



# Artificial Intelligence in teacher education: A systematic review of its role in enhancing digital literacy and pedagogical content knowledge in STEM

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## Abstract

Artificial Intelligence (AI) is progressively incorporated into teachers' preparation and professional development in the Science, Technology, Engineering and Technology (STEM) fields. This systematic review examines how AI tools may strengthen STEM teacher education using content analysis and the PRISMA guideline. Four key AI tools were identified: AI-based augmented or virtual reality, intelligent tutoring systems, personalised learning, and lesson preparation. These tools have been indicated to profoundly improve teaching strategies, assist teachers in teaching learning process, and boost learning involvement in STEM classes. Despite their potential, there are still challenges that exist. These challenges include the compulsion for appropriate teacher preparation and training, issues related to data security and privacy, the sporadic generation of inaccurate or irrelevant answers by AI, and the lack of developed technology infrastructure in educational institutions. Moreover, AI-related content has also been neglected in the curriculum. Research gaps that require clear AI-generated data, more robust personal data protections, and AI tools that can be adapted according to the needs of individual teachers. However, this systematic review promotes the utilisation of artificial intelligence in STEM teacher education, identifying that it can improve instructional efficacy and promote professional growth.

**Keywords:** *adult learning, STEM education, digital literacy, pedagogical content knowledge*

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## 1. Introduction

Artificial intelligence (AI) is revolutionizing education, particularly STEM teacher training, by fostering innovation in teaching, learning, and assessment (Popkova et al., 2019). The application of AI in STEM education is significant because it can enhance pedagogical content knowledge (PCK), address challenges related to abstract STEM concepts, and equip teachers with the digital skills required for effective teaching and learning. However, this innovation also presents challenges related to equity, ethics, and teacher preparation (Kamalov et al., 2023). Given the rapid development of digital pedagogy, AI tools, and instructional technologies, it is essential for teachers to be competent in both STEM content and emerging technologies.

Teacher education plays a crucial role in shaping student learning and achievement. PCK encompasses not only subject-matter expertise but also the ability to plan, implement, and assess instruction in ways that address the diverse needs of learners. This is particularly challenging in STEM education, where the subject matter is often abstract and technical, posing difficulties for both instructors and students (Nilsson & Karlsson, 2018). Therefore, integrating AI into STEM teacher education has the potential to strengthen PCK, enabling teachers to better support student learning and improve instructional quality (Su & Zhong, 2022b). However, existing research indicates persistent gaps in STEM education, particularly in teacher preparedness, access to resources, and instructional quality. Although AI in education has been widely studied, there remains a lack of systematic reviews specifically examining its role in STEM teacher education and the development of teachers' PCK.

Rapid technological advancements in the education sector are increasing the demand for teachers to adopt advanced digital pedagogies alongside subject-matter expertise. This shift enables educators to design adaptive learning environments that accommodate individual differences, visualize complex concepts, and assess student progress in real time through AI-driven tools (Faikhamta et al., 2020). Therefore, this review is necessary to systematically evaluate how AI tools are currently used in STEM teacher education and to identify gaps in the existing literature. It explores how artificial intelligence can be most effectively integrated into STEM teacher education, identifies challenges associated with its implementation, and proposes directions for future research (Abbas, 2023).

Accordingly, this systematic review aims to examine the role of artificial intelligence in STEM teacher education, with a specific focus on its contribution to the development of

teachers' PCK. Specifically, it seeks to identify the AI tools currently used in STEM teacher education, evaluate their effectiveness in enhancing teachers' STEM competencies and digital literacy, examine the limitations and ethical challenges associated with their implementation, and highlight gaps in the literature to inform future research and practice.

## **2. Literature Review**

### ***2.1 What is Artificial Intelligence?***

AI refers to the integration of computer hardware and software designed to perform tasks that typically require human intelligence, such as reasoning, language comprehension, pattern recognition, problem-solving, and decision-making (Pannu, 2015). As a rapidly evolving twenty-first-century technology, AI has significantly influenced various sectors, including education, where it affects both student performance and teacher effectiveness in the classroom (Chen & Chen, 2020). The Fraunhofer Institutes for Cognitive Systems define AI as a field of computer science capable of analyzing, identifying, and organizing data in ways that mimic human cognitive processes (Fraunhofer et al., 2024). Similarly, according to Mori (2018), the U.S. Defense Science Board defines AI as a system capable of performing functions such as observation, communication, comprehension, and decision-making that ordinarily require human intelligence.

### ***2.2 What Is Pedagogical Content Knowledge?***

The concept of PCK was introduced by educational psychologist Lee Shulman at the 1985 American Educational Research Association conference (Shing et al., 2015). PCK refers to the integration of content knowledge and pedagogical expertise that teachers require to effectively teach subject matter to learners. It encompasses several key components, including subject-matter knowledge, pedagogy, understanding of student misconceptions, curriculum and learning objectives, content-specific instructional strategies, and assessment methods (Berry et al., 2016).

While content knowledge (CK) refers to a teacher's understanding of the subject matter, pedagogical knowledge (PK) involves knowledge of teaching strategies, classroom management, and assessment practices. PCK integrates these domains, enabling teachers to select appropriate instructional approaches, address misconceptions, and facilitate meaningful learning experiences (Mishra & Koehler, 2006). Ozden (2008) and Park et al. (2011) further

argue that PCK includes identifying student learning difficulties, developing instructional objectives, and understanding classroom dynamics.

### ***2.3 STEM Education***

STEM education promotes creativity, critical thinking, innovation, and problem-solving skills, addresses global challenges and prepares learners for careers in science and technology fields. AI has increasingly influenced STEM education. For example, in Germany, approximately two-thirds of students use AI tools such as ChatGPT, with the highest usage reported among students majoring in mathematics, engineering, and natural sciences (Beege et al., 2024).

The integration of AI and machine learning in STEM education has demonstrated positive effects on student learning outcomes, particularly through the development of personalized learning tools. Intelligent Tutoring Systems (ITS), a prominent AI application, use algorithms to provide individualized instruction and feedback based on learners' needs and learning styles. In STEM contexts, where concepts are often complex and cumulative, ITS can effectively identify learners' areas for improvement and provide targeted support (Chassignol et al., 2018). Moreover, various AI-powered solutions are increasingly being adopted to enhance and advance STEM education (Almusaed et al., 2023).

### ***2.4 Artificial Intelligence Tools and Techniques in Education: Linking with PCK***

The expanding application of AI in education has led to the development of tools such as ChatGPT, Duolingo, and Moodle Analytics, as well as instructional approaches including personalized learning and customized feedback that enhance teaching and learning processes (Ning et al., 2024). When teachers integrate these tools within PCK framework, they are better positioned to plan, deliver, and assess instruction in adaptive, learner-centered, and evidence-based ways (Amplo & Butler, 2023).

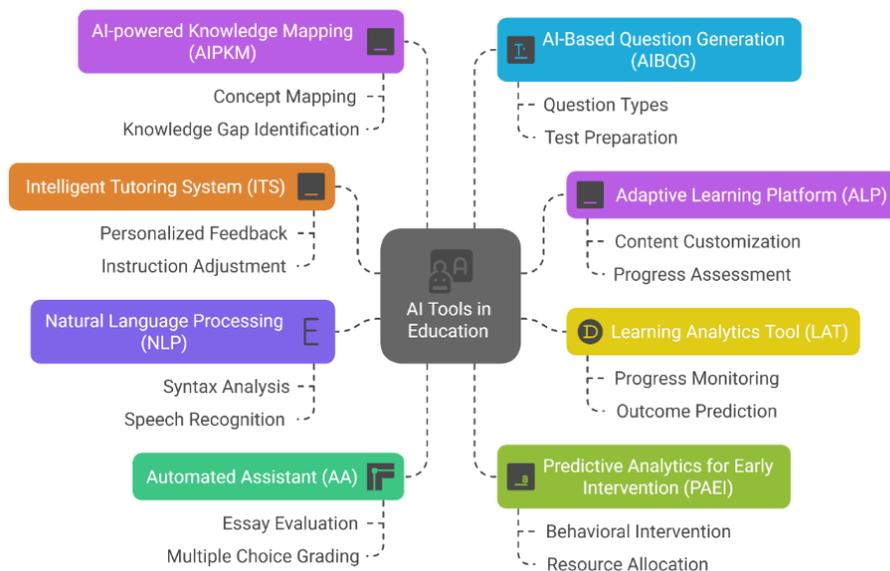
AI techniques such as Learning Analytics Techniques (LAT), Adaptive Learning Platforms (ALP), and Intelligent Tutoring Systems (ITS) enable teachers to tailor instructional content according to learners' prior knowledge, understanding, and learning preferences. Additionally, Natural Language Processing (NLP) applications, including AI-based question generators and automated assistants, support formative assessment by providing immediate feedback, automating grading, and reducing teacher workload (Janice et al., 2024). AI-driven

content mapping and predictive analytics also facilitate early intervention by identifying students at risk of falling behind, reducing dropout rates, and informing curriculum design (Maun et al., 2025).

PCK emphasizes the teacher's ability to transform subject knowledge into effective instructional strategies by understanding student misconceptions, selecting appropriate pedagogical approaches, and designing meaningful assessments (Berry et al., 2016; Shing et al., 2015). In this review, AI is conceptualized as a mediating tool that can strengthen these PCK components by providing data-driven support for instructional decision-making. For example, intelligent tutoring systems and adaptive learning platforms offer personalized feedback and customized learning pathways, enabling teachers to identify misconceptions and adjust instruction accordingly (Chassignol et al., 2018; Conati et al., 2021). AI-based learning analytics further support teachers in monitoring student progress and making evidence-based pedagogical decisions using real-time data (Shibani et al., 2020). Additionally, AI-enhanced teacher professional development programs grounded in the TPCK framework demonstrate how AI tools can facilitate the integration of content, pedagogy, and technology (Amplo & Butler, 2023). Thus, AI tools are theorized to contribute to PCK development by enhancing teachers' capacity to identify student needs, plan instruction strategically, and assess learning more effectively.

**Figure 1**

*AI tools in education*



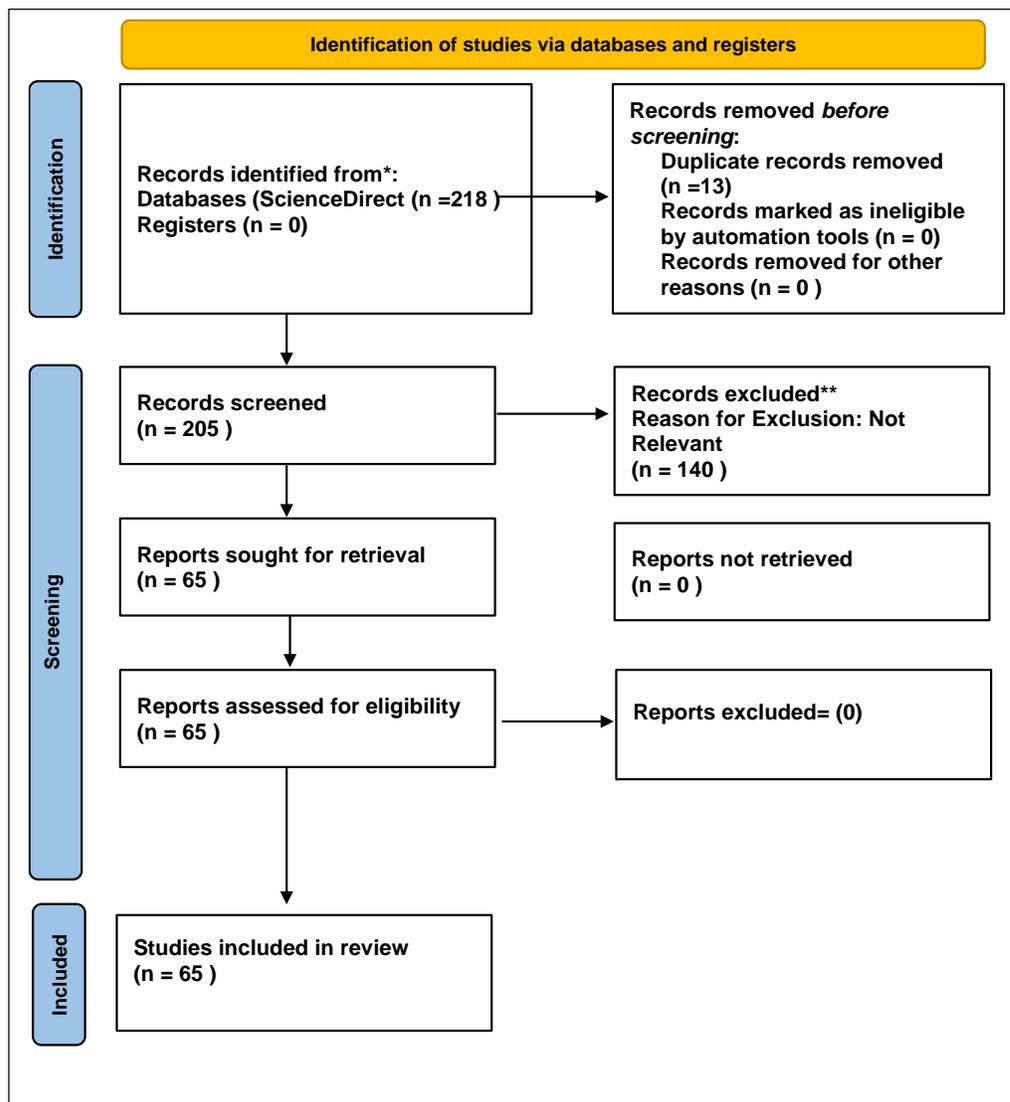
### 3. Methods

#### 3.1 Research Design

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A systematic review is a structured and rigorous process used to answer research questions by critically analyzing and synthesizing evidence from multiple empirical studies (Zawacki-Richter et al., 2020). The PRISMA framework consists of four main stages: (1) identification, (2) screening, (3) eligibility, and (4) inclusion. The systematic review process is illustrated in Figure 2.

Figure 2

Systematic review process



### 3.2 Search and Selection Process

Research articles were retrieved from the ScienceDirect database, selected for its advanced search features, time efficiency, institutional accessibility, and extensive coverage of journals related to artificial intelligence and education (Charoenthammachoke et al., 2020). Initial search terms included “artificial intelligence” and “teachers” to ensure a broad search. Following a preliminary review of the results, the keywords were refined and expanded to improve relevance and comprehensiveness. The final set of search terms included “AI tools in education,” “AI in teacher education,” “AI and pedagogical content knowledge,” “AI and STEM education,” and “the application of AI in education.”

In the next stage, the retrieved articles were screened to identify and remove duplicates and irrelevant records. A total of  $n = 218$  empirical studies were initially identified. After removing  $n = 13$  duplicate records, 205 studies remained for title and abstract screening. Following this screening process, 140 studies were excluded due to irrelevance, leaving 65 articles for full-text review. After the full-text assessment, 65 studies met the inclusion criteria and were included in this systematic review.

### 3.3 Inclusion and Exclusion Criteria

During the third stage of the PRISMA process, eligibility criteria were established, as presented in Table 1. Research articles containing the specified search terms in their titles, abstracts, keywords, hypotheses, or research questions were considered for inclusion in the screening process.

**Table 1**

*Eligibility criteria for inclusion and exclusion*

Inclusion Criteria	Exclusion Criteria
Published from 2018 to 2024	Published before 2018
Research article in English language	Research article not in English language
Primary research	Not primary research, e.g., review papers
Empirical studies	Not empirical studies
Research articles involved teachers as a participant	Research articles not involving teachers as participants
Research involved learners of B.Ed. or teacher education	Research not involved learners of B.Ed. or teacher education
Research study that relates AI tool in education	Research study that does not relate to AI tool in education
Research articles about AI and STEM education	Research articles did not talk about AI and STEM education
Research articles that connect AI to teacher PCK and competencies	Research articles that did not connect AI to teacher PCK and competencies
Complete full text studies	Incomplete full-text studies

### 3.4 Scheme of Themes and Coding

In conducting this systematic review, content analysis was employed to extract and synthesize information from the selected research articles. Content analysis is a research method used to systematically describe, analyze, and quantify information within a body of literature (Krippendorff, 2009). This approach is structured and rigorous, making it appropriate for the objectives of the present study.

The research goals and objectives were identified through a careful examination of the content of the selected articles. Initially, the research sections of each paper were reviewed to locate the stated research questions or objectives. Subsequently, content analysis was applied to identify recurring patterns and key themes across the studies. Once themes were identified, similar themes were grouped into broader categories based on shared core concepts (see Table 2). In this systematic review, the research questions presented in each study were treated as indicators of the respective research goals.

**Table 2**

*Themes and research questions of the study*

<b>Research Question</b>	<b>Themes</b>
What AI tools currently support teacher education in developing Pedagogical Content Knowledge?	AI tool enhances lesson planning. AI tool provides personalized learning AI tool provides feedback and identifies learners' grey areas An AI tool that visualises complex concepts in STEM education
How effective are these AI-based tools in enhancing teacher competencies in STEM and digital literacy?	Provide vast data for effective lesson planning to promote STEM education Personalised learning techniques enhance teacher competencies in STEM education Feedback of ITS in-STEM education gives extra supplement to teachers Animation and visualisation of 3D models of different complex topics increases teacher performance in STEM education
What are the limitations and ethical challenges associated with AI in the education context?	Teacher guidance and training about AI Teacher and student data privacy and protection Irrelevant data provided by AI Unverified data provided by AI Insufficient resources for ICT Individual differences regarding AI technology Teacher perception and readiness to use AI Learners copy-paste patterns without understanding the concepts

**Table 3***Country-wise summary of research articles*

S No.	Country Name	Frequency
1	Australia	3
2	Bulgaria	1
3	Canada	2
4	China	8
5	Denmark	2
6	Finland	3
7	Egypt	1
8	Germany	2
9	Ghana	1
10	Greece	1
11	Hongkong	1
12	Hungary	1
13	India	5
14	Indonesia	1
15	Italy	1
16	Libya	1
17	Lesotho	1
18	Malaysia	1
19	Netherland	1
20	Norway	1
21	Nigeria	3
22	Poland	2
23	Pennsylvania	1
24	Russia	1
25	Morocco	1
26	Spain	4
27	South Africa	4
28	Serbia	2
29	Switzerland	1
30	Taiwan	2
31	Thailand	3
32	UK	2
33	USA	4
34	UAE	1

## 4. Results

***Research Question 1: What Artificial Intelligence tools currently support teacher education in developing Pedagogical Content Knowledge?***

***AI-powered lesson planning.*** Fourteen studies published between 2018 and 2024 were identified as demonstrating the use of AI-powered lesson-planning tools that support and enhance teachers' PCK in teacher education. The details of these studies are presented in Table 3. The integration of AI-related content into teacher education programs has been shown to be highly beneficial, as it enables teachers to design more effective lesson plans and deliver improved instruction (Acquah et al., 2024; Hastomo et al., 2024; Isma'il et al., 2024).

The use of tools such as ChatGPT has been reported to enhance lesson preparation and increase classroom engagement, assisting educators in developing interactive and pedagogically sound lesson plans and instructional materials more efficiently (Tunjera &

Chigona, 2023). Similarly, research indicates that incorporating AI into teacher education promotes professionalism, reduces workload, and saves time, particularly in lesson planning (Moylan et al., 2024) and significantly support the development of inquiry-based lesson plans within teacher education contexts (Moundridou et al., 2024).

In language education, AI-powered lesson-planning tools enable teachers to design effective instructional materials that emphasize vocabulary, reading, grammar, and speaking skills (Haleem et al., 2022; Moorhouse & Kohnke, 2024). For instance, ChatGPT, in particular, can generate engaging lesson plans and study materials tailored to learners' needs and proficiency levels. Consequently, its use may enhance both teachers' instructional design capabilities and students' subject understanding.

**Table 3**

*Summary of studies that indicate AI-powered lesson planning tools enhance pedagogical knowledge*

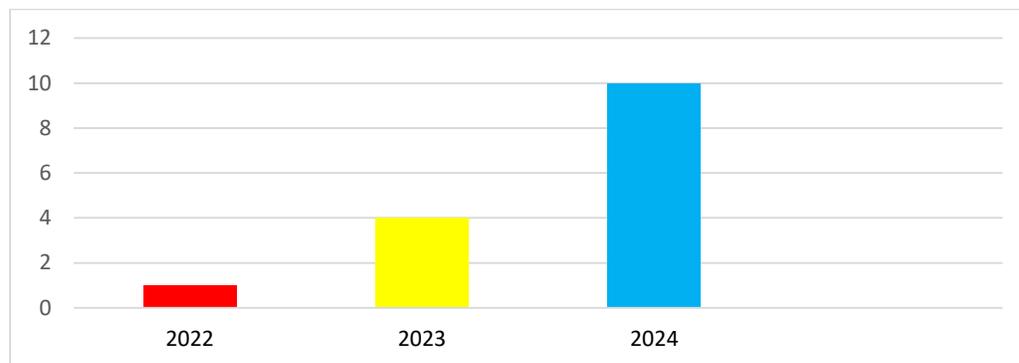
SN	Author and Year	Country	Title	Study type	Population
1	Isma'il et al., 2024	Nigeria	Preparing Teachers of the Future in the Era of Artificial Intelligence	Mixed method	Pre-service teachers
2	Tunjera & Chigona, 2023	South Africa	Investigating Effective Ways to Use Artificial Intelligence in Teacher Education	Qualitative	Pre-service teachers
3	Hastomo et al., 2024	Indonesia	Scrutinizing Indonesian pre-service teachers' technological knowledge in Utilising AI-powered tools	Mixed method	Pre-service teachers
4	Moundridou et al., 2024	Greece	Generative AI tools as educators' assistants: Designing and implementing inquiry-based lesson plans	Qualitative	Pre-service teachers
5	Moorhouse & Kohnke, 2024	China	The effects of generative AI on initial language teacher education: The perceptions of teacher educators	Qualitative	Pre-service teachers
6	Acquah et al., 2024)	Ghana	Preservice teachers' behavioral intention to use artificial intelligence in Lesson planning: A dual-staged PLS-SEM-ANN approach	Quantitative	Pre-service teachers
7	Wilson et al., 2024	USA	Navigating AI-Powered Personalised Learning in Special Education: A Guide for Preservice Teacher Faculty	Qualitative	Pre-service teachers
8	Mnguni et al., 2024b	South Africa and Thailand	The behavioral intentions for integrating artificial intelligence in science teaching among pre-service science teachers in South Africa and Thailand	Quantitative	Pre-service teachers
9	Moylan et al., 2024	Canada	Teaching and AI in the post-digital age: Learning from teachers' perspectives	Qualitative	Pre-service teachers

SN	Author and Year	Country	Title	Study type	Population
10	Moorhouse, 2024	China	Beginning and first-year language teachers' readiness for the generative AI age	Qualitative	Pre-service teachers
11	Celik, 2023	Finland	Towards Intelligent-TPACK: An empirical study on teachers' professional knowledge to ethically integrate artificial intelligence (AI)-based tools into education	Quantitative	Pre-service teachers
12	Sanusi et al., 2024	Nigeria	Investigating pre-service teachers' artificial intelligence perception from the perspective of planned behavior theory	Quantitative	Pre-service teachers
13	Javaid et al., 2023	India	Unlocking the opportunities through ChatGPT Tool towards ameliorating the education system	Qualitative	Pre-service teachers
14	Su & Zhong, 2022a	China	Artificial Intelligence (AI) in early childhood education: Curriculum design and future directions	Qualitative	Pre-service teachers

Figure 3 illustrates the number of studies published per year, indicating that no relevant studies were identified between 2018 and 2021.

**Figure 3**

*Studies published from 2018 to 2024 on AI-powered lesson planning*



***AI-Based personalizing learning.*** Table 4 summarizes nine studies published between 2014 and 2018 that demonstrate how AI technologies can enhance student outcomes and teachers' pedagogical expertise through individualized learning. Ouyang and Jiao (2021) identified three AI paradigms in education, AI-directed (learner as recipient), AI-supported (learner as collaborator), and AI-empowered (learner as leader), highlighting their potential to foster personalized learning. Copur-Gencturk et al. (2024) further emphasized that AI technologies providing tailored learning solutions positively influence teachers' professional

development. Their findings indicate that instructors' subject-matter knowledge and technological proficiency are closely linked to improved student achievement, underscoring the importance of reliable internet access for educators.

Empirical evidence suggests that integrating customized learning systems into teacher development programs enhances student performance while significantly improving instructors' TPACK (Chaipidech et al., 2022). Similarly, greater teacher engagement with AI tools strengthens their capacity to leverage these technologies effectively, enhancing TPACK and informing instructional decisions (Celik, 2023). Hence, incorporating AI in teacher development not only supports the growth of PCK but also promotes individualized learning (Charania et al., 2024) and facilitates a deeper understanding of students' learning styles, thereby improving student outcomes (Bajaj & Sharma, 2018).

Several AI tools have been recommended to support effective teaching and learning. Javaid et al. (2023) highlighted ChatGPT's potential for individualized learning, enabling instructors and students to generate diverse, tailored educational content. Khosravi et al. (2022) emphasized that Explainable AI (XAI) allows teachers to customize explanations to meet learners' specific needs, while Lalitha and Sreeja (2020) proposed a Personalised Self-Directed Learning Recommendation System (PSDLR) to guide learners in selecting self-directed learning materials aligned with their individual needs.

**Table 4**

*Summary of the studies that indicate AI-based personalizing learning improve teacher PCK*

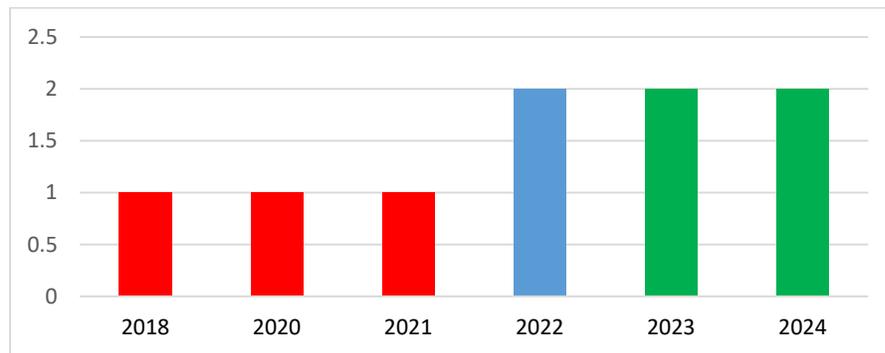
SN	Author and Year	Country	Title	Study type	Population
1	Copur-Gencturk et al., 2024	USA	The impact of an interactive, personalised, computer-based teacher professional development program on student performance: A randomised controlled trial	Quantitative	In service teacher
2	Chaipidech et al., 2022	Thailand	A personalised learning system-supported professional training model for teachers' TPACK development	Quantitative	In service teacher
3	Celik, 2023	Finland	Towards Intelligent-TPACK: An empirical study on teachers' professional knowledge to ethically integrate artificial intelligence (AI)-based tools into education	Quantitative	In service teacher
4	Charania et al., 2024	India	Exploring teacher characteristics and participation in TPACK-related online teacher professional development in Assam, India	Quantitative	In service teacher

SN	Author and Year	Country	Title	Study type	Population
5	Bajaj & Sharma, 2018	India	Smart Education with artificial intelligence-based determination of learning styles	Quantitative	Learning model Analysis
6	Lalitha & Sreeja, 2020	India	Personalised Self-Directed Learning Recommendation System	Quantitative	Online learners
7	Ouyang & Jiao, 2021	China	Artificial intelligence in education: The three paradigms	Qualitative	Content Analysis
8	(hosravi et al., 2022	Australia	Explainable Artificial Intelligence in education	Qualitative	pre and in-service teacher
9	Javaid et al., 2023	India	Unlocking the opportunities through ChatGPT Tool towards ameliorating the education system	Qualitative	In service teacher

Figure 4 illustrates the number of studies regarding AI-powered personalize learning published per year, indicating that no relevant studies were identified between 2019.

**Figure 4**

*Studies published from 2018 to 2024 on AI-powered personalize learning*



***AI-based intelligent tutoring system.*** Studies published between 2018 and 2024 (Table 5) underscore the positive impact of AI-based ITS on student performance and teachers' PCK. In terms of student learning, ITS selects relevant learning resources based on individual progress and adapts materials to meet learners' specific needs within e-learning environments (Marciniak & Szczepański, 2020). ITS also provides immediate, personalized feedback, including error categorization and accuracy indicators (Chi & VanLehn, 2018; Conati et al., 2021; Sychev, 2024). Regarding the affective dimension of learning, ITS can assess learners' emotional responses through facial recognition (Bouhlal et al., 2020), which in turn influences cognitive processes that affect engagement and motivation (Schaper et al., 2022). Additionally,

Learning Analytics (LA), a key component of ITS, has been shown to enhance learners' writing skills and self-assessment abilities (Shibani et al., 2020). For instance, Mnguni et al. (2024) reported that pre-service science teachers in Thailand and South Africa held positive attitudes toward ITS, resulting in improvements in both content knowledge and pedagogical skills.

ITS also contributes to educational outcomes by reducing teacher workload (Oke & Fernandes, 2020) and facilitating academic tutoring that strengthens collaboration between instructors and learners (Toro et al., 2024; Vujinović et al., 2024). Because ITS enhances instructors' pedagogical knowledge and AI literacy (Kong et al., 2024), integrating ITS into teacher development programs has been recommended as a strategy to further strengthen teacher capabilities (Molefi et al., 2024).

Several ITS platforms have been evaluated for effectiveness. Lamb et al. (2022) assessed the Synthetic Adaptive Learning Environment (SALE) program in the United States, which leverages neurocognitive data to predict student outcomes with 85% accuracy while saving instructional time. Similarly, the Reading Assistant (RA) was found to enhance reading fluency and pronunciation while reducing learners' cognitive load (Srinivasan, 2022). These findings highlight the importance of AI literacy for educators to effectively implement ITS and accurately interpret predictive outcomes (Ayanwale et al., 2024).

**Table 5**

*Summary of the studies that indicate AI-based intelligent tutoring system improve teachers PCK*

SN	Author and Year	Country	Title	Study type	Population	Remarks
1	Chi & VanLehn, 2018	Pennsylvania	Eliminating the Gap between the High and Low Learners through Meta-cognitive Strategy Instruction	Quantitative	Teachers	Improve teachers PCK
2	Marciniak & Szczepański, 2020	Poland	Individualised learning in a course with a tight schedule	Qualitative	Algorithm analysis	Provide suitable content to the learners in e-learning
3	Oke & Fernandes, 2020	Africa	Innovations in Teaching and Learning: Exploring the Perceptions of the Education Sector on the 4th Industrial Revolution (4IR)	Qualitative	Teachers	Reduce teacher workload
4	Sychev, 2024	Russia	Educational models for cognition: Methodology of modeling intellectual skills for intelligent tutoring systems	Quantitative	In service teachers	Provide feedback and find errors

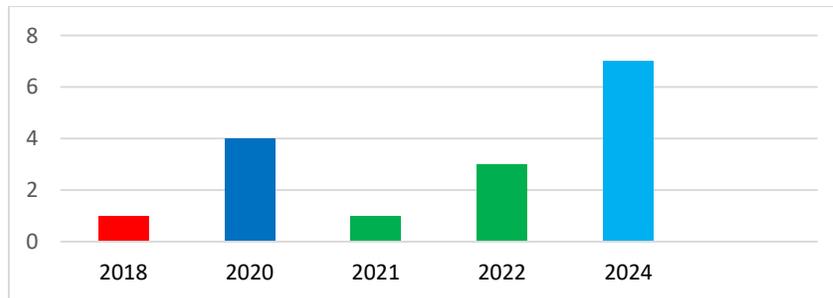
SN	Author and Year	Country	Title	Study type	Population	Remarks
5	Bouhlal et al., 2020	Morocco	Emotions recognition as innovative tool for improving learners' performance and learning approaches	Mixed	Teachers	Improve teacher PK regarding Educational Psychology
6	Shibani et al., 2020	Australia	Educator Perspectives on Learning Analytics in Classroom Practice	Qualitative	Teacher	Improve teachers PK regarding student assessment
7	Conati et al., 2021	Canada	Towards Personalised XAI: A Case Study in Intelligent Tutoring Systems	Quantitative	In service Teachers	Improve teachers PK regarding student assessment
8	Schaper et al., 2022	Denmark	Computational empowerment in practice: Scaffolding teenagers' learning about emerging technologies and their ethical and societal impact	Mixed	Teachers and Learners	Improve learners and teacher interest
9	Lamb et al., 2022	America	Real-time prediction of science student learning outcomes using machine learning classification of hemodynamics during virtual reality and online learning sessions	Quantitative	Teachers	Improve and boost teacher time management skills
10	Srinivasan, 2022	America	AI & learning: A preferred future	Mixed	Pre service teachers	Improve teacher competencies Learners Reading skills
11	Ayanwale et al., 2024	Nigeria	Examining artificial intelligence literacy among pre-service teachers for future classrooms	Quantitative	Pre service teachers	Improve teacher PCK
12	Toro et al., 2024	Poland	28th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems (KES 2024)	Qualitative	In Service teachers	Improve tutoring skills of teachers
13	Vujinović et al., 2024	Serbia	Using ChatGPT to annotate a dataset: A case study in intelligent tutoring systems	Qualitative	Chat GPT Analysis	Reduce teacher workload
14	Kong et al., 2024	Hongkong	Examining teachers' behavioural intention of using generative artificial	Quantitative	Inservice teachers	Increase AI literacy and teacher PK

SN	Author and Year	Country	Title	Study type	Population	Remarks
			intelligence tools for teaching and learning based on the extended technology acceptance model			
15	Mnguni et al., 2024b	Africa and Thailand	The behavioural intentions for integrating artificial intelligence in science teaching among pre-service science teachers in South Africa and Thailand	Quantitative	Pre service science teacher	Increase science teacher competencies
16	Molefi et al., 2024	Lesotho	Do in-service teachers accept artificial intelligence-driven technology? The mediating role of school support and resources	Quantitative	Inservice teacher	Improve teaching skills

Figure 5 illustrates the number of studies on AI-based intelligent tutoring system published per year, indicating that no relevant studies were identified in 2019 and 2023.

**Figure 5**

*Studies published from 2018 to 2024 on AI-based intelligent tutoring system*



***AI-based augmented/virtual reality in classroom.*** Twenty-six papers from 2018 to 2024 (Table 6) investigated AI-based AR/VR in classrooms, which, when implemented, enhance both student performance and teacher PCK. enhances instructional effectiveness, learner engagement, and conceptual understanding across disciplines. It enables dynamic visualization of text, diagrams, and complex concepts, thereby improving teaching and comprehension (Terzieva et al., 2021; Grodotzki et al., 2018; Kumar et al., 2021). AR and VR also overcome limitations of time, location, and learning resources, expanding access to meaningful learning experiences (Hwang & Chien, 2022; Wang et al., 2023). Additionally, AR fosters learner creativity, collaboration, and communication while strengthening instructors' assessment skills and PCK (Berezcki & Kárpáti, 2021; Iftene & Trandabăț, 2018; Gutierrez et

al., 2023). In language and online learning contexts, AR improves efficiency, sustains attention, and accelerates instruction (Dalim et al., 2020; Neffati et al., 2021). It emerges as a transformative tool that integrates pedagogy and technology to enhance academic achievement (Børte & Lillejord, 2024).

Various examples illustrate how AR and related immersive technologies enhance teaching and learning. For instance, 360-degree videos have been shown to support the learning process and strengthen teacher self-efficacy, particularly among novice instructors (Walshe & Driver, 2019), while immersive VR environments improve learners' focus and visualization of content (Hallberg et al., 2020). The adoption of AR in higher education is further supported by the Technology Acceptance Model (TAM), which facilitates its integration and helps make complex content more comprehensible (Cabero-Almenara et al., 2019). Gamification combined with VR has been found to increase engagement for both teachers and students (Bucchiarone, 2022), with tools such as Kahoot enhancing student involvement and academic performance in chemistry and pharmacy courses (Al Ghawail & Yahia, 2022). In science education, AI-powered AR has been recommended for visualizing complex chemical concepts (Macariu et al., 2020), and 3D simulations with intelligent objects have been proposed to improve physics skills among teachers and students alike (Ghoniem et al., 2018).

The application of AR and related AI-driven virtual technologies in education remains at an emerging stage, yet their potential for transforming teaching and learning is widely recognized. Qiu et al. (2023) noted that AI virtual technologies are still in their infancy but hold significant promise when supported by adequate facilities and faculty training. Similarly, Sanchez-Cabrero et al. (2019) projected that the increasing availability of VR and AR applications will position them as essential instructional tools in the future. Empirical evidence supports this potential, as Darayseh (2023) found that integrating AI and AR enhanced educational effectiveness and student engagement, with instructors reporting positive instructional outcomes.

However, the successful application of AR depends largely on effective teacher preparation. Huang et al. (2021) emphasized that meaningful VR integration and the creation of optimal classroom environments require comprehensive teacher training. In support of this, Delamarre et al. (2021) developed a virtual training system combining AR and VR for classroom management, which strengthened instructors' PCK. Basantes et al. (2022) further highlighted the need for teacher training programs that build AI and technological

competencies, while Lan (2024) reported strong intentions among pre-service teachers to integrate AI and AR into their professional preparation. Moreover, AI has been identified as a means of overcoming persistent barriers in STEM teacher professional development (Lin et al., 2024).

**Table 6**

*Summary of the studies that indicate AI-based AR/VR in classroom*

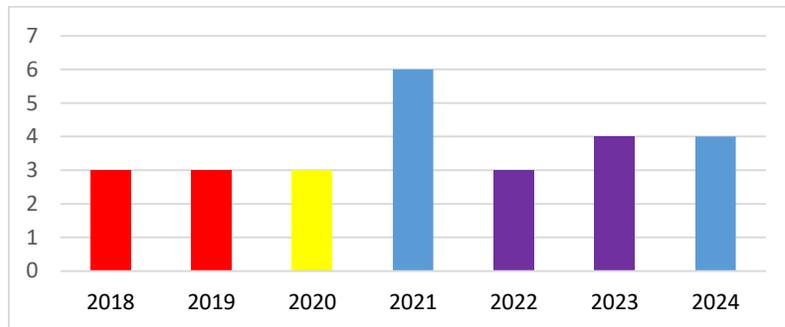
SN	Author and Date	Country	Title	Study Type	Population	Remarks
1	Ghoniem et al., 2018	Egypt	Three-dimensional Simulation System based Intelligent Object-oriented Paradigm for Conducting Physics Experiments	Mixed	Teachers	Improve teacher practical skills
2	Terzieva et al., 2021	Bulgaria	Towards a Design of an Intelligent Educational System	Quantitative	Teachers	Make teaching interest and enhances teacher efficiency
3	Hwang & Chien, 2022	Tiawan	Definition, roles, and potential research issues of the metaverse in education: An artificial intelligence perspective	Qualitative	Teachers	Improve teacher teaching skills
4	Iftene & Trandabăț, 2018	Romania	Enhancing the Attractiveness of Learning through Augmented Reality	Quantitative	Professor	Enhance teacher Pedagogical skills
5	Grodotzki et al., 2018	Germany	Remote and Virtual Labs for Engineering Education 4.0	Qualitative	Teacher student	Improve teacher teaching skills
6	Walshe & Driver, 2019	UK	Developing reflective trainee teacher practice with 360-degree video	Qualitative	Teacher	Improve teacher PK
7	Cabero-Almenara et al., 2019	Spain	Adoption of augmented reality technology by university learners	Quantitative	Teacher	Improve teacher PK
8	Sanchez-Cabrero et al., 2019	Spain	Early virtual reality adopters in Spain: sociodemographic profile and interest in the use of virtual reality as a learning tool	Quantitative	VR Users	Enhanced teacher teaching skills
9	Macariu et al., 2020	Romania	Learn Chemistry with Augmented Reality	Quantitative	Teacher and Student	Improve science teacher competencies
10	Hallberg et al., 2020	Finland	Experiences and outcomes of craft skill learning with a 360 virtual learning environment and a head-mounted display	Mixed	Teachers	Improve teaching skills

SN	Author and Date	Country	Title	Study Type	Population	Remarks
11	Dalim et al., 2020	Malaysia	Using Augmented Reality with Speech Input for Non-Native Children's Language Learning	Quantitative	Teachers and learners	Improve both teachers and student efficiency
12	Neffati et al., 2021	India	An educational tool for enhanced mobile e-Learning for technical higher education using mobile devices for augmented reality	Quantitative	Teachers and learners	Increase student attraction and teacher teaching skills
13	Bereczki & Kárpáti, 2021	Hungary	Technology-enhanced creativity: A multiple case study of digital technology-integration expert teachers' beliefs and practices	Qualitative	Teachers	Enhance teacher PK and Student creativity
14	Huang et al., 2021b	Germany	Classroom complexity affects student teachers' behavior in a VR classroom	Quantitative	Teachers and learners	Improve teacher classroom management
15	Kumar et al., 2021	Denmark and Netherland	Virtual reality in chemical and biochemical engineering education and Training	Mixed	Teachers	Increase teacher PCK and learners understanding
16	Delamarre et al., 2021	USA	The Interactive Virtual Training for Teachers (IVT-T) to Practice Classroom Behavior Management	Mixed	Teachers	Improve teachers PCK
17	Bucchiarone, 2022	Italy	Gamification and virtual reality for digital twin learning and training: architecture and challenges	Mixed	Teachers and learners	Improve teacher and learners performance
18	Basantos-Andrade et al., 2022	Spain	NANO-MOOCs to train university professors in digital competences	Quantitative	Professors	Increase Teacher PCK
19	Darayseh, 2023	UAE	Acceptance of artificial intelligence in teaching science: Science teachers' perspective	Quantitative	Teachers	Increase teacher self-efficacy
20	Qiu et al., 2023	China and Spain	Perceptions and use of metaverse in higher education: A descriptive study in China and Spain	Quantitative	Teachers	Improve teacher TPCK
21	Gutierrez et al., 2023	Australia	What do secondary teachers think about digital games for learning: Stupid fixation or the future of education?	Quantitative	Teachers	Improve PCK
22	Wang et al., 2023	China	Utilising virtual reality to assist social competence education and social support for children from under-represented backgrounds	Quantitative	Teachers and Learners	Improve quality of education
23	Mnguni et al., 2024a	South Africa	The behavioural intentions for integrating artificial intelligence	Quantitative	Pre service teachers	Improve PCK

SN	Author and Date	Country	Title	Study Type	Population	Remarks
			in science teaching among pre-service science teachers in South Africa and Thailand			
24	Lan, 2024	China	Through tensions to identity-based motivations: Exploring teacher professional identity in Artificial Intelligence-enhanced teacher training	Mixed	Teachers	Improve PCK
25	Lin et al., 2024	China	Teacher learning community for AR-integrated STEM education	Quantitative	Teachers	Improve teacher PCK
26	Børte & Lillejord, 2024	Norway	Learning to teach: Aligning pedagogy and technology in a learning design tool	Qualitative	Teachers	Improve PCK

**Figure 6**

*Studies published from 2018 to 2024 on AI-based VR/AR in classroom*



***Research Question 2: How effective are AI-based tools in enhancing teacher competencies in STEM and digital literacy?***

Four AI tools were identified as enhancing teachers' PCK and competencies in STEM education. These tools include AI-based lesson planning, AI-based personalized learning, AI-based intelligent tutoring systems, and AI-based augmented/virtual reality applications in the classroom. Further details are presented in Table 7.

These tools demonstrate significant potential for enhancing teacher competencies in STEM education. The first tool, AI-based lesson planning, analyzes data to generate effective lesson plans aligned with student needs, learning objectives, and curriculum standards. It strengthens teacher competencies in time efficiency, customization, and data-driven decision-making (Table 3). The second tool, AI-based personalized learning, enables teachers to assess individual student performance and learning styles in order to provide tailored instructional

strategies. This enhances competencies related to skill development, individualized attention, student engagement, and motivation (Table 4).

**Table 7**

*Summary of the studies on AI tools from 2018 to 2024*

SN	Tools	No. of Studies	Teacher Competencies in STEM Education
1	AI-based lesson planning	14	<ul style="list-style-type: none"> <li>a. Time efficacy</li> <li>b. Customization</li> <li>c. Vast amount of data</li> <li>d. Data driven decision</li> </ul>
2	AI-based Personalized learning	9	<ul style="list-style-type: none"> <li>a. Skill development</li> <li>b. Individualized attention</li> <li>c. Student engagement</li> <li>d. Student motivation</li> </ul>
3	AI-based intelligent tutoring system	16	<ul style="list-style-type: none"> <li>a. Provide supplemental support</li> <li>b. Insight into student learning</li> <li>c. Teacher professional growth</li> </ul>
4	AI-based augmented reality	26	<ul style="list-style-type: none"> <li>a. Innovative teaching method</li> <li>b. Conceptualise teaching</li> <li>c. Student engagement</li> <li>d. Joy able learning environment</li> </ul>

The third tool, AI-based ITS, delivers real-time feedback that helps learners identify areas requiring further improvement. It also supports instructors by offering instructional insights, enhancing understanding of student learning patterns, and promoting professional growth (Table 5). The fourth tool, AI-based AR/VR, has numerous applications in STEM education, enabling instructors to explain complex content through animations, 3D models, gamification, and 360-degree videos. These technologies facilitate the visualization of challenging concepts such as chemical reactions, human anatomy, thermodynamics, and projectile motion. AR/VR strengthens teacher competencies by promoting innovative teaching approaches, increasing learner engagement, and fostering more interactive and meaningful learning experiences (Table 6).

***Research Question 3: What are the limitations and ethical challenges associated with AI in teacher education?***

A comprehensive review of the literature published between 2014 and 2018 (see Tables 3–6) reveals several limitations and ethical challenges associated with the use of AI in

education, particularly in teacher education. One concern is that certain AI-based tools, such as the Smart Personal Assistant, may not be suitable for all teachers due to individual differences and diversity, limiting their applicability across entire classrooms (Winkler et al., 2021). Studies conducted in the United States and Nigeria emphasize that effective AI implementation requires prior teacher training; insufficient knowledge may pose risks in classroom use (Gerard et al., 2022; Ismail et al., 2024). Ismail et al. (2024) further highlighted the need for foundational AI training in teacher education programs, noting the absence of AI-related subjects in pre-service preparation and professional development, as well as resistance among some senior teachers who demonstrate reluctance to adopt AI technologies.

Ethical and practical concerns also emerge in the literature. Teachers report challenges related to data privacy and the safeguarding of personal information when using AI tools (Tunjera & Chigona, 2023). Additionally, AI systems may lack the capacity to build human rapport, provide emotional support, or foster critical thinking in the same way as human instructors (Tunjera & Chigona, 2023). Moorhouse and Kohnke (2024) found that excessive reliance on generative AI may undermine teachers' confidence, creativity, and critical thinking skills. Broader limitations include social and financial constraints, communication and knowledge gaps, and concerns about the reliability of AI-generated outputs (Faresta, 2024). Faresta (2024) also identified issues related to generic or irrelevant content, inconsistencies in AI pedagogy, misuse of AI resources, transparency concerns, data bias, accountability challenges, and learners' discomfort with AI-based assessment. Similarly, teacher readiness and limited resources remain barriers to AI integration in teacher training and professional development (Mnguni et al., 2024a). Concerns regarding inaccurate or biased responses from tools such as ChatGPT, as well as the absence of clear institutional guidelines and protocols for AI use in education, have also been documented (Javaid et al., 2023).

***Research Question 4: What gaps exist in the literature on AI applications for teacher education, specifically related to PCK?***

Following a brief review of the literature published between 2018 and 2024 on the role of AI in teacher education and its contribution to enhancing teachers' pedagogical content knowledge, several research gaps have been identified that warrant further investigation. Future studies are needed to address the following areas:

1. Research is required to develop AI tools that align with individual differences among teachers and learners. Such tools should be designed at multiple levels (e.g., basic, intermediate, and advanced) to accommodate varying abilities and needs.
2. Further studies should focus on designing AI tools that ensure robust data privacy, protection, and safeguarding, given the large volumes of teacher and student data processed for instructional and administrative purposes.
3. Additional research is essential to develop AI tools that support, rather than diminish, teacher and student competencies. AI-generated responses should encourage critical thinking and conceptual understanding rather than promoting superficial, copy-and-paste learning.
4. Future research should examine how AI tools can be designed and implemented without negatively affecting the social development of teachers and students. Excessive reliance on AI may reduce social interaction and adversely impact communication skills and social engagement.
5. Researchers should investigate how teachers and students in underdeveloped and resource-constrained contexts can effectively utilize AI tools despite limited technological infrastructure and access.
6. Most existing studies focus on secondary and higher education; therefore, further research is needed to explore effective AI integration and teacher training at the kindergarten and early childhood education levels.
7. Studies are needed to examine whether and how AI tools contribute to the development of students' 21st-century skills, including critical thinking, creativity, collaboration, problem-solving, communication, and new forms of literacy.
8. Future research should aim to develop systems or mechanisms that can verify and validate the accuracy and reliability of information generated by AI tools.
9. Further investigation is required to identify strategies for minimizing biased, sexist, and racist outputs in AI-generated responses, ensuring fairness and ethical use of AI in teacher education.

## **5. Discussion**

The review of 26 studies published between 2018 and 2024 indicates that AI tools are increasingly being integrated into teacher education to enhance PCK. The main AI tools

identified include AI-powered lesson planning, AI-based personalized learning systems, ITS, and AI-supported AR/VR technologies. AI-powered lesson planning supports teachers in designing efficient lessons, improving classroom engagement, and developing student-centered instructional materials (Acquah et al., 2024; Moylan et al., 2024; Tunjera & Chigona, 2023). Personalized learning systems enable teachers to understand students' learning styles and provide tailored instruction, thereby strengthening competencies in instructional planning and assessment (Celik, 2023; Chaipidech et al., 2022; Khosravi et al., 2022). ITS provides real-time feedback, facilitates error correction, and reduces teacher workload, allowing educators to focus more on pedagogical strategies and individualized guidance (Chi & VanLehn, 2018; Shibani et al., 2020; Vujinović et al., 2024). AI-based AR/VR technologies enhance teachers' ability to explain complex concepts through immersive visualization and gamification, supporting practical teaching skills and building instructional confidence (Ghoniem et al., 2018; Lan, 2024; Walshe & Driver, 2019).

The reviewed studies also demonstrate the effectiveness of AI tools in improving teacher competencies in STEM education and digital literacy. AI-based lesson planning enhances time efficiency, data-driven decision-making, and instructional customization, key competencies for STEM educators (Table 3). Personalized learning systems promote individualized attention, increase student motivation, and develop teachers' adaptive teaching skills (Table 4). ITS supports professional growth by offering insights into student learning patterns, supplementary instructional support, and improved assessment practices (Table 5). Similarly, AI-based AR/VR applications foster innovative teaching strategies by enabling the explanation of challenging STEM concepts through simulations and 3D models, while increasing student engagement and interactivity (Table 6). These findings suggest that AI tools not only enhance PCK but also strengthen digital literacy and STEM teaching competencies, aligning with global educational priorities for technology integration.

Despite these benefits, the review identifies several limitations and ethical challenges associated with AI use in teacher education. Teacher training and professional development remain critical concerns, as many educators lack sufficient AI knowledge and confidence to effectively integrate these tools into their practice (Gerard et al., 2022; Ismail et al., 2024). Data privacy and security are additional issues, given that AI systems require substantial amounts of teacher and student data, raising concerns about protection and ethical use (Tunjera & Chigona, 2023). Furthermore, AI tools may not adequately replicate human interaction,

emotional support, or foster critical thinking development, core elements of effective teaching and learning (Tunjera & Chigona, 2023). The reliability of AI-generated responses also presents challenges, as outputs may be inaccurate or biased, often without established verification mechanisms (Faresta, 2024; Javaid et al., 2023). Limited technological infrastructure and access to resources, particularly in developing countries, further constrain effective implementation (Mnguni et al., 2024b). Therefore, while AI offers significant potential, its integration must be carefully managed through structured training, ethical safeguards, and adequate infrastructure support.

The literature also reveals several research gaps that warrant further investigation to strengthen AI's role in teacher education and PCK development. AI tools should be designed to accommodate individual differences by incorporating varying levels of difficulty and personalization. Greater attention is needed to enhance data privacy and security mechanisms. Future AI systems should promote critical thinking and minimize dependency or superficial learning behaviors. Research should also examine the social implications of AI use, including its effects on communication skills and interpersonal interaction. Additionally, more studies are required to explore AI integration in resource-constrained contexts and in early childhood and kindergarten education, where research remains limited. Finally, future investigations should assess AI's contribution to developing 21st-century skills, establish verification systems for AI-generated information, and implement strategies to minimize biased or discriminatory outputs. Addressing these gaps will strengthen both the theoretical and practical contributions of AI in teacher education.

## **6. Conclusion**

This systematic review identifies key AI tools that enhance teachers' pedagogical content knowledge (PCK) and promote STEM education. The review highlights four major AI applications: (1) AI-based lesson planning, which supports efficient and effective instructional design; (2) AI-based personalized learning, which provides feedback and adaptive responses based on learners' needs and individual differences; (3) AI-based Intelligent Tutoring Systems (ITS), which deliver immediate, customized feedback while reducing routine teacher workload; and (4) AI-based augmented and virtual reality (AR/VR), which create immersive learning and training opportunities that extend beyond the limitations of traditional classroom environments and strengthen teachers' instructional skills.

The findings indicate that these four tools collectively enhance digital literacy, lesson planning efficiency, personalized instruction, student engagement, and teacher performance in STEM education. By supporting instructional design, adaptive teaching, and innovative classroom practices, AI integration contributes significantly to the development of PCK in teacher education. However, several challenges remain. Major concerns include insufficient teacher training, data security and privacy issues, the lack of AI-related curriculum content in teacher education programs, infrastructural limitations, and the occasional generation of biased or inaccurate AI outputs. Furthermore, important research gaps persist, including the need to design human-centered AI tools, strengthen data protection mechanisms, ensure that AI promotes critical thinking rather than rote learning, address equity issues in resource-limited contexts, and expand research to early childhood and primary education settings. Addressing these issues is essential for maximizing the responsible and effective integration of AI in teacher education.

## **7. Recommendation**

The study recommends the integration of several AI tools to enhance teacher education and pedagogical content knowledge. Specifically, AI-based lesson planning is advised to support the development of effective and well-structured lesson plans for future teachers, while AI-based personalized learning can enable teachers to assess individual students and provide tailored content and instructional materials according to their needs and proficiency levels. The use of AI-based ITS is also recommended, as these systems deliver immediate feedback to learners and reduce teacher workload. Additionally, the study highlights the importance of training teachers in the use of virtual labs, which facilitate the conceptual understanding of complex STEM content. Incorporating AI-related content into teacher education curricula is recommended to strengthen teachers' PCK and overall teaching competencies. Finally, the study emphasizes the broader application of AI tools to develop teachers' 21st-century competencies, enhance digital literacy, and promote familiarity with ICT in educational practice.

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## References

- Abbas, T. (2023). Ethical implications of AI in modern education: Balancing innovation and responsibility. *Social Sciences Spectrum*, 2(1), 51–57. <https://socialsciencespectrum.com/index.php/sss/article/view/75/207>
- Acquah, B. Y. S., Arthur, F., Salifu, I., Quayson, E., & Nortey, S. A. (2024). Preservice teachers' behavioural intention to use artificial intelligence in lesson planning: A dual-staged PLS-SEM-ANN approach. *Computers and Education: Artificial Intelligence*, 7, 100307. <https://doi.org/10.1016/j.caeai.2024.100307>
- Al Ghawail, E. A., & Yahia, S. Ben. (2022). Using the e-learning gamification tool Kahoot! to learn chemistry principles in the classroom. *Procedia Computer Science*, 207, 2667–2676.
- Almusaed, A., Almssad, A., Yitmen, I., & Homod, R. Z. (2023). Enhancing student engagement: Harnessing “AIED”’s power in hybrid education—A review analysis. *Education Sciences*, 13(7), 632. <https://doi.org/10.3390/educsci13070632>
- Amplo, E., & Butler, D. (2023). A learning programme based on TPCK (Technological Pedagogical Content Knowledge), Constructionism, and Design to enhance teacher learning of the key ideas and competencies of Artificial Intelligence (AI). In *Society for Information Technology & Teacher Education International Conference Proceedings* (pp. 1914–1923). Association for the Advancement of Computing in Education (AACE).
- Ayanwale, M. A., Adelana, O. P., Molefi, R. R., Adeeko, O., & Ishola, A. M. (2024). Examining artificial intelligence literacy among pre-service teachers for future classrooms. *Computers and Education Open*, 6, 100179. <https://doi.org/10.1016/j.caeo.2024.100179>
- Bajaj, R., & Sharma, V. (2018). Smart education with artificial intelligence based determination of learning styles. *Procedia Computer Science*, 132, 834–842. <https://doi.org/10.1016/j.procs.2018.05.095>
- Basantes-Andrade, A., Cabezas-González, M., Casillas-Martín, S., Naranjo-Toro, M., & Benavides-Piedra, A. (2022). NANO-MOOCs to train university professors in digital competences. *Heliyon*, 8(6). <https://doi.org/10.1016/j.heliyon.2022.e09456>
- Beege, M., Hug, C., & Nerb, J. (2024). AI in STEM education: The relationship between teacher perceptions and ChatGPT use. *Computers in Human Behavior Reports*, 16, 100494. <https://doi.org/10.1016/j.chbr.2024.100494>
- Bereczki, E. O., & Kárpáti, A. (2021). Technology-enhanced creativity: A multiple case study of digital technology-integration expert teachers' beliefs and practices. *Thinking Skills and Creativity*, 39, 100791. <https://doi.org/10.1016/j.tsc.2021.100791>

- Berry, A., Depaepe, F., & Van Driel, J. (2016). Pedagogical content knowledge in teacher education. In *International Handbook of Teacher Education: Volume 1* (pp. 347–386). [https://doi.org/10.1007/978-981-10-0366-0\\_9](https://doi.org/10.1007/978-981-10-0366-0_9)
- Børte, K., & Lillejord, S. (2024). Learning to teach: Aligning pedagogy and technology in a learning design tool. *Teaching and Teacher Education*, *148*, 104693. <https://doi.org/10.1016/j.tate.2024.104693>
- Bouhlal, M., Aarika, K., Abdelouahid, R. A., Elfilali, S., & Benlahmar, E. (2020). Emotions recognition as innovative tool for improving students' performance and learning approaches. *Procedia Computer Science*, *175*, 597–602. <https://doi.org/10.1016/j.procs.2020.07.086>
- Bucchiarone, A. (2022). Gamification and virtual reality for digital twin learning and training: Architecture and challenges. *Virtual Reality & Intelligent Hardware*, *4*(6), 471–486. <https://doi.org/10.1016/j.vrih.2022.08.001>
- Cabero-Almenara, J., Fernández-Batanero, J. M., & Barroso-Osuna, J. (2019). Adoption of augmented reality technology by university students. *Heliyon*, *5*(5), e01597. <https://doi.org/10.1016/j.heliyon.2019.e01597>
- Celik, I. (2023). Towards Intelligent-TPACK: An empirical study on teachers' professional knowledge to ethically integrate artificial intelligence (AI)-based tools into education. *Computers in Human Behavior*, *138*, 107468. <https://doi.org/10.1016/j.chb.2022.107468>
- Chaipidech, P., Srisawasdi, N., Kajornmanee, T., & Chaipah, K. (2022). A personalized learning system-supported professional training model for teachers' TPACK development. *Computers and Education: Artificial Intelligence*, *3*, 100064. <https://doi.org/10.1016/j.caeai.2022.100064>
- Charania, A., Cross, S., Wolfenden, F., Sen, S., & Adinolfi, L. (2024). Exploring teacher characteristics and participation in TPACK-related online teacher professional development in Assam, India. *Computers and Education Open*, *7*, 100227. <https://doi.org/10.1016/j.caeo.2024.100227>
- Charoenthammacheke, K., Leelawat, N., Tang, J., & Kodaka, A. (2020). Business continuity management: A preliminary systematic literature review based on ScienceDirect database. *Journal of Disaster Research*, *15*(5). <https://doi.org/10.20965/jdr.2020.p0546>
- Chassignol, M., Khoroshavin, A., Klimova, A., & Bilyatdinova, A. (2018). Artificial intelligence trends in education: A narrative overview. *Procedia Computer Science*, *136*, 16–24. <https://doi.org/10.1016/j.procs.2018.08.233>
- Chatree Faikhamta, Kornkanok Lertdechapat, & Tharuesejan Prasoblarb. (2020). The impact of a PCK-based professional development program on science teachers' ability to teach STEM. *Journal of Science & Mathematics Education in Southeast Asia*, *43*.
- Chen, L., & Chen, P. (2020). Artificial intelligence in education: A review. *IEEE Access*, *8*. <https://doi.org/10.1109/ACCESS.2020.2988510>
- Chi, M., & VanLehn, K. (2018). Eliminating the gap between high- and low-achieving students through meta-cognitive strategy instruction. In *Intelligent Tutoring Systems: 9th International Conference, ITS 2008, Montreal, Canada, June 23–27, 2008 Proceedings* (Vol. 9, pp. 603–613). Springer.
- Conati, C., Barral, O., Putnam, V., & Rieger, L. (2021). Toward personalized XAI: A case study in intelligent tutoring systems. *Artificial Intelligence*, *298*, 103503. <https://doi.org/10.1016/j.artint.2021.103503>

- Copur-Gencturk, Y., Li, J., Cohen, A. S., & Orrill, C. H. (2024). The impact of an interactive, personalized computer-based teacher professional development program on student performance: A randomized controlled trial. *Computers & Education*, 210, 104963. <https://doi.org/10.1016/j.compedu.2023.104963>
- Dalim, C. S. C., Sunar, M. S., Dey, A., & Billinghamurst, M. (2020). Using augmented reality with speech input for non-native children's language learning. *International Journal of Human-Computer Studies*, 134, 44–64. <https://doi.org/10.1016/j.ijhcs.2019.10.002>
- Darayseh, A. (2023). Acceptance of artificial intelligence in teaching science: Science teachers' perspective. *Computers and Education: Artificial Intelligence*, 4, 100132. <https://doi.org/10.1016/j.caeai.2023.100132>
- Delamarre, A., Shernoff, E., Buche, C., Frazier, S., Gabbard, J., & Lisetti, C. (2021). The interactive virtual training for teachers (IVT-T) to practice classroom behavior management. *International Journal of Human-Computer Studies*, 152, 102646. <https://doi.org/10.1016/j.ijhcs.2021.102646>
- Faresta, R. A. (2024). AI-powered education: Exploring the potential of personalised learning for students' needs in Indonesian education. *Path of Science*, 10(5), 3012–3022. <https://doi.org/10.22178/pos.104-19>
- Fraunhofer, I. K. S., Heidemann, L., Herd, B., Kelly, J., Mata, N., Tsai, W., Zafar, S., & Zamanian, A. (2024). The European Artificial Intelligence Act. Whitepaper-EU-AI-Act-Fraunhofer-IKS-4.
- Gerard, L., Linn, M. C., & Berkeley, U. C. (2022). Computer-based guidance to support students' revision of their science explanations. *Computers & Education*, 176, 104351. <https://doi.org/10.1016/j.compedu.2021.104351>
- Ghoniem, R. M., Abas, H. A., & Bdair, H. A. (2018). Three-dimensional simulation system based intelligent object-oriented paradigm for conducting physics experiments. *Procedia Computer Science*, 135, 490–502. <https://doi.org/10.1016/j.procs.2018.08.201>
- Grodotzki, J., Ortelt, T. R., & Tekkaya, A. E. (2018). Remote and virtual labs for engineering education 4.0: Achievements of the ELLI project at the TU Dortmund University. *Procedia Manufacturing*, 26, 1349–1360. <https://doi.org/10.1016/j.promfg.2018.07.126>
- Gutierrez, A., Mills, K., Scholes, L., Rowe, L., & Pink, E. (2023). What do secondary teachers think about digital games for learning: Stupid fixation or the future of education? *Teaching and Teacher Education*, 133, 104278. <https://doi.org/10.1016/j.tate.2023.104278>
- Haleem, A., Javaid, M., Asim, M., & Suman, R. (2022). Understanding the role of digital technologies in education: A review. *Sustainable Operations and Computers*, 3, 275–285. <https://doi.org/10.1016/j.susoc.2022.05.004>
- Hallberg, S., Hirsto, L., & Kaasinen, J. (2020). Experiences and outcomes of craft skill learning with a 360 virtual learning environment and a head-mounted display. *Heliyon*, 6(8), e04705. <https://doi.org/10.1016/j.heliyon.2020.e04705>
- Hastomo, T., Mandasari, B., & Widiati, U. (2024). Scrutinizing Indonesian pre-service teachers' technological knowledge in utilizing AI-powered tools. *Journal of Education and Learning (EduLearn)*, 18(4), 1572–1581. <https://doi.org/10.11591/edulearn.v18i4.21644>

- Huang, Y., Richter, E., Kleickmann, T., Wiepke, A., & Richter, D. (2021a). Classroom complexity affects student teachers' behavior in a VR classroom. *Computers & Education*, *163*, 104100. <https://doi.org/10.1016/j.compedu.2020.104100>
- Huang, Y., Richter, E., Kleickmann, T., Wiepke, A., & Richter, D. (2021b). Classroom complexity affects student teachers' behavior in a VR classroom. *Computers & Education*, *163*(December 2020), 104100. <https://doi.org/10.1016/j.compedu.2020.104100>
- Hwang, G.-J., & Chien, S.-Y. (2022). Definition, roles, and potential research issues of the metaverse in education: An artificial intelligence perspective. *Computers and Education: Artificial Intelligence*, *3*, 100082. <https://doi.org/10.1016/j.caeai.2022.100082>
- Iftene, A., & Trandabăţ, D. (2018). Enhancing the attractiveness of learning through augmented reality. *Procedia Computer Science*, *126*, 166–175. <https://doi.org/10.1016/j.procs.2018.07.220>
- Ismail, A., Aliu, A., Ibrahim, M., & Sulaiman, A. (2024). Preparing teachers of the future in the era of artificial intelligence. *Journal of Artificial Intelligence, Machine Learning and Neural Network*, *44*, 31–41. <https://doi.org/10.55529/jaimlenn.44.31.41>
- Janice, B. G., Agbong, A.-C., & Iris, J. G. (2024). Instructors' presence and communication strategies on student engagement in asynchronous online classes. *International Journal of Educational Management and Development Studies*, *5*(2), 206–232. <https://doi.org/10.53378/353071>
- Javaid, M., Haleem, A., Singh, R. P., Khan, S., & Khan, I. H. (2023). Unlocking the opportunities through ChatGPT tool towards ameliorating the education system. *BenchCouncil Transactions on Benchmarks, Standards and Evaluations*, *3*(2), 100115. <https://doi.org/10.1016/j.tbench.2023.100115>
- Kamalov, F., Calonge, D. S., & Gurrib, I. (2023). New era of artificial intelligence in education: Towards a sustainable multifaceted revolution. *Sustainability*, *15*(16), 1–27. <https://doi.org/10.3390/su151612451>
- Khosravi, H., Shum, S. B., Chen, G., Conati, C., Tsai, Y.-S., Kay, J., Knight, S., Martinez-Maldonado, R., Sadiq, S., & Gašević, D. (2022). Explainable artificial intelligence in education. *Computers and Education: Artificial Intelligence*, *3*, 100074. <https://doi.org/10.1016/j.caeai.2022.100074>
- Kong, S. C., Yang, Y., & Hou, C. (2024). Examining teachers' behavioural intention of using generative artificial intelligence tools for teaching and learning based on the extended technology acceptance model. *Computers and Education: Artificial Intelligence*, *7*, 100328. <https://doi.org/10.1016/j.caeai.2024.100328>
- Krippendorff, K. (2009). *The content analysis reader*. Sage.
- Kumar, V. V., Carberry, D., Beenfeldt, C., Andersson, M. P., Mansouri, S. S., & Gallucci, F. (2021). Virtual reality in chemical and biochemical engineering education and training. *Education for Chemical Engineers*, *36*, 143–153. <https://doi.org/10.1016/j.ece.2021.05.002>
- Lalitha, T. B., & Sreeja, P. S. (2020). Personalised self-directed learning recommendation system. *Procedia Computer Science*, *171*, 583–592. <https://doi.org/10.1016/j.procs.2020.04.063>
- Lamb, R., Neumann, K., & Linder, K. A. (2022). Real-time prediction of science student learning outcomes using machine learning classification of hemodynamics during

- virtual reality and online learning sessions. *Computers and Education: Artificial Intelligence*, 3, 100078. <https://doi.org/10.1016/j.caeai.2022.100078>
- Lan, Y. (2024). Through tensions to identity-based motivations: Exploring teacher professional identity in artificial intelligence-enhanced teacher training. *Teaching and Teacher Education*, 151, 104736. <https://doi.org/10.1016/j.tate.2024.104736>
- Lin, X.-F., Chiu, T. K. F., Luo, S., Wong, S. Y., Hwang, H., Hwang, S., Li, W., Liang, Z.-M., Peng, S., & Lin, W. (2024). Teacher learning community for AR-integrated STEM education. *Teaching and Teacher Education*, 141, 104490. <https://doi.org/10.1016/j.tate.2024.104490>
- Macariu, C., Iftene, A., & Gifu, D. (2020). Learn chemistry with augmented reality. *Procedia Computer Science*, 176, 2133–2142. <https://doi.org/10.1016/j.procs.2020.09.250>
- Marciniak, J., & Szczepański, M. (2020). Individualized learning in a course with a tight schedule. *Procedia Computer Science*, 176, 2059–2068. <https://doi.org/10.1016/j.procs.2020.09.242>
- Maun, D., Sharma, P., & Hung, T. (2025). Current trends and best practices of how in-service teachers can develop and apply PCK in social sciences. In *Current trends and best practices of pedagogical content knowledge (PCK)* (pp. 213–236). IGI Global Scientific Publishing. <https://doi.org/10.4018/978-8-3693-0655-0.ch008>
- Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record*, 108(6), 1017–1054. <https://doi.org/10.1111/j.1467-9620.2006.00684.x>
- Mnguni, L., Nuangchalerm, P., El Islami, R. A. Z., Sibanda, D., Sari, I. J., & Ramulumo, M. (2024b). The behavioural intentions for integrating artificial intelligence in science teaching among pre-service science teachers in South Africa and Thailand. *Computers and Education: Artificial Intelligence*, 100334. <https://doi.org/10.1016/j.caeai.2024.100334>
- Molefi, R. R., Ayanwale, M. A., Kurata, L., & Chere-Masopha, J. (2024). Do in-service teachers accept artificial intelligence-driven technology? The mediating role of school support and resources. *Computers and Education Open*, 6, 100191. <https://doi.org/10.1016/j.caeo.2024.100191>
- Moorhouse, B. L. (2024). Beginning and first-year language teachers' readiness for the generative AI age. *Computers and Education: Artificial Intelligence*, 6, 100201. <https://doi.org/10.1016/j.caeai.2024.100201>
- Moorhouse, B. L., & Kohnke, L. (2024). The effects of generative AI on initial language teacher education: The perceptions of teacher educators. *System*, 122, 103290. <https://doi.org/10.1016/j.system.2024.103290>
- Mori, S. (2018). US defense innovation and artificial intelligence. *Asia-Pacific Review*, 25(2), 16–44. <https://doi.org/10.1080/13439006.2018.1545488>
- Moundridou, M., Matzakos, N., & Doukakis, S. (2024). Generative AI tools as educators' assistants: Designing and implementing inquiry-based lesson plans. *Computers and Education: Artificial Intelligence*, 7, 100277. <https://doi.org/10.1016/j.caeai.2024.100277>
- Moylan, R., Code, J., & O'Brien, H. (2024). Teaching and AI in the postdigital age: Learning from teachers' perspectives. *Teaching and Teacher Education*, 153, 104851. <https://doi.org/10.1016/j.tate.2024.104851>
- Neffati, O. S., Setiawan, R., Jayanthi, P., Vanithamani, S., Sharma, D. K., Regin, R., Mani, D., & Sengan, S. (2021). An educational tool for enhanced mobile e-learning for technical

- higher education using mobile devices for augmented reality. *Microprocessors and Microsystems*, 83, 104030. <https://doi.org/10.1016/j.micpro.2021.104030>
- Nilsson, P., & Karlsson, G. (2018). Capturing student teachers' pedagogical content knowledge (PCK) using CoRes and digital technology. *International Journal of Science Education*, 1–29. <https://doi.org/10.1080/09500693.2018.1551642>
- Ning, Y., Zhang, C., Xu, B., Zhou, Y., & Wijaya, T. T. (2024). Teachers' AI-TPACK: Exploring the relationship between knowledge elements. *Sustainability*, 16(3), 978. <https://doi.org/10.3390/su16030978>
- Oke, A., & Fernandes, F. A. P. (2020). Innovations in teaching and learning: Exploring the perceptions of the education sector on the 4th industrial revolution (4IR). *Journal of Open Innovation: Technology, Market, and Complexity*, 6(2), 31. <https://doi.org/10.3390/joitmc6020031>
- Ouyang, F., & Jiao, P. (2021). Artificial intelligence in education: The three paradigms. *Computers and Education: Artificial Intelligence*, 2, 100020. <https://doi.org/10.1016/j.caeai.2021.100020>
- Ozden, M. (2008). The effect of content knowledge on pedagogical content knowledge: The case of teaching phases of matters. *Educational Sciences: Theory and Practice*, 8(2), 633–645.
- Pannu, A. (2015). Artificial intelligence and its application in different areas. *Artificial Intelligence*, 4(10), 79–84.
- Park, S., Jang, J.-Y., Chen, Y.-C., & Jung, J. (2011). Is pedagogical content knowledge (PCK) necessary for reformed science teaching?: Evidence from an empirical study. *Research in Science Education*, 41, 245–260. <https://doi.org/10.1007/s11165-009-9163-8>
- Popkova, E. G., & Sergi, B. S. (Eds.). (2019). *Technological revolution in the 21st century digital society vs. artificial intelligence*. Springer.
- Qiu, Y., Isusi-Fagoaga, R., & García-Aracil, A. (2023). Perceptions and use of metaverse in higher education: A descriptive study in China and Spain. *Computers and Education: Artificial Intelligence*, 5, 100185. <https://doi.org/10.1016/j.caeai.2023.100185>
- Sanchez-Cabrero, Costa-Rom, O., Pericacho, F. J., Novillo-Lopaz, M. A., Arigita-García, A., & Barrientos-Fernandez, A. (2019). Early virtual reality adopters in Spain: Sociodemographic profile and interest in the use of virtual reality as a learning tool. *Heliyon*, 5(8), e01338. <https://doi.org/10.1016/j.heliyon.2019.e01338>
- Sanusi, I. T., Ayanwale, M. A., & Tolorunleke, A. E. (2024). Investigating pre-service teachers' artificial intelligence perception from the perspective of planned behavior theory. *Computers and Education: Artificial Intelligence*, 6, 100202. <https://doi.org/10.1016/j.caeai.2024.100202>
- Schaper, M.-M., Smith, R. C., Tamashiro, M. A., Van Mechelen, M., Lunding, M. S., Bilstrup, K.-E. K., Kaspersen, M. H., Jensen, K. L., Petersen, M. G., & Iversen, O. S. (2022). Computational empowerment in practice: Scaffolding teenagers' learning about emerging technologies and their ethical and societal impact. *International Journal of Child-Computer Interaction*, 34, 100537. <https://doi.org/10.1016/j.ijcci.2022.100537>
- Shibani, A., Knight, S., & Shum, S. B. (2020). Educator perspectives on learning analytics in classroom practice. *The Internet and Higher Education*, 46, 100730. <https://doi.org/10.1016/j.iheduc.2020.100730>
- Shing, C. L., Saat, R. M., & Loke, S. H. (2015). The knowledge of teaching – Pedagogical content knowledge (PCK). *MOJES: Malaysian Online Journal of Educational Sciences*, 3(3), 40–55.

- Srinivasan, V. (2022). AI & learning: A preferred future. *Computers and Education: Artificial Intelligence*, 3, 100062. <https://doi.org/10.1016/j.caeai.2022.100062>
- Su, J., & Zhong, Y. (2022a). Artificial intelligence (AI) in early childhood education: Curriculum design and future directions. *Computers and Education: Artificial Intelligence*, 3, 100072. <https://doi.org/10.1016/j.caeai.2022.100072>
- Sychev, O. (2024). Educational models for cognition: Methodology of modeling intellectual skills for intelligent tutoring systems. *Cognitive Systems Research*, 87, 101261. <https://doi.org/10.1016/j.cogsys.2024.101261>
- Terzieva, V., Ilchev, S., Todorova, K., & Andreev, R. (2021). Towards a design of an intelligent educational system. *IFAC-PapersOnLine*, 54(13), 363–368. <https://doi.org/10.1016/j.ifacol.2021.10.474>
- Toro, C., Rios, S. A., Howlett, R. J., & Jain, L. C. (2024). 28th KES International Conference on Knowledge-Based and Intelligent Information & Engineering Systems KES2024 (Vol. 246, pp. 1–9). Elsevier. <https://doi.org/10.1016/j.procs.2024.09.152>
- Tunjera, N., & Chigona, A. (2023). Investigating effective ways to use artificial intelligence in teacher education. *European Conference on E-Learning*, 22, 331–340.
- Vujinović, A., Luburić, N., Slivka, J., & Kovačević, A. (2024). Using ChatGPT to annotate a dataset: A case study in intelligent tutoring systems. *Machine Learning with Applications*, 16, 100557. <https://doi.org/10.1016/j.mlwa.2024.100557>
- Walshe, N., & Driver, P. (2019). Developing reflective trainee teacher practice with 360-degree video. *Teaching and Teacher Education*, 78, 97–105. <https://doi.org/10.1016/j.tate.2018.11.009>
- Wang, X., Young, G. W., Plechatá, A., Mc Guckin, C., & Makransky, G. (2023). Utilizing virtual reality to assist social competence education and social support for children from under-represented backgrounds. *Computers & Education*, 201, 104815. <https://doi.org/10.1016/j.compedu.2023.104815>
- Wilson, R. N., Holman, P. J., Dragan, M., MacPherson, R. E. K., & Beaudette, S. M. (2024). The effects of supplemental instruction derived from peer leaders on student outcomes in undergraduate human anatomy. *Anatomical Sciences Education*, 17(6), 1239–1250.
- Winkler, R., Söllner, M., & Leimeister, J. M. (2021). Enhancing problem-solving skills with smart personal assistant technology. *Computers & Education*, 165, 104148. <https://doi.org/10.1016/j.compedu.2021.104148>
- Zawacki-Richter, O., Kerres, M., Bedenlier, S., Bond, M., & Buntins, K. (2020). *Systematic reviews in educational research: Methodology, perspectives and application*. Springer VS Wiesbaden. <https://doi.org/10.1007/978-3-658-27602-7>