	Developed the Intelligent-TPACK framework extending TPACK with ethical and pedagogical components for AI-based instruction. Found that teachers often separate technological and pedagogical understanding.	Integrate AI-specific TPK training that aligns tool use with clear pedagogical objectives and ethical awareness.
	Dilling & Herrmann (2024)	Pre-service mathematics teachers showed superficial understanding of LLMs and limited ability to align AI use with learning outcomes.	Embed explicit instruction on connecting AI affordances to subject-specific pedagogy and reasoning.
	Wang et al. (2024)	Analysis of university GenAI policies found a lack of discipline-specific guidance for aligning GenAI with curricular goals.	Institutions should create discipline-aligned GenAI teaching frameworks and promote pedagogical integrity.
	Moorhouse & Kohnke (2024)	Teacher educators saw GenAI reshaping curricula but lacked clarity on how to embed tools within pedagogical frameworks.	Support educators in aligning GenAI with curriculum design, learning outcomes, and assessment.
Critical Literacy	Guan et al. (2025)	Pre-service teachers used AI mechanically, lacking conceptual understanding and critical AI literacy.	Foster critical reflection and awareness of AI's epistemic and ethical dimensions in teacher education.
	Kamoun et al. (2024)	Faculty and students demonstrated trust in ChatGPT's outputs without adequate critical evaluation; over 60% lacked training.	Develop critical digital literacy frameworks that challenge blind reliance on AI and promote informed skepticism.
	Eaton (2024)	Highlighted the need to move beyond fear-based restrictions toward hands-on engagement with AI tools.	Embed AI ethics and authorship debates into coursework to cultivate reflective and critical engagement.
	Aagaard et al. (2022)	Introduced "transformative agency" to help educators confront digital epistemological shifts.	Train educators to exercise agency by questioning and reshaping pedagogical practices through critical inquiry.
Professional Development Opportunities	Mathew & Stefaniak (2024)	Needs assessment revealed performance gaps in knowledge, skills, and policy literacy for GenAI integration.	Design targeted professional development linking AI policy, pedagogy, and practical application.
	Wang et al. (2024)	Universities are beginning to offer workshops and resources, but support remains inconsistent.	Build sustained, cross-institutional PD programs addressing both pedagogical and ethical GenAI integration.

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Table 6 (*continued*)

Subtheme	Study (Authors, Year)	Core Findings / Focus	Key Implications
	Moorhouse & Kohnke (2024)	TEs expressed low confidence in teaching with GenAI despite recognizing its importance.	Offer capacity-building initiatives and community-of-practice models for GenAI teaching competence.
	Guan et al. (2025)	Highlighted the need for explicit training on role shifts and new teacher identities in AI-augmented classrooms.	Incorporate identity-oriented PD modules to help educators navigate professional and pedagogical transformations.

This includes engaging with expanded frameworks like Intelligent-TPACK [1] and XK [59], which address the broader societal and ethical implications of GenAI.

Institutional support and strategy

Institutions play a critical role in shaping the ethical and pedagogical integration of GenAI in teacher education. Studies, summarized below in Table 7, illustrate how universities are defining responsibilities, addressing emerging challenges, and implementing strategic solutions to support TEs and students in the effective and equitable adoption of GenAI.

HEIs play a pivotal role in shaping how GenAI is adopted and integrated into educational practice [51,48]. While many institutions are beginning to develop policies around GenAI, there remains a widespread lack of comprehensive strategies and governance frameworks, resulting in inconsistent implementation and unclear guidance for faculty [56,58,48]. Some HEIs have adopted a cautious yet open approach, issuing policies focused on academic integrity, ethical use, and data privacy [49]. To address these gaps, HEIs are increasingly engaging in capacity-building efforts through workshops, syllabus templates, consultations, and faculty development programmes. These initiatives aim to enhance AI literacy and support the ethical, technical, and pedagogical integration of GenAI in teaching [26,49]. However, to achieve meaningful and sustainable integration, GenAI must be embedded systematically across initial teacher education (ITE) programmes, rather than being limited to isolated workshops or one-off modules [51]. It should be integrated into core components such as subject-specific teaching methodology, assessment design, and ICT integration modules [58,59]. The content of these modules should be hands-on, providing TEs and pre-service teachers with practical skills in areas such as prompt engineering, evaluating AI-generated outputs [58,50], and applying ethical considerations in classroom contexts [59].

For TEs, institutional strategy has direct implications for the development of their TPK. Access to structured professional development, clear policies, and interdisciplinary collaboration strengthens their ability to model effective and ethical GenAI integration. When HEIs invest in robust, programme-wide frameworks, they not only equip TEs with cutting-edge TPK but also support the cultivation of critical, ethical, and context-sensitive teaching practices. This level of institutional support is essential to ensure that GenAI becomes an integral part of teacher education in a way that drives innovation while upholding pedagogical integrity and professional responsibility.

Overall, the findings illustrate that the effective integration of GenAI in teacher education is inherently interdisciplinary, requiring the convergence of educational theory, AI ethics, instructional design, and teacher development. Addressing the pedagogical, ethical, and institutional challenges identified across the themes demands collaboration among educators, technologists, policymakers, and curriculum designers. This cross-disciplinary engagement not only enhances teacher preparation but also provides a foundation for developing coherent frameworks that connect ethical governance with classroom innovation and professional learning. In doing so, the study extends its relevance beyond teacher education, offering insights applicable across multiple educational sectors and informing wider discussions on the responsible and equitable use of AI in learning environments.

Conclusion

The integration of GenAI into education is reshaping the landscape of teacher education and instructional practice, bringing both significant opportunities and complex ethical, pedagogical, and professional challenges. Importantly, the ethical dimensions foregrounded in this review should be understood not as a separate or retrospectively imposed line of inquiry, but as an emergent and integral component of GenAI-specific TPK as represented across the reviewed literature. As this study has shown, TEs occupy a critical role in shaping how GenAI is understood, adopted, and enacted in classrooms. However, the findings highlight a pressing need to reconceptualize TPK in ways that go beyond mere tool proficiency. In a GenAI-infused educational environment, TPK must be grounded in ethical awareness, critical reflection, and contextual sensitivity. TEs must be equipped not only with technical competencies

Table 7
Summary of key studies on institutional support and strategy for GenAI integration in teacher education.

Subtheme	Authors, Year	Core Findings	Key Implications
Roles and Responsibilities	Wang et al. (2024)	Examined GenAI-related university policies and resources across U. S. institutions. Found that most universities adopted open-but-cautious approaches emphasizing ethical use, data privacy, and academic integrity.	Institutions should clearly define responsibilities for faculty and students, establish transparent data management policies, and develop discipline-specific guidelines for GenAI use.
	Eaton (2024)	Highlighted the lack of coordinated institutional policy and leadership around GenAI integration in teacher education.	Universities and teacher education programs should clarify the roles of educators, policymakers, and students in AI use to avoid fragmented practice and policy lag.
Challenges	Dilling & Herrmann (2024)	Identified limited AI understanding among pre-service teachers and inadequate institutional scaffolding for GenAI integration in math education.	Lack of institutional infrastructure and guidance hinders meaningful adoption and creates uneven confidence among educators.
	Warr & Heath (2025)	Exposed the "hidden curriculum" of GenAI, showing how institutional policies risk reproducing social inequities through uncritical adoption.	Institutions must confront systemic bias in AI adoption and embed critical auditing and equity-focused evaluation into policy.
	Dilek et al. (2025)	Found that institutional narratives often prioritize efficiency over teacher agency, limiting educators' voice in AI decision-making.	Institutions should balance innovation with participatory governance, ensuring educators are co-designers in AI integration.
Solutions	Mathew & Stefaniak (2024)	Conducted needs assessment identifying performance gaps in faculty knowledge, policy understanding, and technology integration.	Propose data-informed professional development and strategic AI planning tied to institutional missions.
	Dilek et al. (2025)	Introduced "critical co-discovery" pedagogy to empower educators through participatory engagement with AI tools.	Promote institutional cultures that prioritize reflective, hands-on engagement and co-creation of AI literacy initiatives.

but with the capacity to interrogate issues of bias, accountability, privacy, and academic integrity that GenAI tools inevitably surface. While this review offers important insights into the emerging field of GenAI-specific TPK for TEs, its findings should be interpreted with caution. The small sample size of studies and the nascent state of GenAI research in education limit the generalizability of the conclusions drawn. These constraints highlight the need for further empirical research to validate and extend current understandings across diverse educational contexts and teacher education settings. Continued investigation will be essential to build a more robust evidence base to guide TEs and institutions in integrating GenAI ethically and effectively.

The ethical and critical use of GenAI underscores the need for teacher education programmes to address not just what GenAI can do, but what it should do in pedagogically sound and socially responsible ways. This demands an evolution in both curriculum and mindset, where TEs guide pre-service teachers to approach AI technologies with a balance of curiosity and scepticism. This need is particularly urgent at the post-primary level, where GenAI tools are increasingly being integrated into subject-specialist instruction, advanced assessment practices, and complex disciplinary tasks. Consequently, post-primary teachers encounter more immediate and nuanced challenges, including ethical tool use, assessment validity, subject-specific adaptation, and the preservation of learner autonomy. Addressing these challenges requires a clear articulation of the GenAI-specific TPK that both pre-service and in-service post-primary teachers must develop. Understanding these demands provides critical insight into the TPK that TEs themselves must possess. As GenAI continues to evolve at a rapid pace, this study offers a proactive response to the emerging pedagogical and ethical challenges it presents, serving as a guiding resource for HEIs and TEs seeking to navigate its responsible and effective adoption within teacher education. By anticipating these shifts, the study underscores the importance of translating ethical and theoretical insights into concrete educational practice, guiding how teacher education programmes can meaningfully integrate GenAI into curriculum and pedagogy.

To prepare post-primary teachers for GenAI-enhanced classrooms, teacher education programmes must integrate AI-specific pedagogical frameworks that align tool use with ethical, disciplinary, and learning objectives. Embedding AI literacy into ITE, particularly through frameworks such as Intelligent-TPACK [1] and Contextual Knowledge [59], provides a pathway for developing reflective practitioners who can navigate the complexities of AI integration while maintaining student agency, creativity, and equity at the core of their practice. Furthermore, GenAI's potential to support personalized learning and instructional design highlights the importance of intentional and subject-specific integration. TEs must be supported to make informed pedagogical choices about when and how to use GenAI tools in ways that enhance learning without compromising educational values. This includes preparing future teachers to understand the limitations of AI-generated outputs, evaluate their reliability, and design learning experiences that preserve the essential human elements of teaching, critical thinking, empathy, and professional judgment. The ethical dimension of GenAI integration must remain central to the development of GenAI-specific TPK. As teacher education increasingly incorporates AI-enabled tools, ethical reasoning should be recognised as a foundational competence, equal in importance to technical proficiency and pedagogical design. Embedding ethics explicitly within teacher education curricula is essential to ensure that future teachers can critically evaluate AI systems, address issues of bias, transparency, and accountability, and uphold principles of fairness, inclusivity, and academic integrity.

The study also reveals persistent professional knowledge gaps among TEs, pointing to the inadequacy of traditional professional development models in addressing the complexities of GenAI. Without targeted and sustained opportunities to build AI-related pedagogical expertise, TEs may struggle to model ethical and effective practices for their students. Therefore, institutional strategies must prioritize the development of TEs' TPK by embedding GenAI training across core modules, offering hands-on experiences, and promoting interdisciplinary collaboration. Such strategies can be enacted through case-based learning that immerses pre-service teachers in AI-supported classroom scenarios, alongside interdisciplinary modules linking education, computer science, and ethics to foster a holistic understanding of GenAI's pedagogical and ethical dimensions. AI literacy workshops and micro-credentials can further develop TEs' capacity to critically evaluate and responsibly apply GenAI. Ethical and critical engagement should underpin these initiatives, incorporating AI bias audits, explainable AI (XAI) tasks (i.e. initiatives dedicated to clarifying how GenAI functions and operates), prompt engineering and explicit instruction on fairness, accountability, and privacy. Ultimately, the future of GenAI in teacher education depends on the extent to which HEIs can provide coherent, well-resourced, and ethically grounded frameworks for its integration. This requires moving beyond ad hoc responses toward comprehensive, systemic approaches that align technological innovation with pedagogical integrity [26]. Strong institutional frameworks and participatory governance can ensure transparency, data protection, and shared ownership of AI integration. Through deliberate investment in capacity-building, curriculum redesign, and policy development, HEIs can ensure that TEs are not only responsive to the technological shifts but are also proactive leaders in shaping a just, reflective, and future-ready educational system. As GenAI continues to evolve, so too must our pedagogical frameworks, anchored in ethics, guided by critical inquiry, and committed to inclusive, meaningful learning.

This study's interdisciplinary foundation, bridging educational theory, AI ethics, instructional design, and teacher development, positions it to inform practice and policy across multiple educational sectors. By integrating perspectives from these domains, the study contributes not only to teacher education but also to broader conversations on curriculum innovation, ethical governance, and professional learning in AI-enhanced education. Its insights can guide policymakers, curriculum designers, and institutional leaders in developing coherent frameworks that align technological advancement with ethical integrity and pedagogical purpose. As such, the study offers several actionable implications for HEIs, TEs, and policymakers seeking to integrate GenAI responsibly within teacher education. HEIs should embed GenAI across curricula through case-based learning and interdisciplinary modules that link education, computer science, and ethics, supported by policies that promote transparency, data protection, and academic integrity. Teacher education programmes must prioritise ethical and critical engagement by incorporating AI literacy workshops, bias audits, explainable AI (XAI) tasks, and explicit instruction in fairness, accountability, and privacy. Professional development should provide sustained, hands-on experiences that enable TEs to model reflective and responsible AI use while cultivating pre-service teachers' autonomy, agency, and ethical discernment. Policymakers and institutional leaders must align governance, infrastructure, and resourcing to ensure coherent frameworks that balance innovation with equity. Collectively, these strategies move beyond compliance toward a sustainable, values-driven integration of GenAI that empowers educators to engage GenAI as a pedagogical partner, enhancing creativity, criticality, and inclusive learning. Building on these implications, it is essential to extend inquiry into how such approaches can be systematically developed, evaluated, and sustained through future research.

As this paper focused on TEs preparing student teachers for the post-primary sector, the following recommendations in terms of future research specifically aim to advance GenAI-informed TPK inthis context.. Future research should prioritise empirical and longitudinal studies examining how TEs and pre-service teachers develop critical TPK, particularly in understanding and addressing AI-related bias, transparency, and accountability. Embedding AI ethics into teacher education curricula remains underexplored and offers a path to strengthening this dimension of TPK. Further investigation is also needed into how GenAI can support subject-specific instructional design while preserving student agency and academic integrity, core aspects of

pedagogically sound TPK and areas where empirical evidence remains limited. Theoretical frameworks such as Intelligent-TPACK and Contextual Knowledge (XK) should be further developed and tested, as they expand traditional TPK to include ethical, societal, and contextual considerations unique to AI. Additionally, research on institutional and policy-level enablers, including sustained professional learning, governance frameworks, and cross-disciplinary collaboration,can illuminate how systemic supports influence TPK development. . Finally, research should examine how GenAI shapes student teachers' engagement, authorship, and learning behaviours, providing insight into how TPK can guide TEs in fostering thoughtful, reflective AI use. By identifying the GenAI-specific TPK needed at the post-primary level and aligning this with the preparation and professional growth of TEs, we can begin to build a more cohesive, future-ready teacher education system, one that is critically aware, ethically informed, and pedagogically grounded in the realities of a GenAI-driven world.

CRediT authorship contribution statement

T. J. Ó Ceallaigh: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Stephen Murphy:** Writing – original draft, Methodology.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. They have no financial, personal, or professional relationships that could be construed to influence the work reported in this paper.

Appendix 1

Coding Framework for Within-Case and Cross-Case Analysis

This coding framework was adapted from Miles and Huberman [45] to support both vertical (within-case) and horizontal (cross-case) analyses of the 17 studies reviewed. The template guided systematic comparison across studies in relation to the three research questions concerning GenAI-specific TPK and teacher/TE professional learning.

Category		Description / Coding Guidance
1	Author(s) and Year	Record citation details (APA format).
2	Country / Region	Identify where the study was conducted.
3	Study Type / Methodology	Qualitative, quantitative, mixed-methods, or conceptual/theoretical.
4	Sample Characteristics	Describe participant group(s): pre-service teachers, in-service teachers, teacher educators, etc.
5	Definition or Description of TPK / GenAI-TPK	Summarize how TPK or GenAI-related knowledge is defined, framed, or operationalized.
6	Key Components or Dimensions	Identify elements emphasized (technological, pedagogical, ethical, critical, creative, socio-cultural).
7	Epistemological / Theoretical Lens	Note theoretical stance (critical pedagogy, postdigital learning, socio-constructivism, etc.).
8	Type of Educators Studied	Specify whether the study focuses on pre-service, in-service, or teacher educators.
9	Forms of GenAI-TPK Required / Observed	Identify knowledge types (ethical awareness, critical literacy, AI-augmented instructional design, reflective practice).
10	Pedagogical Practices or Learning Activities	Record teaching or learning strategies involving GenAI (co-design, inquiry-based learning, prompt engineering).
11	Challenges and Tensions Identified	Capture issues such as lack of training, policy ambiguity, ethical uncertainty, or infrastructure gaps.
12	Teacher Educator Competences Required	Identify competences such as ethical facilitation, critical mentoring, or AI-integrated curriculum design.
13	Institutional / Professional Supports	Note existing or recommended supports (PD initiatives, policy frameworks, communities of practice).
14	Identified Gaps in TE Preparation	Summarize deficits in knowledge, training, or institutional readiness.
15	Recommendations / Implications	Record authors' recommendations for research, practice, or policy.
16	Summary of Main Findings	Concise summary of each study's main outcomes.
17	Contribution to GenAI-TPK Framework	Indicate how the study advances understanding of TPK in GenAI contexts (ethical-critical dimensions, frameworks, pedagogical models).

Analytic Approach: Each study was first analyzed vertically using the 17 categories above, with the article as the unit of analysis. Findings were then compared horizontally across all studies to identify systematic similarities, differences, and emerging patterns related to the three research questions.

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