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REVIEW

Generative AI in Pre-Service Science Teacher Education: A Systematic Review

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Abstract: Despite the increasing adoption of Generative Artificial Intelligence (GenAI) in education, there is a lack of comprehensive reviews on how GenAI is being utilized within Pre-Service Teachers (PSTs) in science. This systematic literature review (SLR) aims to address this gap by examining the extent and nature of GenAI integration in future science teachers' preparation programs. Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, 21 peer-reviewed empirical studies published between 2022 and 2025 were identified and analyzed through qualitative thematic synthesis. The analysis addresses three research questions: 1) the extent to which GenAI is used in the curriculum of PSTs in science education; 2) how PSTs use GenAI tools to develop a deeper understanding of science and develop scientific reasoning; and 3) how PSTs in science education are using GenAI tools to plan and carry out teaching activities. Findings reveal that the integration of GenAI into curricula remains fragmented and often experimental, typically confined to technology-related courses or pilot projects. PSTs primarily utilize GenAI tools for conceptual clarification, hypothesis generation, and self-regulated learning. Furthermore, these tools serve as cognitive partners in designing lesson plans, differentiating instruction, and simulating classroom scenarios. However, the absence of structured pedagogical guidance often leads to superficial use and limited critical evaluation of AI-generated content. This review highlights the transformative potential of GenAI in science education while underscoring the need for institutional frameworks, faculty training, and the development of AI literacy. Future research should focus on how to sustainably integrate GenAI into teacher education to foster scientific reasoning, pedagogical adaptability, and responsible use of technology.

Keywords: Generative AI, ChatGPT, Large Language Models, Pre-Service Teacher Education, PSTs, PRISMA

1 Introduction

Educational systems worldwide have undergone a profound shift toward digital transformation in recent years, driven by the rapid evolution of artificial intelligence (AI) technologies. Among the most influential developments is the emergence of Generative Artificial Intelligence (GenAI), particularly Large Language Models (LLMs), which have begun to reshape teaching and learning practices across disciplines (Brunton et al., 2024). Initially confined to experimental pilot programs or niche applications, GenAI has entered mainstream education through widely accessible, conversational tools such as ChatGPT. These tools offer dynamic language generation, contextual interaction, and user-friendly interfaces, expanding their potential as cognitive partners and instructional resources.

Within science education, where fostering conceptual understanding, scientific reasoning, and inquiry-based practices is critical, the integration of GenAI presents unique affordances and challenges. Specifically, GenAI may act as a scaffold for learners' cognitive processes, support knowledge construction, and enhance instructional design. These possibilities have sparked increasing scholarly attention and practical experimentation; yet, the extent and nature of GenAI's pedagogical impact in PSTs' science education remain underexplored (Sotiropoulos & Kalogiannakis, 2025).

PSTs' science education offers a unique context in which these tools may have a transformative impact (Stinken-Rösner et al., 2023). Future science teachers are expected to master scientific knowledge and develop pedagogical strategies that promote inquiry, critical thinking, and engagement in their classrooms (Marangio et al., 2024). Integrating GenAI into PSTs training could facilitate this dual development, both as a means for improving conceptual understanding and as a support for designing innovative teaching practices (Bae et al., 2024).

Despite the growing body of literature on AI in education, a significant gap remains in understanding how PSTs in science education utilize GenAI tools, the extent to which they are integrated into teacher education curricula, and the challenges and opportunities associated with their implementation (Arantes, 2024). This systematic review addresses that gap by synthesizing current empirical studies on the integration and pedagogical application of GenAI tools in PSTs' science education.

2 Literature Review

2.1 Science Education

Science education is a specialized branch of pedagogy that focuses on teaching and learning the natural sciences, including physics, chemistry, biology, and earth sciences. It emphasizes the development of scientific thinking, understanding scientific methodology, and acquiring basic scientific literacy (Qiao et al., 2024).

In contrast to general pedagogy, which emphasizes broader learning theories and the psychosocial dimensions of education, science education demands in-depth cognitive engagement with scientific subject matter, active involvement in inquiry-based practices, modeling, and experimentation. As Dyachenko et al. (2024) highlight, teaching disciplines like chemistry or physics cannot be reduced to the simple application of general didactic principles; it requires methodological specialization that reflects the unique nature of each scientific field.

Valladares (2021) underscores that science education draws upon the philosophy of science, cognitive psychology, and science and technology studies (STS) while contributing to the development of a "scientific culture" among citizens. Science education is not merely about knowledge transmission but about fostering a critical understanding of how science operates and its broader societal implications (Yazidi & Rijal, 2024).

Thus, the distinction between science education and general pedagogy lies in the content focus and their philosophical, methodological, and analytical foundations. Mukhamejanova et al. (2025) and Khalaf (2018) demonstrated that traditional pedagogical methods often fail to convey scientific understanding when applied without adaptation to the specific nature of scientific disciplines.

2.2 Theoretical Framework

This study is grounded in an interdisciplinary theoretical framework from four intersecting domains: Artificial Intelligence in Education, Science Teacher Preparation, Pedagogical Content Knowledge (PCK), and Technology Integration Models.

First, the role of GenAI tools in education has evolved from static information providers to interactive cognitive partners (Chiu, 2023). As Sotiropoulos & Kalogiannakis (2025) and Hu & Chan (2023) highlight, GenAI can support learners in constructing scientific explanations, generating hypotheses, and simulating classroom dialogue activities deeply connected to scientific reasoning and cognitive engagement. Similarly, Ragab (2025) emphasizes the transformative potential of GenAI for enabling personalization and inquiry-based learning in STEM education (Nguyen et al., 2025; Abduljalil et al., 2025). These capacities indicate GenAI's ability to stimulate metacognitive processes and curiosity, especially when embedded in constructivist learning contexts.

Second, Pedagogical Content Knowledge (PCK) remains central in science teacher education (Kind, 2009; Nilsson & Vikström, 2015). PCK enables teachers to transform content knowledge into pedagogically meaningful representations for learners (Blonder et al., 2024; Yip et al., 2024). In the context of GenAI, tools like ChatGPT can act as scaffolds for developing PCK (Buck et al., 2010), for example, by prompting PSTs to explain scientific ideas (Lee & Zhai, 2024), anticipate student misconceptions, or design contextually relevant instructional strategies (Warr et al., 2023). However, the review findings indicate that many teacher candidates use GenAI in a limited, surface-level way, often due to a lack of structured pedagogical guidance. This suggests that AI literacy should be treated as a dimension of PCK, equipping future teachers with content knowledge and the critical awareness needed to use AI responsibly and pedagogically (Yue et al., 2024; Daniela & Tenberga, 2024).

Third, technology integration models, such as TPACK (Technological Pedagogical Content Knowledge), offer a conceptual lens for understanding how GenAI intersects with content and pedagogy (Salinas-Navarro, 2024; Chiu, 2024). GenAI is part of this model's Technological

Knowledge (TK) domain but only becomes effective when it aligns with pedagogical purposes and content understanding (Kohnke et al., 2025). The reviewed studies show that PSTs often succeed in integrating GenAI into lesson planning, particularly in designing student-centered content and adapting instruction (Karataş & Yüce, 2024; Küchemann et al., 2023; Peikos & Stavrou, 2025; Uğraş et. al., 2024). These applications support the development of TPACK. However, they also reveal weaknesses: many GenAI uses were limited to content generation or automation (e.g., quiz creation), without deeper integration into instructional decision-making (Vilalta-Perdomo et al., 2024; Sharma et al., 2024). This underscores the importance of intentional design and reflective practice as essential foundations for meaningful TPACK development with GenAI.

Finally, this review adopts the stance that GenAI can support both cognitive development (e.g., scientific reasoning, hypothesis generation) and instructional design (e.g., lesson planning, differentiation), provided it is embedded within coherent educational frameworks (Blonder et al., 2024; Cooper et al., 2025). Bridging theory and practice, this review aims to map the current use of GenAI and critically evaluate its pedagogical depth, highlighting where theoretical integration remains underdeveloped and where future research and training should focus.

2.3 Pedagogical Models and Frameworks

To contextualize the use of GenAI in science education, this section outlines key pedagogical models and frameworks that inform the development of scientific reasoning and the integration of technology. These models also help interpret the review's findings and provide guidance on implications for practice.

2.3.1 The 5E Instructional Model

The 5E model (Engage, Explore, Explain, Elaborate, Evaluate) emphasizes a constructivist cycle of inquiry and reflection (Peña & Maatubang, 2025; Bahtaji, 2021). The review findings show that PSTs frequently use GenAI to generate student questions (Engage phase), simulate experiments or create inquiry prompts (Explore), and clarify scientific concepts (Explain) (Jyothy et al., 2024). However, the Elaborate and Evaluate phases, which require synthesis and critical thinking, are less commonly supported by GenAI, suggesting that teacher candidates may not yet leverage GenAI for deeper instructional engagement (Peikos & Stavrou, 2025; Sun et al., 2025; Wood & Moss, 2024). This highlights the need to scaffold GenAI use across all phases of the 5E model, particularly in fostering student reflection and designing formative assessments.

2.3.2 Inquiry-Based Learning (IBL)

IBL promotes learner autonomy and reasoning through problem-solving and investigation (Carracedo, 2025). Many reviewed studies confirm that GenAI can support this model, for instance, by helping trainees pose research questions, interpret data, or simulate experiments (Cooper, 2023; Kotsis, 2024). However, few studies explicitly assess how GenAI enhances students' scientific reasoning processes, such as forming hypotheses or critiquing evidence (Abualrob, 2025). To more effectively embed GenAI in IBL environments, teacher education programs must develop specific instructional strategies that combine AI prompts with inquiry tasks and reflection.

2.3.3 TPACK Framework

The TPACK framework identifies effective teaching as the intersection of Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK) (Tseng et al., 2022; Xu et al., 2024; Tseng et al., 2020). Within this model, GenAI's role is promising but uneven. The review reveals that GenAI is often employed as a technology enhancer for lesson planning, which can facilitate TK and PK, but it is rarely utilized to transform how content is conceptualized (CK) (Ceylan & Karakus, 2024; Yan et al., 2024; Vilalta-Perdomo et al., 2024). A key implication is that teacher training should not treat GenAI merely as a tool for content production, but as a platform for reconceptualizing science teaching (Yan et al., 2024), for example, using GenAI to generate alternative explanations, identify misconceptions, or model scientific thinking (Peikos & Stavrou, 2025). This requires deliberate efforts to strengthen AI-supported TPACK, with an emphasis on reflection and ethics (Celik, 2022; Feldman-Maggor et al., 2025; Petousi & Sifaki, 2020; Warr et al., 2023).

2.3.4 SAMR Model

The SAMR model (Substitution, Augmentation, Modification, and Redefinition) frames technological integration on a continuum from Substitution to Redefinition (Hamilton et al., 2016). The review identifies that most GenAI use by PSTs currently falls within Substitution (e.g., replacing search engines) (Barbieri & Nguyen, 2025; Bae et al., 2024) or Augmentation (e.g., streamlining lesson planning) (Wang K. et al., 2024; Blonder et al., 2024; Markos et al., 2024). Only a few studies demonstrate Modification (e.g., tailoring AI prompts for inquiry-based learning), and almost none reach Redefinition, where GenAI enables fundamentally new pedagogical experiences (e.g., real-time AI feedback during student experiments) (Brunton et al., 2024; Salinas-Navarro et al., 2024). This suggests that while GenAI has transformative potential, realizing that potential requires intentional instructional design and scaffolding, both of which are still largely absent from current PSTs' training.

3 Materials and Methods

To gain a comprehensive understanding of how GenAI is integrated within the context of science education, a Systematic Literature Review (SLR) was conducted. The review adheres to the PRISMA 2020 guidelines to ensure methodological transparency and replicability (Page et al., 2020). The methodological approach included the following stages:

(1) Formulation of research questions based on the study objectives;
(2) Search for relevant studies in selected scientific databases;
(3) Definition of inclusion and exclusion criteria for selecting articles;
(4) Evaluation and selection of relevant studies;
(5) Extraction and organization of data from the selected publications;
(6) Analysis and interpretation of the findings concerning the research questions;
(7) Synthesis of conclusions in the context of writing this systematic review.

3.1 Research Questions

To explore the current state of the literature regarding the use of GenAI in PSTs' science education, the following research questions have been formulated:

RQ1: To what extent and in what ways has GenAI been integrated into the curriculum of PSTs' science education?

RQ2: In what ways do PSTs use GenAI tools to enhance their understanding of scientific concepts and reasoning?

RQ3: How do PSTs' science education employ GenAI tools to design and implement teaching practices?

3.2 Search Strategy

Four internationally recognized databases were selected to collect relevant academic sources. These databases span the interdisciplinary domains of science education, teacher education, and educational technology: ERIC (Education Resources Information Center), Scopus, IEEE XPLORE, and ProQuest Education.

The selection of these four databases aims to ensure the validity, representativeness, and thematic relevance of the sources included in the review. Given the diversity of terminology in the literature concerning GenAI and PSTs' science education, the search strategy incorporated synonyms and alternative terms, as recommended by each controlled vocabulary and thesaurus tool. The principal thematic axes of the search included the following concepts: 1) GenAI (e.g., ChatGPT); 2) Science Education; 3) PSTs.

These keywords were strategically combined to generate powerful search queries, ensuring broad coverage of the relevant scientific literature, as presented in Table 1.

Table 1 Core Concepts and Synonyms

Core Concepts	Synonyms
GenAI	Generative AI, Generative Artificial Intelligence, GenAI, ChatGPT, LLMS, Large Language Models.
Science	Science, Scientific Reasoning, Scientific Thinking, Science Understanding, Inquiry Skills, Scientific Thinking Skills, Scientific Practices, Critical Thinking in Science.
Teaching practice	Teaching strategies, lesson planning, instructional design, pedagogical practices, classroom implementation, science teaching, Curriculum, Curriculum Integration.
Pre-service Teachers	Pre-service Teachers, Pre-service Science Teachers, Future Teachers, Teacher Education, Teacher candidates.

The search strategy for this systematic review was designed to comprehensively capture empirical and theoretical studies at the intersection of GenAI, science education, scientific reasoning, and PST training. To this end, a Boolean search string was constructed based on key concepts derived from the research questions and informed by terminology frequently used in the relevant literature.

The following Boolean string was applied across selected academic databases (ERIC, Scopus, IEEE XPORE, ProQuest):

(“Generative AI” OR “Generative Artificial Intelligence” OR “GenAI” OR “ChatGPT” OR “LLMs” OR “Large Language Models”) AND (“Science” OR “Scientific Reasoning” OR “Scientific Thinking” OR “science understanding” OR “inquiry skills” OR “Inquiry Skills” OR “Scientific Thinking Skills” OR “Scientific Practices” OR “Critical Thinking in Science”) AND (“teaching strategies” OR “lesson planning” OR “instructional design” OR “pedagogical practices” OR “classroom implementation” OR “science teaching” OR “Curriculum” OR “Curriculum Integration”) AND (“Pre-service Teachers” OR “Preservice Teachers” OR “Preservice Science Teachers” OR “Future Teachers” OR “Teacher Education” OR “Teacher candidates”)

The above general search string was applied in all databases, encompassing all core concepts and synonyms. Additionally, when databases provided filtering options (e.g., by publication date or language), further refinements were applied according to the predefined inclusion and exclusion criteria. The detailed database-specific search strings, applied filters, and date limits are provided in Table 2. This ensures transparency and replicability of the search process across ERIC, Scopus, IEEE Xplore, and ProQuest.

Table 2 Database-specific search strategies, filters, and Boolean search strings were applied in this review.

Data Source	Filters	String
ERIC	2022-25, Peer-peer, full text, artificial intelligence, higher education,	(“Generative AI” OR “Generative Artificial Intelligence” OR “GenAI” OR “ChatGPT” OR “LLMs” OR “Large Language Models”) AND (“Science” OR “Scientific Reasoning” OR “Scientific Thinking” OR “science understanding” OR “inquiry skills” OR “Inquiry Skills” OR “Scientific Thinking Skills” OR “Scientific Practices” OR “Critical Thinking in Science”) AND (“teaching strategies” OR “lesson planning” OR “instructional design” OR “pedagogical practices” OR “classroom implementation” OR “science teaching” OR “Curriculum” OR “Curriculum Integration”) AND (“Pre-service Teachers” OR “Preservice Teachers” OR “Preservice Science Teachers” OR “Future Teachers” OR “Teacher Education” OR “Teacher candidates”)
Scopus	2022-25, journals, conference papers.	(“Generative AI” OR “Generative Artificial Intelligence” OR “GenAI” OR “ChatGPT” OR “LLMs” OR “Large Language Models”) AND (“Science” OR “Scientific Reasoning” OR “Scientific Thinking” OR “science understanding” OR “inquiry skills” OR “Inquiry Skills” OR “Scientific Thinking Skills” OR “Scientific Practices” OR “Critical Thinking in Science”) AND (“teaching strategies” OR “lesson planning” OR “instructional design” OR “pedagogical practices” OR “classroom implementation” OR “science teaching” OR “Curriculum” OR “Curriculum Integration”) AND (“Pre-service Teachers” OR “Preservice Teachers” OR “Preservice Science Teachers” OR “Future Teachers” OR “Teacher Education” OR “Teacher candidates”)
IEEE XPLORE	2022-25, journals, conference papers	(“Generative AI” OR “Generative Artificial Intelligence” OR “GenAI” OR “ChatGPT” OR “LLMs” OR “Large Language Models”) AND (“Science” OR “Scientific Reasoning” OR “Scientific Thinking” OR “science understanding” OR “inquiry skills” OR “Inquiry Skills” OR “Scientific Thinking Skills” OR “Scientific Practices” OR “Critical Thinking in Science”) AND (“teaching strategies” OR “lesson planning” OR “instructional design” OR “pedagogical practices” OR “classroom implementation” OR “science teaching” OR “Curriculum” OR “Curriculum Integration”) AND (“Pre-service Teachers” OR “Preservice Teachers” OR “Preservice Science Teachers” OR “Future Teachers” OR “Teacher Education” OR “Teacher candidates”)
ProQuest	2022-25, journals, conference papers, Artificial intelligence	(“Generative AI” OR “Generative Artificial Intelligence” OR “GenAI” OR “ChatGPT” OR “LLMs” OR “Large Language Models”) AND (“Science” OR “Scientific Reasoning” OR “Scientific Thinking” OR “science understanding” OR “inquiry skills” OR “Inquiry Skills” OR “Scientific Thinking Skills” OR “Scientific Practices” OR “Critical Thinking in Science”) AND (“teaching strategies” OR “lesson planning” OR “instructional design” OR “pedagogical practices” OR “classroom implementation” OR “science teaching” OR “Curriculum” OR “Curriculum Integration”) AND (“Pre-service Teachers” OR “Preservice Teachers” OR “Preservice Science Teachers” OR “Future Teachers” OR “Teacher Education” OR “Teacher candidates”)

Truncations, wildcards, and syntax adjustments were made according to each database’s specific requirements. This search string was used to retrieve peer-reviewed journal articles and conference papers published from 2022 to 2025, aligning with the rapid development of GenAI tools in educational settings.

While this review focuses on the use of GenAI in PSTs’ science education, we also included studies that involved PSTs preparing to teach general science subjects, particularly in primary education. At the elementary level, science education is typically integrated, and prospective teachers often cover content from physics, chemistry, and biology. Therefore, studies that addressed GenAI-supported instruction without isolating specific scientific disciplines were deemed relevant to this review's scope.

3.3 Inclusion and Exclusion Criteria of Studies

Explicit inclusion and exclusion criteria were established to select the most relevant and appropriate studies for this systematic literature review. These criteria supported the identification, assessment, and final selection of articles that adequately addressed the research questions.

3.3.1 Inclusion Criteria

The studies selected for this systematic review were required to meet the following criteria:
(1) Publication Date: Published between 2022 and 2025, reflecting the emergence and rise of GenAI, particularly Large Language Models (LLMs), now widely accessible through chat-based educational tools like ChatGPT.
(2) Publication Type: Peer-reviewed journal articles or papers at reputable academic conferences.
(3) Content Focus: Empirical studies or well-substantiated theoretical papers specifically analyzing the use of GenAI (with emphasis on LLMs).
(4) Educational Context: Focus on science education, particularly in settings involving experimental or inquiry-based learning activities.
(5) Participants: Undergraduate or postgraduate PSTs preparing for Careers involving teaching in science education.

3.3.2 Exclusion Criteria

The following types of studies were excluded from the review:
(1) General discussions on Artificial Intelligence that do not specifically address GenAI or its role in education.
(2) Studies focusing exclusively on primary or secondary students without a clear connection to teacher education or instructional practices.
(3) Articles without full-text availability or those not published in English.
(4) Non-academic sources, such as blog posts, opinion pieces, or commentary, often lack scholarly rigor or peer-reviewed validation.
(5) Systematic literature reviews and meta-analyses.

3.4 Article Evaluation and Selection Process

To maintain feasibility while ensuring relevance, we limited our screening to the first 300 search results per database, following recommendations in systematic review literature (Haddaway et al., 2015). This approach has been applied in previous studies, particularly where the relevance of results declines rapidly beyond the initial pages. Although this practice originates in searches using Google Scholar, we extended the 300-result limit to all databases to maintain consistency and manageability, while acknowledging this as a methodological limitation (Kanaki & Kalogiannakis, 2023). In cases where fewer than 300 results were returned, all available records were screened for eligibility.

All databases initially retrieved 1,278 records (see Table 3). Of these, 918 records were included in the identification stage. Following a multi-step screening process - including removal of duplicates, filtering by publication year, and title relevance - 15 articles were excluded. Abstracts of the remaining 903 were examined in more depth to assess alignment with the scope of this review. Among these, 759 were eliminated due to their lack of direct connection with GenAI or PST education topics.

Table 3 Systematic review stages

Data Source	Initial search	1^{st} Stage (Identification)	2^{nd} Stage (Screening)	3^{rd} Stage (Eligibility)	4^{th} Stage (Eligibility)	5^{th} Stage (Included)
ERIC	422	300	297	58	12	4
Scopus	24	18	14	7	7	7
IEEE Xplore	353	300	297	46	14	6
ProQuest	479	300	295	33	8	4
Sum	1.278	918	903	144	41	21

The remaining 144 studies were evaluated thoroughly against the inclusion criteria and the research questions guiding this study. A thematic analysis approach (Braun & Clarke, 2006) was employed, with each reviewer maintaining individual annotations and reading each study multiple times to ensure an accurate interpretation of the methodological design and findings. All assessments were subsequently compared and discussed collaboratively. One hundred and three studies were excluded at this stage because they did not focus on science education activities. To enhance the credibility of this review and minimize the risk of bias, the research team employed triangulation methods during the data extraction and synthesis phases, applying them to the remaining 41 articles. This included cross-referencing study characteristics (e.g., methodology, sample size, intervention clarity, and reported outcomes) across multiple reviewers.

Studies were assessed for transparency in reporting, alignment between objectives and findings, and potential overstatements of results. Although no formal checklist was used (e.g., ROBIS or MMAT), this triangulated evaluation process allowed for a systematic appraisal of the robustness and reliability of each study. As a result, 20 studies demonstrating adequate relevance were excluded from the final synthesis. The decision was made based on the article's alignment with the inclusion criteria, particularly its relevance to PSTs' science education, the integration of GenAI, and science-related teaching practices or reasoning.

Screening and coding were conducted by three independent reviewers who each examined the titles, abstracts, and full texts against the inclusion criteria. Disagreements were resolved through open discussion and a consensus-based approach. Although no formal inter-rater reliability statistic (e.g., Cohen's kappa) was calculated, the team-based approach, with joint review sessions, helped ensure consistency and transparency in the study selection and thematic coding process.

At the final stage, 21 studies were retained, and the final dataset of this review was formed (summarized in Table 4). The PRISMA flow diagram used for article selection is presented in Figure 1.

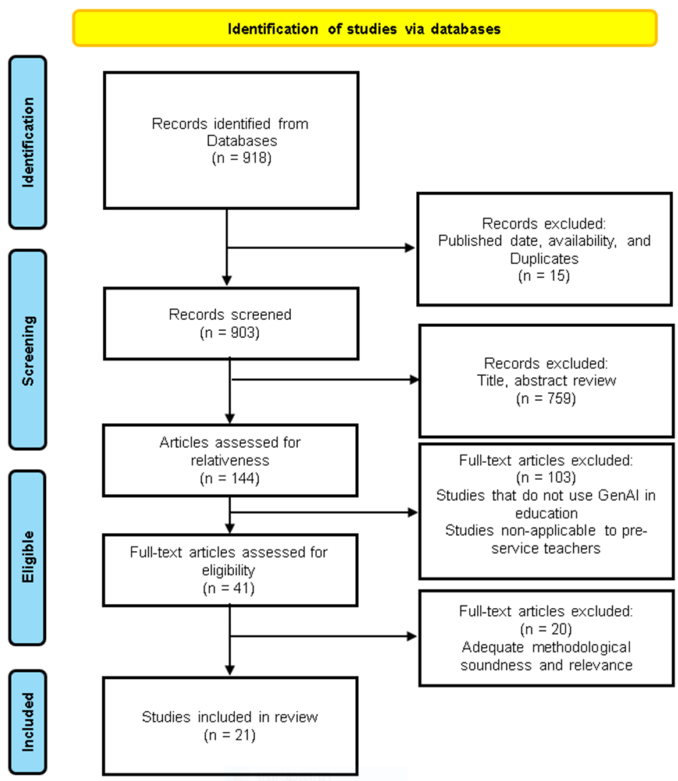

Figure 1 PRISMA review processes

4 Data Extraction and Analysis

A set of 21 articles was examined to generate consolidated findings relevant to the research questions. Table 4 summarizes the final set of studies examining the use of GenAI tools in preparing future science teachers. It showcases a range of tools (e.g., ChatGPT, Copilot, Bard), with ChatGPT being the most frequently used. The titles reflect themes such as lesson planning, PCK development, and inquiry-based teaching. Overall, it highlights the rapid growth of research on integrating AI in education from 2022 to 2025.

Table 4 Final set of articles reviewed

No	Author(s)	Year	GenAI Tool used	Title
1	Abri et al.	2025	NearPod, Curipod, Steve AI, Flipgrid	Exploring the Implications of Generative-AI Tools in Teaching and Learning Practices
2	Abualrob	2025	Copilot	How pre-service teachers use AI to teach science to fourth graders
3	Bae et al.	2024	ChatGPT	Pre-Service Teachers' Dual Perspectives on Generative AI: Benefits, Challenges, and Integration into Their Teaching and Learning
4	Blonder et al.	2024	ChatGPT	Are They Ready to Teach? GenAI as a Means to Uncover PCK
5	Ceylan & Karakus	2024	ChatGPT, PlantNet API	AI-Based Mobile App for Plant Blindness in Science Education
6	Cooper et al.	2025	ChatGPT	Intersections of Mind and Machine: AI and Science Education
7	Cooper	2023	ChatGPT	Examining Science Education in ChatGPT: An Exploratory Study of Generative Artificial Intelligence
8	Doorsamy et al.	2025	ChatGPT, Copilot	Generative Artificial Intelligence and Encounters with Knowledge in STEM Higher Education Curricula
9	Feldman-Maggor & Blonder	2024	ChatGPT 3.5, ChatGPT 4	Perspectives of Generative AI in Chemistry Education Within the TPACK Framework
10	Geesje van den Berg & Plessis	2023	ChatGPT	ChatGPT and Generative AI: Possibilities for Its Contribution to Lesson Planning, Critical Thinking, and Openness in Teacher Education
11	Karatas & Yüce	2024	ChatGPT	AI and the Future of Teaching: Preservice Teachers' Views on the Integration of Artificial Intelligence in Education
12	Küchemann et al.	2024	ChatGPT 3.5	Can ChatGPT support prospective teachers in physics task development?
13	Lee & Zhai	2024	ChatGPT	Using ChatGPT for Science Learning: A Study on Pre-service Teachers' Lesson Planning
14	Markos et al.	2024	ChatGPT 3.5	Pre-Service Teachers' Assessment of ChatGPT's Utility in Higher Education: SWOT and Content Analysis
15	Peikos & Stavrou	2025	ChatGPT-4o	ChatGPT for Science Lesson Planning: An Exploratory Study Based on Pedagogical Content Knowledge
16	Pellas et al.	2024	Visla, Sudowrite, Jasper	The Impact of AI-Generated Instructional Videos on Pre-Service Teachers' Motivation and Self-Efficacy
17	Pernaa & Haatainen	2024	ChatGPT, Bard, pdf2gpt	Artificial Intelligence Chatbots in Chemical Information Seeking Tasks
18	Prentzas & Sidiropoulou	2023	ChatGPT	Assessing the Use of OpenAI Chat-GPT in a University Department of Education
19	Ramnarain et al.	2024	ChatGPT	Pre-Service Science Teachers' Intention to Use Generative Artificial Intelligence in Inquiry-Based Science Teaching
20	Wang K. et al.	2025	ChatGPT, Gemini, Copilot	Scaffold or Crutch? Examining College Students' Use and Views of Generative AI Tools for STEM Education
21	Wang T. et al.	2024	BERT	Exploring Pre-service Science Teachers' Cognitive and Emotional Patterns.

Initially, a thorough review and thematic analysis of the selected articles was conducted, focusing primarily on methodological approaches, theoretical frameworks, research objectives, learning outcomes, and the connections between the use of GenAI and its application in science education.

In addition to analyzing the studies on the three research questions, Table 5 summarizes 21 studies that examine how GenAI tools have been integrated into PST education across various countries and institutions. It highlights the type of integration (e.g., compulsory courses, workshops, exploratory examples) and pedagogical purposes such as AI literacy, lesson planning, critical thinking, and inquiry-based teaching. While many entries lack detailed integration data, others provide concrete examples of structured approaches to developing future teachers' competence with AI.

Table 6 presents the alignment of each included study with the three research questions (RQ1–RQ3) concerning the integration, application, and pedagogical use of GenAI in PSTs' science education. A checkmark ($\surd$) indicates that the study addresses the research question, while a cross mark ($\times$) denotes that it does not.

Table 5 Overview of 21 studies integrating GenAI in PSTs' education curriculum

No	Author(s)	Institution Context	Type of Integration	Pedagogical Purpose
1	Abri et al.	Sultan Qaboos University	Compulsory course (TECH 3006)	AI literacy, lesson planning, producing digital content, and critical thinking
2	Abualrob	Arab American University	Not specified	Not specified
3	Bae et al.	Southeastern University	Asynchronous online courses	AI literacy, reducing anxiety, lesson planning, and ethical reasoning
4	Blonder et al.	Weizmann Institute of Science; KTH Royal Institute of Technology	Not specified	Not specified
5	Ceylan & Karakus	Muğla Sıtkı Koçman University	Not specified	Not specified
6	Cooper et al.	Curtin University; Higher Colleges of Technology	Not specified	Not specified
7	Cooper	Curtin University	Not specified	Not specified
8	Doorsamy et al.	University of Leeds; University of the Witwatersrand; University of Johannesburg	Not specified	Not specified
9	Feldman-Maggor & Blonder	Weizmann Institute of Science	Not specified	Not specified
10	Geesje van den Berg & Plessis	University of South Africa, Pretoria	Single exploratory example	Lesson planning support, critical thinking development;
11	Karataş & Yüce	Nevsehir Haci Bektas Veli Univ., Aksaray Univ.	3-week online workshop via Zoom	Develop AI literacy, integrate ChatGPT into teaching practices, and reflect on its ethical implications.
12	Küchemann et al.	LMU Munich, RPTU Kaiserslautern-Landau	Not specified	Not specified
13	Lee & Zhai	University of Georgia	Not specified	Not specified
14	Markos et al.	Democritus University of Thrace	Not specified	Not specified
15	Peikos & Stavrou	The University of Crete, Department of Primary Education	Not specified	Not specified
16	Pellas et al.	University of Western Macedonia	Training module in teacher education	Enhance PSTs' self-efficacy, task performance, and knowledge transfer in applying scientific concepts in PBL.
17	Pernaa & Haatainen	University of Helsinki; University of Ljubljana	Mandatory undergraduate course	Support development of modern information literacy; scaffold AI-assisted info seeking; foster critical thinking, academic writing, concept mapping, problem-solving
18	Prentzas & Sidiropoulou	Democritus University of Thrace, Department of Education Sciences in Early Childhood	Undergraduate elective course	Critically assess Chat-GPT as a learning, teaching, and support tool; educate PSTs in AI use; support creative writing, academic writing, student support, and staff productivity.
19	Ramnarain et al.	Faculty of Education, University of Johannesburg	Undergraduate BEd program	Investigate intention to use genAI in inquiry-based teaching; understand predictors (AI literacy, attitude, subjective norm, perceived usefulness, perceived behavioral control)
20	Wang K. et al.	Stanford University (Graduate School of Education, Department of Physics, Department of Mechanical Eng)	No formal curriculum integration	Not specified
21	Wang T. et al.	China, Artificial Intelligence Education Department	Not specified	Not specified

This systematic review analyzed 21 studies examining the role of GenAI in PSTs' science education, revealing both strong developments and notable gaps. A total of 8 studies (approximately 38%) reported the integration of GenAI into teacher education curricula. This included its use in instructional design, course restructuring, and reflective practices, often through tools such as ChatGPT and BERT. Similarly, 15 studies (71%) demonstrated that PSTs used GenAI to enhance their understanding of scientific concepts and reasoning. Applications included concept clarification, exploration of scientific ideas, and assistance with data interpretation and cognitive scaffolding. Another 12 studies (57%) also documented the use of GenAI in designing

Table 6 Mapping Research Questions to Included Studies

No	Author(s)	RQ1: GenAI in Curriculum	RQ2: GenAI for Understanding Science	RQ3: GenAI in Teaching Practices
1	Abri et al.	√	×	×
2	Abualrob	×	√	√
3	Bae et al.	√	√	√
4	Blonder et al.	×	√	√
5	Ceylan & Karakus	×	√	×
6	Cooper et al.	×	√	√
7	Cooper	×	√	√
8	Doorsamy et al.	×	√	√
9	Feldman-Maggor & Blonder	×	×	√
10	Geesje van den Berg & Plessis	√	×	×
11	Karataş & Yüce	√	×	×
12	Küchemann et al.	×	√	√
13	Lee & Zhai	×	√	√
14	Markos et al.	×	√	×
15	Peikos & Stavrou	×	×	√
16	Pellas et al.	√	√	√
17	Pernaa & Haatainen	√	√	×
18	Prentzas & Sidiropoulou	√	×	×
19	Ramnarain et al.	√	√	√
20	Wang K. et al.	×	√	×
21	Wang T. et al.	×	√	×

and implementing teaching practices, such as lesson planning, activity creation, and reflective teaching analysis.

However, only 3 out of the 21 studies (approximately 14%) addressed all three research questions simultaneously, indicating that the current literature focuses more on specific, rather than holistic, applications of GenAI. While the overall picture is promising and reflects a growing interest in AI-supported science education, the findings also highlight a fragmented research landscape. There remains a need for more comprehensive approaches that integrate GenAI consistently across curriculum design, conceptual learning, and pedagogical practice in science teacher preparation programs.

To support the methodological mapping of the selected studies, Table 7 provides a structured overview of their samples, research methods, and data collection instruments. This descriptive synthesis enables readers to assess the breadth and depth of empirical designs employed in the field.

4.1 Integration of GenAI into the Curriculum of PSTs' Science Education

Analysis of the reviewed studies reveals that integration of GenAI into PSTs' science education curricula remains fragmented, uneven, and often pilot-based, yet shows promising developments across diverse contexts. Among the 21 studies analyzed, only seven offered evidence of formal or structured curricular integration, with varying degrees of scope, depth, and pedagogical intent. Table 8 summarizes 21 studies showcasing diverse uses of GenAI tools by PSTs for lesson planning, content creation, problem-solving, and reflective learning within varied pedagogical frameworks.

A notable approach involved integrating formal courses within university curricula. Abri et al. (2025) described a compulsory undergraduate course in Oman that systematically incorporated ChatGPT to support lesson planning, critical thinking, and digital content production through a mixed in-person and online delivery approach. Similarly, Bae et al. (2024) detailed an asynchronous online module in the United States that aimed to build AI literacy, reduce adoption anxiety, and encourage ethical reflection in lesson planning. These studies highlight how GenAI can be formally integrated into teacher education programs to address both technological skills and critical pedagogical considerations.

Short-term workshops and elective modules provided another mode of integration, typically focusing on the practical application of AI paired with ethical awareness. For example, Karataş and Yüce (2024) implemented a three-week online workshop in Türkiye, emphasizing hands-on use of ChatGPT for lesson planning while explicitly addressing fairness, critical thinking, and data security. In Greece, Prentzas and Sidiropoulou (2023) offered an undergraduate elective

Table 7 Overview of Samples, Methods, and Instruments in Included Studies.

No	Author(s)	Sample (Number and Type)	Method (Data Collection)	Data Collection Instrument
1	Abri et al.	65 undergraduate students	Mixed-methods	Focus groups; Reflection essays; Questionnaires
2	Abualrob	46 undergraduate PSTs' science education	Qualitative	Semi-structured interviews
3	Bae et al.	54 undergraduate PSTs' science education	Mixed-methods	Online discussion posts; AI anxiety survey
4	Blonder et al.	Conceptual paper – no empirical sample	Conceptual/theoretical paper	Analysis of sample ChatGPT dialogues
5	Ceylan & Karakus	24 prospective science teachers	Quasi-experimental design	Academic Achievement Test; Plant Awareness Survey; Mobile Application Feedback Form
6	Cooper et al.	None	Conceptual editorial/review (no empirical data collection)	None
7	Cooper	1 (self-study; the author himself experimenting with ChatGPT prompts)	Self-study methodology; exploratory and reflective analysis of ChatGPT prompts	ChatGPT prompts and outputs used as both subject and tool of study
8	Doorsamy et al.	No student sample; exploratory analysis of AI responses to STEM questions	Conceptual/analytical study using Bloom's Taxonomy, SOLO Taxonomy, and Luckett's Knowledge Planes to analyze AI-generated answers	AI prompts with physics questions; authors' expert analysis and reflections
9	Feldman-Maggor & Blonder	No empirical student sample; position paper with constructed teacher-ChatGPT dialogues	Conceptual/analytical position paper; analysis of three constructed teacher-ChatGPT dialogues illustrating TPACK and AI literacy	ChatGPT dialogues constructed by authors and analyzed as exemplars.
10	Geesje van den Berg & Plessis	No human participants; analysis of one ChatGPT-generated lesson plan	Qualitative approach; exploratory case study design within an interpretative paradigm; document analysis of ChatGPT-generated lesson plan	ChatGPT-generated texts; authors' interpretive analysis of these materials
11	Karatas & Yüce	141 preservice teachers	Narrative inquiry	Reflection papers with structured prompts after a 3-week online module
12	Küchemann et al.	26 prospective physics teachers	Randomized controlled trial	Task development assignments, FCI pretest, SUS, TAM2 survey
13	Lee & Zhai	29 science PSTs	Mixed-method	Lesson plans, open-ended survey, GenAI-TPACK rubric
14	Markos et al.	257 undergraduate science PSTs	Mixed-method approach	Structured online questionnaire, content analysis of student ChatGPT queries, and reflections
15	Peikos & Stavrou	*No student sample*: This is an exploratory study based on the authors' interactions with ChatGPT-4.0	Qualitative content analysis of ChatGPT-generated lesson plans across four structured interactions	ChatGPT conversation transcripts
16	Pellas et al.	55 Greek science PSTs: Chemistry, Biology, Geology, Physics	Within-subjects experimental design; pre-test, post-test, transfer assessments; online surveys	AI-generated instructional videos; adapted Standards Self-Efficacy Scale; structured tests; Google Forms
17	Pernaa & Haatainen	No empirical student sample; designed for PSTs' chemistry education students	Theoretical/narrative literature review; design of learning activities; SWOT analysis	Not applicable; designed activities
18	Prentzas & Sidiropoulou	Preliminary results from 40 senior science PSTs	Mixed-methods planned; preliminary qualitative data; SWOT analysis by 10 groups of 4 students; class discussions.	SWOT analysis template, facilitated class discussion, no standardized survey/test instruments yet
19	Ramnarain et al.	42 third-year undergraduate science PSTs, natural science, and physical sciences	Sequential explanatory mixed-methods; Phase 1: survey, Phase 2: focus group interviews	Survey with a construct focus group interview guide
20	Wang K. et al.	40 undergraduate STEM students in the US;	Online student survey; parallel faculty survey; quantitative + qualitative analysis; prompt-writing task	Online survey with sections on genAI use, prompt engineering, helpfulness ratings, open-ended benefits/risks questions, demographics
21	Wang T. et al.	7–12 science PSTs per session;	Two phases (without/with multimodal analysis reports); transcription and BERT-based coding; Epistemic Network Analysis (ENA) visualization	Video-based automatic multimodal analysis reports; transcribed reflection text; pre-trained BERT model; ENA software for visualization

Table 8 Summary of GenAI tools, activities, and pedagogical framing in 21 studies on teacher education

No	Author(s)	GenAI Tool Used	Teaching Design Use	Pedagogical Framing / Course Context
1	Abri et al.	Curipod, Steve AI	Mind maps, lesson plan generation, interactive presentations, quiz/assessment integration.	Undergraduate course "TECH 3006: Technology for Learning", TPACK, ADDIE, ASSURE models.
2	Abualrob	Copilot	Creating lesson plans, instructional media, authentic assessments, and learner-centered strategies.	Teacher education training, 4th-grade science curriculum; exploratory qualitative case study.
3	Bae et al.	ChatGPT	Brainstorming, lesson plans, assignment prompts, writing support, and personalized study plans.	Undergraduate teacher preparation courses; asynchronous online format, Diffusion of Innovations framework.
4	Blonder et al.	ChatGPT	Lesson planning, generating teaching activities, revealing PCK via chat, and structured prompts.	Conceptual paper on science teacher education; Chemistry teacher education (pre/in-service), PCK/TPACK development.
5	Ceylan & Karakus	ChatGPT, PlantNet API	Designing a mobile app for plant ID, virtual herbarium creation, AI-based quizzes, and mapping collections.	Quasi-experimental study with pre-/post-tests; extracurricular outdoor teaching; focus on botany and environmental awareness.
6	Cooper et al.	ChatGPT	Lesson idea generation, content summarisation, and assessment preparation.	Initial Teacher Education (ITE) programs for pre-service science teachers; Science Education focus, inquiry-based learning, critical AI literacy.
7	Cooper	ChatGPT	Designing science units (e.g., 5Es model), creating rubrics, and generating quizzes with answer keys.	Science education for Year 7 level topics, social-constructivist approaches (5Es model), student-centered pedagogy balanced with teacher-centered methods.
8	Doorsamy et al.	ChatGPT, Microsoft Copilot	Analysis of quiz questions and assessment tasks in physics, exploring genAI's use in producing answers to conceptual and applied questions, examining fit with taxonomies.	STEM higher education curricula (Physics focus), constructivist approach, using Bloom's, SOLO Taxonomy, Luckett's Knowledge Planes for analysis.
9	Feldman-Maggor & Blonder	ChatGPT 3.5, ChatGPT 10	Designing chemistry lesson plans and activities, demonstrating teacher-student dialogue with ChatGPT, prompting engineering to refine responses, and generating images for teaching materials.	Chemistry education within the TPACK framework, integrating technological, pedagogical, and content knowledge, with an emphasis on teacher PCK in prompt creation and evaluation, addressing AI literacy needs beyond TPACK.
10	Geesje van den Berg & Plessis	ChatGPT	Generating lesson plans (e.g., English second language lesson on prepositions), creating worksheets with answer keys; generating visual presentations with guidance for slides, providing suggestions for online resources, exercises, games, and books.	Initial and continuing teacher education; teacher training programs focused on lesson planning, critical thinking, and openness, use of ChatGPT as an Open Educational Resource (OER) generator; fostering critical thinking through evaluation and adaptation of AI-generated content.
11	Karataş & Yüce	ChatGPT	Reflection papers with guiding questions on AI in teaching, Zoom-based course activities on learning theories, AI-assisted lesson planning, cognitive mapping, and personalized learning quests.	Open and distributed learning environment, Preservice teacher education course at the university.
12	Küchemann et al.	ChatGPT 3.5	Task development for high school physics assessment: RCT with ChatGPT-assisted vs. textbook-supported design. Participants generated four conceptual kinematics tasks for 10th-grade students.	Preservice physics teacher education, University-level training, Emphasis on assessment literacy and task design.
13	Lee & Zhai	ChatGPT	Required integration into 45-minute elementary science lesson plans, including teaching methods (POE, analogy, concept mapping), Simulated dialogues with ChatGPT, and Curriculum alignment focus.	Preservice elementary science teacher education, Science Education 1 course at the Korean teachers' university, with an emphasis on GenAI-TPACK framework.
14	Markos et al.	GPT-3.5	Structured questionnaire (SWOT analysis) Integration in an elective course project. Students submitted 10 queries and provided explanations for the recommendations they received.	Pre-service teacher education; Departments of Primary and Early Childhood Education, including lab sessions on digital storytelling, robotics, and AI concepts.
15	Peikos & Stavrou	ChatGPT-4.0	Four designed interactions for primary science lesson planning, used prompt engineering strategies (layer prompts, reference texts); Prompts crafted with PCK elements, focus on floating and sinking topic.	Teacher–AI co-design approach; Focus on PCK framework (Content, Pedagogy, Context overlaps), aimed at primary science education.
16	Pellas et al.	Visla, Sudowrite, Jasper	Designed videos (with/without preview) teaching Newtonian mechanics using the IDEA framework.	PBL in pre-service science teacher education.
17	Pernaa & Haatainen	ChatGPT, Bing Chat, Bard, pdf2gpt	Three activities: AI-supported summaries, concept maps, and code/device building.	ICT in Chemistry Education: The TPACK Framework.
18	Prentzas & Sidiropoulou	OpenAI ChatGPT	Course support: announcements, email drafts, academic writing, lesson planning, pilot: creative writing feedback	The teacher education department focuses on writing courses.
19	Ramnarain et al.	GenAI in general	Inquiry-based science teaching: brainstorming, hypothesis generation, simulation, procedure planning.	Inquiry-Based Learning (IBL), Theory of Planned Behavior.
20	Wang K. et al.	ChatGPT, Gemini, Copilot	Tasks: finding explanations, exploring topics, summarizing readings, solving problem-sets, analyzed prompting behaviors.	STEM problem-solving competency in undergraduate courses.
21	Wang T. et al.	BERT	Compared reflections with/without multimodal analysis reports; supported critical collective reflection.	Teacher education for pre-service science teachers: collective reflection with CoI and ENA frameworks.

course on creative writing that included critical evaluation of AI-generated text, underscoring the need for reflective, cross-disciplinary AI literacy even in non-science contexts.

Blended learning (Ampartzaki et al., 2024) and problem-based learning (PBL) environments also showed promise for integrating GenAI. Pellas (2025) presented a case study from Greece where an online training module on Newtonian mechanics used videos, quizzes, and lab sessions to enhance self-efficacy and support PBL strategies. This approach demonstrated GenAI's potential to scaffold learner autonomy and knowledge transfer when carefully designed. Likewise, Pernaa et al. (2024) described a multi-level integration strategy in Finland and Slovenia, embedding GenAI in both undergraduate and master's programs to foster academic writing, concept mapping, problem-solving, and critical thinking through structured prompt engineering and ethical evaluation.

Broader adoption intentions and readiness were also explored. Ramnarain et al. (2024) in South Africa examined factors influencing PSTs' intention to adopt GenAI, highlighting its potential for supporting learner autonomy, experimental simulation, and

differentiation. However, these studies collectively emphasized persistent challenges—including limited institutional support, variability in instructional design quality, risks of reduced critical thinking, and concerns over data privacy and bias.

Overall, while GenAI's curricular integration in PSTs' science education remains emergent and uneven, these studies demonstrate its potential to enhance lesson planning, inquiry-based learning, critical AI literacy, and reflective practice when implemented deliberately and ethically. The evidence underscores the importance of structured pedagogical design, instructor training, and institutional commitment to realizing GenAI's transformative potential in teacher education.

4.2 Use of Generative AI Tools by PSTs to Enhance Understanding of Scientific Concepts and Reasoning

Across the reviewed studies, PSTs employed GenAI tools in diverse and pedagogically meaningful ways to support their understanding of scientific concepts and reasoning. Rather than a uniform approach, the literature reveals a range of instructional goals and activities, from lesson planning to inquiry-based learning and critical reflection. Table 9 details 21 studies of GenAI use in teacher education, highlighting diverse implementation practices, design tasks ranging from lesson planning to assessment creation, and varied pedagogical frameworks that span TPACK, inquiry-based learning, and reflective practice.

A prominent use case involved lesson planning and content generation. Many studies have documented the use of PSTs, utilizing tools such as ChatGPT, to draft lesson outlines, adapt content to different learning levels, and generate assessment tasks. For example, Bae et al. (2024) found that participants used ChatGPT in asynchronous online courses to brainstorm lesson ideas and refine writing with structured prompts, emphasizing critical analysis and ethical reflection. Similarly, Lee and Zhai (2024) trained elementary science teachers to create 45-minute lesson plans that integrate methods such as Predict–Observe–Explain (POE) and analogy, utilizing ChatGPT to support individualized learning design.

Another key theme was inquiry-based learning and scientific reasoning. Several studies highlighted GenAI's role in supporting hypothesis generation, experimental design, and cognitive scaffolding. Cooper et al. (2025) described the use of large language models for guided discovery learning in topics like global warming, while Ramnarain et al. (2024) reported on PSTs brainstorming hypotheses and simulating experimental procedures to foster learner autonomy in inquiry-based contexts.

Concept clarification and addressing misconceptions emerged as additional affordances. Peikos & Stavrou (2025) demonstrated how primary science teachers in Greece utilized ChatGPT-4 to co-design lessons on floating and sinking, employing layered prompting to identify and address student misconceptions within a 5E instructional framework. Blonder et al. (2024) similarly analyzed the dialogical interactions between chemistry PSTs and ChatGPT to refine prompts and uncover conceptual misunderstandings in molecular and ionic materials.

Ultimately, the literature emphasizes the importance of critical evaluation and reflective practice when utilizing GenAI tools. Studies like Pernaa et al. (2024) in Finland integrated activities such as concept mapping and instrument design with structured reflection and SWOT analyses to promote higher-order thinking and AI literacy. Wang et al. (2024) described collective reflection sessions in China, using multimodal analysis and natural language processing models to support collaborative inquiry and critical assumption-checking.

Table 9 Summary of 21 studies on GenAI use in PSTs' education across science and non-science contexts

No	Author(s)	Implementation Practice	Teaching Design Use	Pedagogical Framing / Course Context
1	Abri et al.	4th-grade science lesson planning	Mind maps, lesson plan generation, interactive presentations, quiz/assessment integration	Undergraduate course "TECH 3006: Technology for Learning"; TPACK, ADDIE, ASSURE models
2	Abualrob	General teacher education context (not subject-specific)	Creating lesson plans, instructional media, authentic assessments, and learner-centred strategies.	Teacher education training, 4th-grade science curriculum; exploratory qualitative case study
3	Bae et al.	Lesson planning in teacher preparation courses, including science topics.	Brainstorming, lesson plans, assignment prompts, writing support, personalized study plans	Undergraduate teacher preparation courses; asynchronous online format; Diffusion of Innovations framework
4	Blonder et al.	Chemistry lesson planning	Lesson planning, generating teaching activities, revealing PCK via chat, structured prompts	Conceptual paper on science teacher education; Chemistry teacher education ; PCK/TPACK development
5	Ceylan & Karakus	General teacher education context (not subject-specific)	Designing a mobile app for plant ID, virtual herbarium creation, AI-based quizzes, and mapping collections	Quasi-experimental study with pre/post-tests; extracurricular outdoor teaching; focus on botany and environmental awareness
6	Cooper et al.	Pre-service science teacher programs	Lesson idea generation, content summarisation, assessment preparation	Initial Teacher Education (ITE) programs for pre-service science teachers; Science Education focus; inquiry-based learning; critical AI literacy
7	Cooper	Designing science units	Designing science units (e.g., 5Es model), creating rubrics, and generating quizzes with answer keys	Science education for Year 7 level topics; social-constructivist approaches (5Es model); student-centred pedagogy balanced with teacher-centered methods
8	Doorsamy et al.	Physics quiz question generation	Analysis of quiz questions and assessment tasks in physics; exploring genAI's use in producing answers to conceptual and applied questions; examining fit with taxonomies	STEM higher education curricula (Physics focus); constructivist approach; using Bloom's, SOLO Taxonomy, Luckett's Knowledge Planes for analysis
9	Feldman-Maggor & Blonder	Chemistry lesson planning	Designing chemistry lesson plans and activities, demonstrating teacher-student dialogue with ChatGPT, prompting engineering to refine responses, and generating images for teaching materials	Chemistry education within the TPACK framework; integrating technological, pedagogical, and content knowledge; emphasis on teacher PCK in prompt creation and evaluation; addressing AI literacy needs beyond TPACK
10	Geesje van den Berg & Plessis	General teacher education context (not subject-specific)	Generating lesson plans; creating worksheets with answer keys; generating visual presentations with guidance for slides; providing suggestions for online resources, exercises, games, and books	Initial and continuing teacher education; teacher training programs focused on lesson planning, critical thinking, and openness; use of ChatGPT as an Open Educational Resource (OER) generator; fostering critical thinking through evaluation and adaptation of AI-generated content
11	Karatas & Yüce	General teacher education context (not subject-specific)	Zoom-based course activities on learning theories; AI-assisted lesson planning, personalized learning quests	Open and distributed learning environment; Preservice teacher education course at the university.
12	Küchemann et al.	Physics assessment task	Task development for high-school physics assessment; RCT with ChatGPT-assisted vs textbook-supported design; Participants generated four conceptual kinematics tasks for 10^th grade	Preservice physics teacher education; University-level training; Emphasis on assessment literacy and task design
13	Lee & Zhai	Elementary science lesson plans	Required integration into 45-minute elementary science lesson plans; Included teaching methods; Simulated dialogues with ChatGPT; Curriculum alignment focus	Preservice elementary science teacher education; Science Education 1 course at the Korean teachers' university; GenAI-TPACK framework emphasis
14	Markos et al.	General teacher education context (not subject-specific)	Structured questionnaire; Integration in elective course project; Students submitted 10 queries; Explained recommendations	Pre-service teacher education; Departments of Primary and Early Childhood Education; Includes lab sessions on digital storytelling, robotics, and AI concepts.
15	Peikos & Stavrou	Primary science lesson planning	Four designed interactions for primary science lesson planning; Used prompt engineering strategies; Prompts crafted with PCK elements; Focus on floating and sinking topic	Teacher–AI co-design approach; Focus on PCK framework (Content, Pedagogy, Context overlaps); Aimed at primary science education
16	Pellas et al.	Newtonian mechanics teaching videos	Designed videos teaching Newtonian mechanics using the IDEA framework	PBL in pre-service science teacher education
17	Pernaa & Haatainen	General teacher education context (not subject-specific)	Three activities: AI-supported summaries, concept maps, code/device building	ICT in Chemistry Education: TPACK framework
18	Prentzas & Sidiropoulou	General teacher education context (not subject-specific)	Course support: announcements, email drafts, academic writing, lesson planning; pilot: creative writing feedback	The teacher education department focuses on writing courses.
19	Ramnarain et al.	Inquiry-based science teaching	Brainstorming, hypothesis generation, simulation, procedure planning	Inquiry-Based Learning (IBL); Theory of Planned Behaviour
20	Wang K. et al.	General teacher education context (not subject-specific)	Tasks: finding explanations, exploring topics, summarizing readings, solving problem sets, and analyzing prompting behaviours	STEM problem-solving competency in undergraduate courses
21	Wang T. et al.	None	Compared reflections with/without multimodal analysis reports; supported critical collective reflection.	Teacher education for pre-service science teachers: collective reflection with CoI and ENA frameworks

Overall, these studies collectively demonstrate that GenAI tools have the potential to scaffold PSTs' scientific reasoning, enhance instructional design, and promote reflective, critical engagement with content. However, the impact depends significantly on how these tools are integrated into pedagogical frameworks and supported by structured guidance and critical evaluation.

4.3 Employment of Generative AI Tools by PSTs' science education to Design and Implement Teaching Practices

Analysis of the reviewed studies shows that PSTs employed GenAI tools in varied ways to design, adapt, and implement instructional practices. Rather than serving as a single-purpose technology, GenAI was used to support lesson planning, differentiation, assessment design, and reflective teaching practices across diverse contexts.

A central use case was lesson planning and instructional design. Many studies have reported that PSTs are leveraging ChatGPT and similar tools to generate lesson outlines, adapt materials for different learning levels, and create formative assessments. For instance, Bae et al. (2024) described undergraduate teacher preparation courses that utilized ChatGPT for brainstorming, personalized writing support, and reducing planning anxiety. Lee & Zhai (2024) similarly required participants to design structured science lessons using inquiry-based methods, such as Predict–Observe–Explain (POE) and concept mapping, while integrating AI-assisted dialogues to promote curriculum alignment.

Co-design approaches and collaborative planning also emerged as promising practices. Peikos & Stavrou (2025) documented how Greek PSTs used ChatGPT-4o in an iterative process to co-design primary science lessons on floating and sinking, employing layered prompting strategies to address misconceptions and support differentiation. Such practices illustrate how AI can act as a collaborative partner in refining lesson quality and pedagogical alignment. However, challenges remained around consistency with models like 5E and avoiding overly generic suggestions.

Assessment design and problem-solving were further areas where GenAI tools supported instructional preparation. Doorsamy et al. (2025) demonstrated the use of ChatGPT and Copilot in generating and evaluating quiz questions on DC/RC circuits in physics higher education contexts, applying Bloom's and SOLO taxonomies. Küchemann et al. (2023) conducted a randomized controlled trial in Germany, where physics PSTs used ChatGPT to create mechanics assessment tasks, thereby improving clarity and assessment literacy while addressing issues such as prompt specificity and quality variability.

Inquiry-based and problem-based learning (PBL) integration was another key theme. Ramnarain et al. (2024) in South Africa found that GenAI tools supported hypothesis generation, simulation planning, and learner autonomy within inquiry-based teaching, helping trainees design safe and creative ways to explore complex concepts. Similarly, Cooper et al. (2025) described teacher education programs that utilized large language models to facilitate guided discovery learning, content summarization, and assessment preparation in topics such as global warming, while also emphasizing critical reflection on bias and the ethical use of these models.

Reflective practices and critical evaluation were highlighted as necessary complements to the use of GenAI. Studies, such as those by Pernaa et al. (2024) in Finland, have integrated activities like concept mapping and SWOT analyses to encourage students to critically assess AI outputs and develop higher-order cognitive skills within the TPACK framework. Wang et al. (2024) in China employed collective reflection sessions, supported by multimodal analysis, to promote assumption-checking and collaborative inquiry in lesson planning.

Finally, innovative content creation was explored in contexts like instructional video development. Pellas (2025) in Greece utilized AI video-generation tools, such as Visla and Jasper, within an online module on Newtonian mechanics to enhance PSTs' self-efficacy and knowledge retention through visualization and adaptive scaffolding, while noting challenges with social presence and engagement.

Overall, these studies demonstrate that GenAI tools are being increasingly utilized as design-time support partners in PSTs' science education. They enable the co-creation of lesson plans, differentiation, assessment design, and reflective practice. However, literature also converges on important cautionary themes, such as the risks of over-reliance, ethical considerations like bias and privacy, and the critical need for structured teacher training to ensure pedagogically informed, ethical, and effective integration of AI into science teaching and learning.

5 Integrated Discussion and Synthesis of Findings

This systematic review reveals a landscape in transition regarding how PSTs engage with GenAI tools in their science training. GenAI is emerging as both a promising instructional innovation and a source of challenges for teacher education programs. Tools like ChatGPT and other large language models are increasingly used in PSTs' science education; however, their integration remains uneven, varying in depth and effectiveness. Below, we synthesize findings across three key dimensions: curriculum integration, conceptual development, and instructional design, followed by a discussion of challenges and prerequisites for effective GenAI use.

A dominant trend is the institutionalization of GenAI within teacher education curricula. Multiple programs have introduced GenAI tools into their course structures, ranging from elective workshops to core science methods classes (Bae et al., 2024; Wang et al., 2025). This aligns with the technological component of the TPACK framework, as educators are beginning to legitimize GenAI as a standard part of instructional technology in teacher preparation (Blonder et al., 2024). For example, some universities are now incorporating ChatGPT-driven assignments into lesson planning or inquiry activities, signaling a shift toward formally acknowledging AI in pedagogy (Lee & Zhai, 2024; Peikos & Stavrou, 2025).

However, the pedagogical and content dimensions of this integration often lag. In many cases, PSTs use GenAI superficially, for example, generating quiz questions or brief explanations, without aligning these activities with deeper learning objectives or science-specific pedagogy. While technology (T) in TPACK is addressed, it often operates in isolation from pedagogy (P) and content knowledge (C), reducing GenAI to a supplementary tool rather than an integrated resource for science teaching (Blonder et al., 2024; Mishra et al., 2024). Most uses fall under SAMR's Substitution/Augmentation levels, with limited but promising examples of Modification and Redefinition (Amar, 2024). Similarly, GenAI's role in models such as 5E and IBL remains partial, supporting phases like Explain and Elaborate, but less so Explore and Evaluate, which require more deliberate scaffolding (Moundridou et al., 2024; Ramnarain et al., 2024; Cooper et al., 2025).

Regarding conceptual development, the review finds that GenAI tools have the potential to scaffold PSTs' understanding of scientific concepts and reasoning processes; however, the outcomes depend significantly on the instructional framing. In optimally designed activities, PSTs leveraged GenAI to generate hypotheses, explore scientific explanations, and engage in inquiry-based dialogues that mirror the scientific method. For instance, studies that embedded ChatGPT in inquiry learning or reflection tasks observed PSTs using AI to refine their arguments and clarify complex concepts (Kotsis, 2024; Abualrob, 2025). In these contexts, GenAI acted as a cognitive partner, prompting learners to articulate reasoning, consider alternatives, and receive immediate feedback in a low-stakes environment (Abualrob, 2025; Blonder et al., 2024; Cooper et al., 2025; Peikos & Stavrou, 2025). Such use can potentially deepen scientific reasoning by encouraging PSTs to think critically about content and anticipate student misconceptions (Blonder et al., 2024; Cooper et al., 2025). However, this benefit is not automatic. Some PSTs relied on AI-generated answers without critical analysis, exhibiting cognitive offloading instead of deeper thinking (Bae et al., 2024; Markos et al., 2024). This highlights the need for structured guidance to ensure GenAI promotes inquiry rather than shortcut learning.

From an instructional design perspective, PSTs have begun using GenAI as a tool for creating lesson plans, designing teaching materials, and simulating classroom interactions. The review found several innovative uses of AI in lesson planning: PSTs employed ChatGPT to draft lesson outlines, suggest lab activities, generate formative assessment questions, and even adapt content to different learning levels (Abualrob, 2025; Bae et al., 2024; Blonder et al., 2024; Feldman-Maggor et al., 2025; Peikos & Stavrou, 2025; Lee & Zhai, 2024; Cooper, 2023; Cooper et al., 2025). In high-engagement contexts, particularly when PSTs approached GenAI as co-designers rather than mere consumers, the technology spurred creativity and helped tailor instruction to student needs. For example, some PSTs iteratively refined AI-generated lesson ideas, combining their pedagogical knowledge with AI suggestions to produce more robust science lessons (Peikos & Stavrou, 2025; Lee & Zhai, 2024; Cooper et al., 2025). In these cases, GenAI functioned as a collaborative partner, augmenting the teachers' ideas and enabling quick prototyping of educational materials. Such practices suggest that GenAI has the potential to enhance the pedagogical content knowledge of PSTs by exposing them to a broader repertoire of examples and explanations (Blonder et al., 2024; Peikos & Stavrou, 2025; Pernaa et al., 2024; Cooper et al., 2025).

Regarding conceptual development, GenAI has the potential to scaffold PSTs' understanding of scientific concepts and reasoning, provided it is used within structured pedagogical frameworks. Studies embedding ChatGPT in inquiry learning reported that PSTs used it to refine arguments, explore alternative explanations, and clarify complex concepts (Kotsis, 2024; Abualrob, 2025). In these contexts, GenAI acted as a cognitive partner, encouraging reasoning and critical engagement (Blonder et al., 2024; Cooper et al., 2025). However, this benefit is not automatic. Some PSTs relied on AI-generated answers without critical analysis, exhibiting cognitive offloading instead of deeper thinking (Bae et al., 2024; Markos et al., 2024). This highlights the need for structured guidance to ensure GenAI promotes inquiry rather than shortcut learning.

Across all dimensions, the review uncovered persistent challenges that temper the enthusiasm for GenAI in teacher education. A foremost concern is the issue of trust and reliability: PSTs and educators reported hesitation due to AI's tendency to produce incorrect or "hallucinated" information, as well as the opaque nature of its responses (Bae et al., 2024; Doorsamy et al., 2025). Incidents of GenAI outputting biased or scientifically inaccurate content have been documented, underscoring the risk of misinformation if PSTs rely on these tools uncritically (Ramnarain et al., 2024; Wang K. et al., 2025). Additionally, ethical issues such as data privacy and plagiarism arise when using AI-generated materials in educational settings (Karataş & Yüce, 2024; Prentzas & Sidiropoulou, 2023; Bae et al., 2024). Most studies noted that PSTs lack formal preparation to navigate these pitfalls. They often lacked training in skills such as verifying GenAI outputs against reliable sources, mitigating biases, or understanding the limitations of large language models. This highlights an urgent need for AI literacy in teacher education: PSTs should learn how GenAI works, how to craft effective prompts, how to critically evaluate AI-provided information, and how to address ethical considerations (Pernaa et al., 2024). Without these competencies, there is a danger that GenAI use in classrooms could reinforce misconceptions or inequities rather than alleviate them.

The synthesis of findings suggests several tentative prerequisites for the successful integration of GenAI in science teacher education, conditions that may be critical in leveraging its potential while mitigating its risks.

(1) Curricular Coherence: GenAI integration must be aligned with clear learning objectives and theoretical frameworks (such as TPACK) rather than treated as an add-on or novelty. In practice, this means designing coursework that simultaneously develops technological, pedagogical, and content knowledge – for example, assignments where PSTs use AI to solve subject-specific problems and then reflect on the pedagogical implications (Celik, 2022; Aslanyan-rad, 2024). A coherent curriculum ensures that the use of GenAI reinforces subject matter understanding and teaching methodology in tandem, truly bridging the T-P-C domains of knowledge.

(2) Reflective Scaffolding: Simply providing access to GenAI is not enough; structured reflection and scaffolding are critical. Teacher educators should incorporate guided reflection prompts, group discussions, and mentor feedback whenever PSTs use AI in their work. This turns GenAI into a catalyst for deeper thinking rather than a shortcut. For example, after PSTs use ChatGPT to generate a lesson plan, they might engage in a reflective exercise to critique the AI's suggestions, discuss what they accepted or modified, and justify those decisions in light of pedagogy. Such scaffolding helps transform GenAI from a content generator into a cognitive partner that supports metacognition and professional growth (Lee & Zhai, 2024; Cooper et al., 2025).

(3) AI Literacy and Ethical Awareness: Effective integration requires that PSTs be trained to understand and manage AI tools responsibly. This includes developing basic AI literacy (understanding how models like ChatGPT function, as well as their strengths and limitations) and ethical awareness (addressing issues of bias, academic integrity, and equitable access). Formal instruction on prompt engineering, fact-checking AI outputs, and recognizing AI biases should be included in teacher preparation programs (Kong et al., 2024; Ayanwale et al., 2024). Equipping PSTs with these skills builds confidence and discernment, enabling them to use GenAI as a supportive tool rather than a crutch. As several scholars argue, tomorrow's teachers need to be critical consumers and conscientious users of AI, prepared to guide their future students in an AI-enhanced learning environment (Kohnke & Zou, 2025; Blonder et al., 2024).

Based on the synthesis of the reviewed studies, we propose that the educational value of GenAI is realized only through deliberate, pedagogy-driven implementation. These emerging prerequisites suggest that GenAI can function as a cognitive and instructional mediator within the TPACK framework, provided that its use is embedded in structured tasks, reflective activities, and guided facilitation by teacher educators. Figure 2 presents our conceptual model, illustrating how GenAI, when thoughtfully integrated, can support the development of PSTs' AI literacy, pedagogical content knowledge, and scientific reasoning. In essence, we argue that GenAI holds significant potential for enhancing science teacher education, provided its application is grounded in sound pedagogical theory and intentional instructional design.

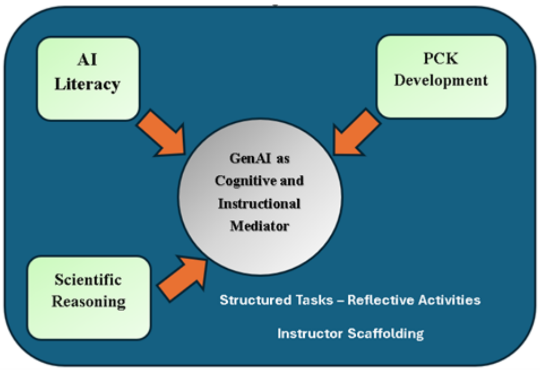

Figure 2 This conceptual model illustrates the role of GenAI as a cognitive and instructional mediator within the TPACK framework. The model highlights GenAI's influence on AI Literacy, PCK Development, and scientific reasoning in PSTE.

In summary, GenAI holds significant potential for enriching PSTs' science education, but realizing this potential requires intentional, pedagogy-driven implementation. Programs must move beyond ad-hoc experimentation toward coherent, reflective, and ethically informed practices that prepare future teachers to use AI critically and creatively in the context of science education.

6 Limitations

While this review provides a comprehensive synthesis of the integration and use of GenAI in PSTs' science education, several limitations should be acknowledged.

First, the scope of the review was limited to studies published between 2022 and 2025, focusing on the period when GenAI tools, such as ChatGPT, saw widespread adoption in education. This excludes earlier exploration or foundational work on AI in education that did not involve generative models.

Second, the review focused exclusively on peer-reviewed journal articles and reputable conference papers, which may have introduced publication bias. Studies with negative or inconclusive findings are often underrepresented in the published literature, potentially skewing the overall conclusions toward more favorable assessments of GenAI.

Third, despite efforts to ensure methodological diversity, the included studies varied significantly in terms of research design, sample size, and educational context. This heterogeneity limits the possibility of quantitatively synthesizing the findings or generalizing them across all teacher education systems. Moreover, most studies relied on self-reported data, which may be affected by biases such as social desirability or novelty effects.

Fourth, the study's disciplinary spread was uneven. While several studies focused on general science education or chemistry, there was a relative lack of research in domains such as physics, biology, or environmental science. This constrains the review's ability to make discipline-specific recommendations.

Finally, "scientific reasoning" was interpreted and operationalized differently across studies. Some addressed it through conceptual understanding, others through epistemic cognition or pedagogical reflection. This conceptual variability introduces ambiguity in the comparison of findings related to Research Question 2.

One methodological limitation concerns the decision to screen only the first 300 results per database. While this decision aligns with established recommendations for platforms like Google Scholar (Haddaway et al., 2015), it may have led to the omission of relevant studies appearing beyond this threshold in more structured academic databases. Future reviews may consider extending the screening range or employing automation tools to capture deeper layers of literature.

Despite these limitations, this review offers valuable insights into an emerging field and provides a solid foundation for further empirical and theoretical work.

7 Conclusions & Future Research

This review reveals that GenAI is not just an emerging technological trend in PSTs' science education; it is a critical catalyst for rethinking how we design, deliver, and reflect on science teaching itself. While current uses often remain superficial or fragmented, the evidence highlights GenAI's untapped potential to act as a powerful cognitive partner that scaffolds scientific reasoning, supports differentiated lesson planning, and fosters inquiry-based learning.

However, without intentional integration grounded in robust pedagogical frameworks such as TPACK, SAMR, and the 5E Model, GenAI risks becoming a gimmick rather than a transformative force. Teacher education programs must move beyond experimentation to design coherent, reflective, and ethically informed curricula that build PSTs' AI literacy, critical thinking, and pedagogical content knowledge.

If harnessed thoughtfully, GenAI can help develop a new generation of science educators who are not only technologically adept but also pedagogically sophisticated and ethically conscious. Realizing this vision will require collaborative efforts among educators, researchers, curriculum designers, and policymakers to ensure that AI in teacher education evolves from promise to practice—and ultimately transforms science teaching for the better.

Ultimately, the integration of GenAI into science teacher education must go beyond technological novelty. It requires a thoughtful reconceptualization of teaching, learning, and assessment practices that acknowledges AI's evolving role as both a tool and a cognitive partner. As educational institutions navigate this transition, there is a clear imperative to cultivate AI literacy, ethical awareness, and pedagogical fluency among the next generation of science educators.

Future research should move beyond descriptive mapping of current GenAI uses and focus on designing, implementing, and evaluating structured, pedagogically aligned interventions in PSTs' science education. There is a critical need for longitudinal and experimental studies that examine how scaffolded GenAI-supported lesson planning and inquiry-based activities shape PSTs' pedagogical content knowledge (PCK), AI literacy, and instructional design skills over time. Such research should be grounded in robust theoretical frameworks, including TPACK, SAMR, and the 5E instructional model, to ensure meaningful integration that aligns technological, pedagogical, and content knowledge domains.

Moreover, future studies should focus on developing critical AI literacy and ethical awareness among PSTs, investigating how targeted interventions can enhance their capacity to evaluate AI outputs, recognize bias, and integrate ethical considerations into lesson planning. Attention must also be paid to issues of equity and access, exploring whether the integration of GenAI risks reinforcing existing disparities in teacher education, and how culturally responsive approaches can mitigate these challenges.

Cross-national and cross-disciplinary comparative research is also necessary to understand how contextual factors influence the adoption and effectiveness of GenAI-enhanced pedagogies across different science disciplines and educational settings. Finally, there is a pressing need to investigate the potential of human-AI co-design approaches, where PSTs collaborate with AI tools as instructional partners, supported by structured reflection to prevent superficial or uncritical adoption. Addressing these research directions will help move the field from documenting GenAI's potential to realizing its role as a transformative partner in preparing critically reflective, ethically aware, and pedagogically skilled science educators.

Ethics Declaration

All procedures followed were conducted in accordance with the ethical standards of the University of Thessaly's Ethics Committee, Greece.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data generated or analyzed during this study are available from the authors upon request.

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