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Artificial Intelligence in Primary Education: A Systematic Literature Review 2020–2025

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Abstract. Artificial Intelligence (AI) is reshaping primary education across literacy, numeracy, inclusion, and classroom orchestration. This systematic review synthesizes empirical research from 2020 to 2025 to clarify how AI enhances learning and teaching in primary education. Drawing on 94 studies identified through a PRISMA-guided process, the evidence shows that AI adds the greatest value when it (a) personalizes feedback and practice, (b) scaffolds inquiry and computational thinking, and (c) augments teacher decision-making through learning analytics. Reported gains include reading fluency, problem-solving, motivation, and participation among diverse learners. Yet progress remains constrained by uneven teacher AI-TPACK and assessment literacy, infrastructural inequities, and ethical concerns regarding transparency, bias, and data governance. Across studies, the most sustainable outcomes emerged from human-in-the-loop approaches where teachers interpret and moderate AI insights. The review argues that adequate and equitable AI integration depends less on technical sophistication than on pedagogically grounded design, robust professional development, and policy frameworks ensuring accountability and equity by design. These findings inform future directions for educational policy, teacher preparation, and the ethical governance of AI-supported learning ecosystems.

Keywords: Artificial Intelligence, AI, teacher training, primary education, systematic review.

1. Introduction

The modern education system, which emerged during the Industrial Revolution, was initially intended to produce disciplined, uniform workers suited to factory work. This system prioritized efficiency and compliance over creativity and adaptability (OECD, 2019). Joel Mokyr (2001) referred to this model as “factory schools”, highlighting the emphasis on discipline, punctuality, and obedience, skills essential for industrial work. Over the past century, the role of teachers has shifted gradually from being transmitters of standardized knowledge to facilitators of diverse and creative learning (Furlong *et al.*, 2001; Labaree, 2008).

Over time, digital transformation and the rise of artificial intelligence (AI) have redefined this landscape. Cynthia Solomon (1986) noted that educators who could integrate computer culture effectively knew when to intervene and when to let learners explore independently. Today, AI tools extend that principle, acting as creative, analytical, and corrective partners in learning (Ilic *et al.*, 2021). AI-assisted pedagogies emphasize active knowledge construction, adaptive support, and metacognitive engagement (Grubaugh *et al.*, 2023). However, the growing integration of AI also raises concerns about the balance between technological innovation and teacher autonomy. Although teachers are expected to be independent, motivated, and lifelong learners, institutional policies often impose rigid mandates for technology adoption without adequate pedagogical support (Bondie & Dede, 2023).

Critical theorists such as Henry A. Giroux (2006) and Bernard Stiegler (2010; 2017) highlight the dual nature of technological progress in education, both emancipatory and disciplinary. Henry A. Giroux (2006) situates AI within a critical pedagogy framework that protects teacher agency, while Bernard Stiegler (2017) argues that without critical awareness, technological tools may standardize thought and diminish creativity. Building on these ideas, Maurizio Ferraris (2022) adds that digitalization reshapes documentation and cognition, reinforcing the need for ethical frameworks that ensure technology serves human learning rather than controls it. Together, these perspectives view AI as both an empowering and regulating force in education, emphasizing the need for ongoing critical engagement with its pedagogical and ethical aspects.

In this setting, primary education serves a crucial role in shaping children's relationship with technology. AI tools like adaptive reading programs and generative writing platforms offer personalized and creative learning experiences from a young age. However, these advancements also prompt important questions about equity, access, and ethical implementation. Despite rapid technological progress, there has been limited systematic analysis of how AI impacts teaching and learning in primary education, where pedagogical, developmental, and ethical factors are uniquely connected.

This review, therefore, focuses on two main research questions:

RQ1: What are the key benefits of developing and implementing AI tools in primary education?

RQ2: What are the main challenges in developing and implementing AI tools in primary education?

By addressing these questions, this review aims to offer a comprehensive understanding of how AI is reshaping teaching and learning practices in primary education, while also identifying the essential conditions for its ethical, equitable, and sustainable integration into educational contexts.

2. Methodology

This review was conducted following the PRISMA 2020 framework to ensure a transparent, replicable, and comprehensive approach to identifying, evaluating, and synthesizing relevant literature (Page *et al.*, 2021). The review was conducted in four main stages (Fig. 1):

(1) **Identification** Identifying potentially relevant studies through database searches and reference tracking.
(2) **Screening** Screening titles and abstracts to remove duplicates and clearly irrelevant works.
(3) **Eligibility** Assessing eligibility through a full-text review against predefined inclusion and exclusion criteria.
(4) **Included** Including studies that met the final criteria for analysis.

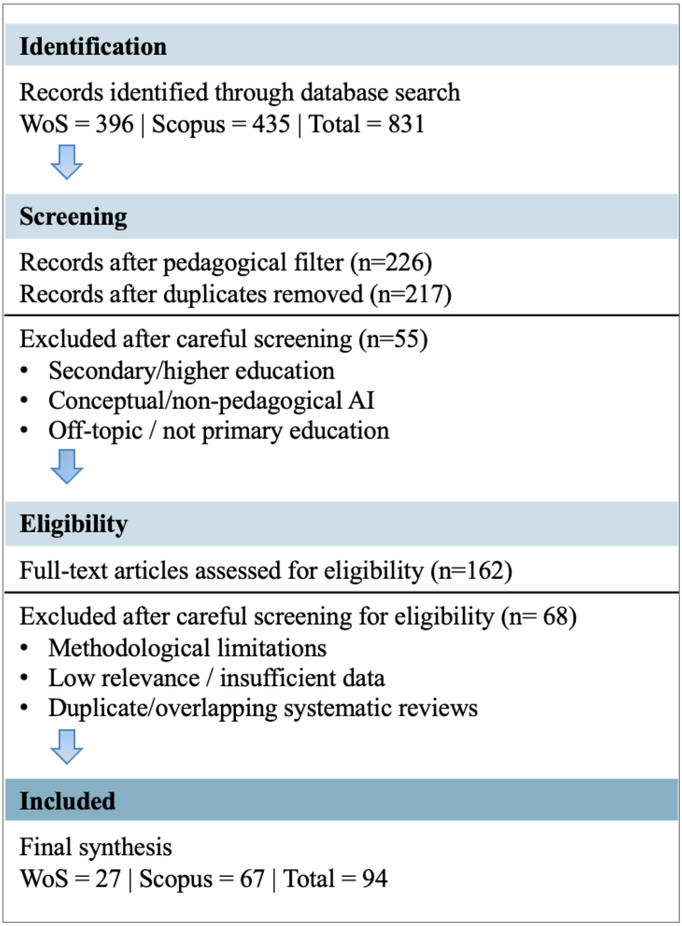

Fig. 1. PRISMA 2020 flowchart of study identification, screening, eligibility, and inclusion.

2.1. *Data Sources and Search Strategy*

A systematic literature search was conducted in 2025 across two major academic databases, Scopus and the Web of Science (WoS) Core Collection, to identify empirical, peer-reviewed studies examining the use of AI in primary education. The search process followed a structured, two-step strategy to ensure both breadth and precision.

A broad query was formulated by combining the keywords "artificial intelligence", "primary education", "elementary education", "primary school", and "elementary school". The search was limited to publications from 2020 to 2025 to capture the most recent developments in AI integration within early education contexts. Additional filters were applied to include only works published in English, classified as journal articles or conference papers, and indexed under the subject areas Social Sciences, Computer Science, or Informatics (see Table 1 for the complete search parameters).

This search identified a wide range of AI applications, including intelligent tutoring systems, learning analytics, educational robotics, and generative AI in primary education settings. All retrieved records were exported to Excel for deduplication and systematic screening in accordance with PRISMA 2020 guidelines (Page *et al.*, 2021).

The initial search yielded 435 records in Scopus and 396 in Web of Science (total = 831).

To focus on pedagogical and instructional dimensions, an additional filter ("teacher," "teaching," "pedagogy," "classroom") was applied, reducing the corpus to 110 documents in Scopus and 116 in Web of Science (total = 226). After deduplication, 217 unique records remained.

The title and abstract screening procedure was carried out in line with the PRISMA 2020 guidance, ensuring consistency and clarity in the application of the inclusion and exclusion criteria (Page *et al.*, 2021). Of the 217 unique records screened, 55 were excluded at the title/abstract level for not meeting inclusion criteria (e.g., non-empirical or non-pedagogical focus). The remaining 162 records underwent full-text assessment, and 68 articles were excluded due to methodological limitations, low relevance, focus

Table 1

Keywords and Search Strings Used in the Review on AI in Primary Education (2020–2025)

Database	Search String
Web of Science (WoS)	TS = (("artificial intelligence" OR "AI tool *" OR "AI application *" OR "AI in education" OR "machine learning" OR "generative AI" OR "ChatGPT") AND ("primary education" OR "elementary education" OR "primary school" OR "K-6" OR "basic education") AND ("teaching" OR "learning" OR "classroom practice") AND ("benefit *" OR "advantage *" OR "effect *" OR "challenge *" OR "barrier *" OR "teacher perception *" OR "student outcome *"))
Scopus	TITLE-ABS-KEY (("artificial intelligence" OR "AI tool *" OR "AI application *" OR "ChatGPT" OR "machine learning" OR "AI in education") AND ("primary education" OR "elementary education" OR "primary school" OR "K-6" OR "basic education") AND ("teaching" OR "learning" OR "classroom practice") AND ("benefit *" OR "challenge *" OR "barrier *" OR "teacher perception *" OR "student outcome *"))

on secondary/higher education, or duplication with other systematic reviews. In total, 94 empirical studies met all inclusion criteria and were retained for data extraction and synthesis (WoS = 27, Scopus = 67).

2.2. *Data Extraction and Synthesis*

Data were extracted into a structured Excel template designed to ensure transparency and traceability throughout the review process. For each study, bibliographic and contextual information (authors, year, title, source, DOI, keywords, database) and educational characteristics (participant group (students, teachers, or multiple groups), subject area, AI tool/type, study design, outcomes) were recorded. Each study was further classified into one or more of the following analytical categories aligned with the review framework: (1) Student learning, (2) Teacher and Professional Development, (3) Ethical–Inclusive–Systemic Implications, and (4) Assessment and Agency.

Key findings were summarized according to two research questions: Benefits (RQ1) and Challenges (RQ2). Where appropriate, studies were assigned to multiple categories to reflect overlapping themes. Screening decisions and reasons for exclusion were documented to maintain a transparent audit trail.

Given the heterogeneity of study designs, contexts, and outcomes, no meta-analysis was conducted. Instead, a narrative and thematic synthesis was applied to identify recurring patterns, contrasts, and trends across educational domains and AI applications.

2.3. *Study Quality Appraisal and Inter-Rater Reliability*

Study quality was evaluated based on clarity of research aims, methodological transparency, and relevance to the review questions. Two reviewers independently screened all records, extracted data, and coded studies using a shared coding framework to ensure consistency. Any differences in inclusion or coding decisions were discussed until complete agreement was reached.

Inter-rater reliability was measured for inclusion and thematic coding, yielding Cohen's $\kappa = 0.82$, indicating strong agreement among reviewers. This verifies the consistency and transparency of the screening and coding procedures.

2.4. *Eligibility Criteria*

We included empirical, peer-reviewed studies that (a) examined AI uses in primary/elementary education, (b) reported pedagogical or instructional outcomes (e.g., teaching practices, assessment, learner engagement/achievement), and (c) involved teachers and/or students in authentic school or classroom-proximate contexts. We excluded studies focused exclusively on secondary/higher education, purely technical system evaluations without an instructional component, opinion/conceptual papers, theses, non-English texts, and grey literature.

2.5. *Limitations*

This review has several limitations that should be acknowledged when interpreting its findings. First, the analysis was limited to English-language studies published between 2020 and 2025, potentially excluding relevant research from other linguistic or regional contexts. As a result, potentially valuable insights from non-English-speaking contexts may be underrepresented.

Second, the relatively small and uneven distribution of available studies limits the generalizability of the results. The majority of identified research originated from technologically advanced or high-income countries, which may not fully reflect the realities of primary education systems in low- and middle-income contexts. Moreover, variations in curricula, technological infrastructure, teacher training, and cultural attitudes toward AI create challenges in comparing outcomes across studies and applying them universally.

Third, differences in research designs and measures further constrain the synthesis of results. Many studies relied on small samples, short intervention durations, or exploratory designs, reducing the robustness of causal claims. In several cases, the methodological transparency regarding AI tools, data sources, and analytical procedures was limited, making replication and comparison difficult.

Finally, the rapid pace of technological development means that findings from current studies may quickly become outdated as new AI models, tools, and pedagogical frameworks emerge. Future research should therefore adopt broader linguistic, geographical, and longitudinal perspectives, while emphasizing methodological rigor, cross-cultural validity, and open data practices to build a more comprehensive and inclusive evidence base on the role of AI in primary education.

3. Results

A total of 94 empirical studies published between 2020 and 2025 were included in this systematic review, providing a comprehensive overview of how AI tools are integrated into primary education across diverse contexts. The reviewed research spans multiple countries and encompasses various AI applications, including adaptive learning systems, intelligent tutoring, generative AI, learning analytics, and AI-assisted tools for inclusive education (Fig. 2).

Most studies (43%) focused on teachers, reflecting a strong research emphasis on educators' readiness, competence, and experiences in integrating AI into teaching practice. Students represented 34% of the research samples, indicating substantial interest in understanding how learners interact with AI tools and benefit from AI-supported learning environments. Studies involving multiple groups (19%) typically include teachers, students, and, sometimes, parents, highlighting a collaborative perspective on AI integration within educational ecosystems. In contrast, only 4% of the studies focused on future teachers, indicating that pre-service teacher preparation for AI integration remains a relatively underexplored area in current research (Fig. 3).

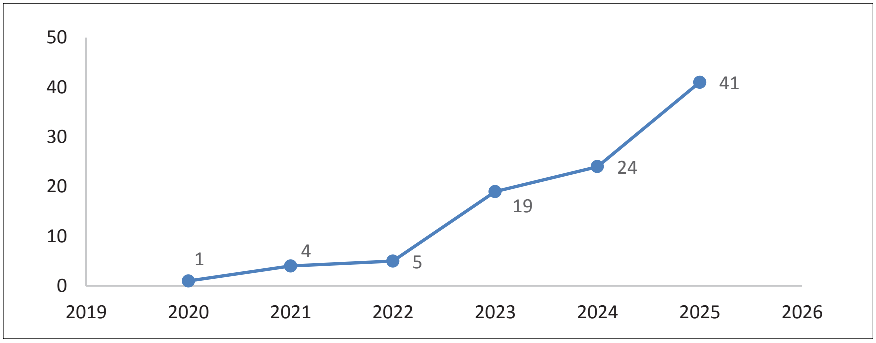

Fig. 2. Number of empirical studies on AI in primary education published between 2020 and 2025.

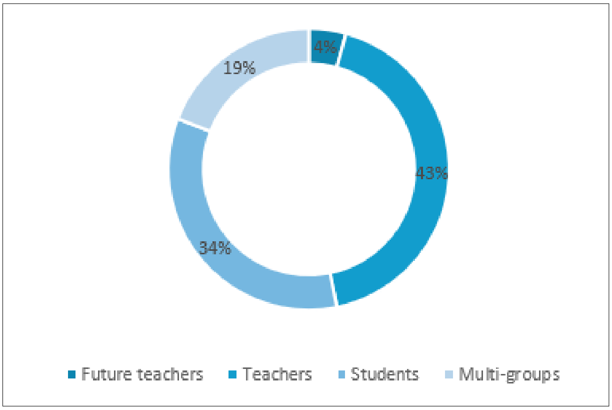

Fig. 3. Distribution of participant groups across the reviewed studies.

Most of the reviewed studies (n = 28) concentrated on AI literacy and general education, highlighting the field's focus on helping teachers and students build a basic understanding of AI concepts and ethics. The following most frequent categories were cross-disciplinary and inclusive education (n = 20) and mathematics (n = 19), highlighting AI's role in fostering problem-solving, computational thinking, and broader educational innovation. STEM/STEAM contexts (n = 14) also received considerable attention, especially in robotics and science education. In contrast, language and writing studies (n = 13) formed a smaller but distinctive group, emphasizing AI's potential to enhance literacy and communication skills in primary classrooms (Table 2).

Furthermore, the analysis of author keywords revealed several recurring concepts that reflect the core research priorities in the emerging field of AI in primary education. As shown in Fig. 4, the most frequently used keywords include artificial intelligence, generative AI, ChatGPT, teachers, students, and TPACK. These terms underscore the dominant focus on technological innovation alongside pedagogical integration. In addition, frequently appearing concepts such as AI literacy, AI ethics, robots, and adap-

Table 2
Thematic distribution of AI-related studies in primary education

Thematic group	Number of studies	Main research focus	Examples of topics
AI literacy and general education	28	Studies focusing on students', teachers', or schools' understanding and application of AI concepts and ethics.	AI literacy, AI/ML education, AI ethics, teacher adoption, general classroom use of AI, AI curriculum, and knowledge building.
Language and writing	13	Studies exploring how AI supports literacy skills, writing, and reading comprehension.	English learning, Chinese writing, reading comprehension, speaking, and composition.
Mathematics	19	Research investigating AI tools in mathematical learning and problem-solving.	Computational thinking, mathematical problem solving, mathematical reasoning, and interactive math lessons.
STEM/STEAM	14	Studies integrating AI into science, technology, engineering, or interdisciplinary design contexts.	Robotics, engineering design, science education, life sciences with AI, STEM with IoT.
Cross-disciplinary, inclusion, and other themes	20	Research addressing interdisciplinary contexts, inclusive education, creativity, or collaborative learning environments.	Inclusion, cross-disciplinary learning, educational innovation, social-emotional learning, and ethics.

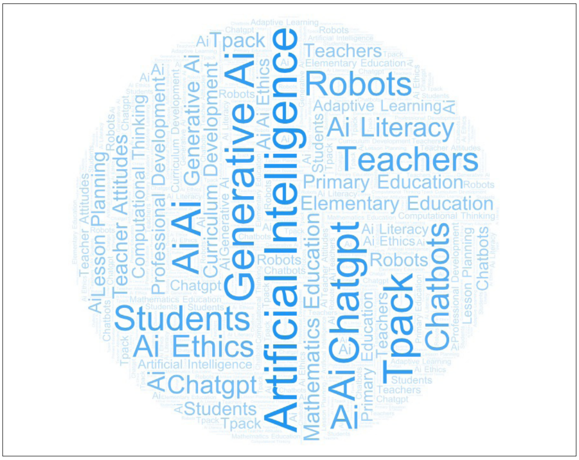

Fig. 4. Mapping of author keywords highlighting research trends in AI and primary education.

tive learning point to a growing research emphasis on ethical awareness, digital competence, and the development of personalized learning environments that respond to individual learner needs.

The dominance of teacher- and student-related keywords indicates that research has mainly focused on how AI tools affect teaching practices, learning outcomes, and professional development. Meanwhile, the rise of generative AI and chatbots as prominent terms indicates a significant shift toward exploring human-AI collaboration and creative learning possibilities in education.

From the analyzed body of literature, four overarching thematic domains were identified: (1) student learning and cognitive processes, (2) teacher perspectives and professional development, (3) ethical, inclusive, and systemic approaches to AI integration, and (4) assessment and learner agency. These domains capture how AI technologies are being conceptualized, implemented, and evaluated within primary education settings. The themes highlight key directions in current research, particularly the use of AI to enhance learning outcomes, support teacher growth, and foster equitable and reflective educational practices.

The following sections explore each thematic domain in detail, highlighting distinctive pedagogical applications, methodological approaches, and emerging challenges that require further research. A comprehensive overview of all reviewed studies and their classification within these domains is included in Appendix I.

3.1. *Student Learning and Cognitive Processes*

Approximately 60 of the 94 studies[1] examine the impacts of AI on learning, engagement, and participation across diverse contexts. Effects are strongest when AI interventions are developmentally appropriate, teacher-guided, and responsive to the specific educational context.

RQ1. Key benefits

Across subjects, AI-supported environments improve performance and metacognitive strategies. In science, Lee *et al.* (2021) introduced PRIMARYAI, a game-based environment that integrates problem-based learning, AI, and ecological science to help upper-primary pupils explore life-science questions and AI concepts. Their study reported greater problem-solving and conceptual improvements, later validated by Ottenbreit-Leftwich *et al.* (2023) in follow-up classroom research.

In literacy, AI tools such as educational robots and automated feedback systems enhanced students' attention, vocabulary, and revision quality, while teachers rated them as highly usable (Huang *et al.*, 2021; 2023). In mathematics, the Squirrel AI Intelligent Adaptive Learning System improved fifth-graders' cognitive development (Qiu *et al.*, 2025), while the ChatGPT-supported word-problem system (ChatGPT-MPS) yielded higher post-test scores and greater learning interest (Liu *et al.*, 2025).

Beyond traditional subjects, AI tools fostered creative engagement and self-reflection: mobile AI drawing applications strengthened students' creative self-efficacy, while robotics-based AI sequences improved metacognitive regulation among low-achieving and special-needs learners (Zeng *et al.*, 2025; Absalon *et al.*, 2025).

[1] Many studies addressed multiple thematic domains, for example, learning and teacher development, and therefore, the reported counts reflect overlapping categories rather than mutually exclusive classifications.

Large-scale initiatives demonstrate that AI can support inclusion. In Brazil, the AIED "Unplugged" program reached over 8,000 schools and 160,000 students, achieving comparable writing gains in both rural and urban contexts, without reliance on the internet (Portela *et al.*, 2024). Rural research further highlights teachers' need for offline resources, flexible curricula, and targeted professional development (Castro *et al.*, 2025). In China, structured frameworks have strengthened AI and computational literacy through a national curriculum defining 90 core AI concepts and 63 learning indicators (Song *et al.*, 2023), graphical programming sequences that strengthened computational thinking (Xue *et al.*, 2024), and classroom activities prompting pupils to reflect on AI's potential benefits and risks (Walan, 2025).

Generative AI tools that customize learning tasks based on students' interests boost intrinsic motivation (Taşdelen & Bodemer, 2025) and enhance language proficiency in English as a Foreign Language settings, including oral skills (Yuan, 2024), vocabulary, and conversational practice through immersive 3D learning environments (Xu *et al.*, 2025). Beyond individual learning, classroom analytics helped teachers refine instruction and foster more interactive learning environments (Zhu *et al.*, 2023). In low-resource contexts, AI-powered social robots enabled individualized tutoring support and helped address high teacher–pupil ratios, enabling one-to-one style assistance in large classrooms (Rutatola *et al.*, 2025), while accessibility-focused innovations such as sign-learning games using gesture recognition expanded learning opportunities for deaf and hard-of-hearing pupils (Ulrich *et al.*, 2024).

RQ2. Main challenges

Positive effects depend on careful pedagogical design and teacher mediation. AI feedback often lacks the multimodal sensitivity of human interaction. Direct comparisons found that human tutors achieved twice the learning gains of AI agents in arithmetic tasks (Anton *et al.*, 2025). Generative systems may also yield inconsistent or overly templated outcomes unless teachers ensure creative ownership and clear evaluation criteria (Xu *et al.*, 2025; Zeng *et al.*, 2025). Teachers frequently struggle to embed AI meaningfully within subject logic; a limited understanding of computational thinking can lead to fragmented or superficial coding activities (Nordby *et al.*, 2022). Similar challenges persist in K-12 contexts, where insufficient technological and content knowledge hinders meaningful AI integration (Yue *et al.*, 2024). Infrastructure barriers such as bandwidth, device access, and maintenance also limit implementation, especially in low-resource settings, though unplugged approaches demonstrate scalable alternatives (Jiang & Li, 2023; Portela *et al.*, 2024). Ethical concerns regarding privacy, bias, and algorithmic transparency continue to arise, highlighting the importance of explicit instruction in teaching AI ethics and explainability to students. (Sperling *et al.*, 2022; Walan, 2025).

Synthesis and future directions

Evidence at the primary education level supports the principle of human-AI complementarity. AI enhances learning most effectively when teachers guide its pedagogical and ethical application (Lee *et al.*, 2021; Huang, 2021). Adaptive and generative systems can scaffold inquiry, writing, and reasoning when guided by teacher interpretation (Huang *et al.*, 2023; Qiu *et al.*, 2025) and refine instruction through real-time insights (Taşdelen & Bodemer, 2025; Zhu *et al.*, 2023). Sustainable impact depends on equity-oriented and context-sensitive AI designs. Teachers in rural schools emphasize the need for adaptable resources and professional development to bridge digital divides (Castro *et al.*, 2025), while large-scale initiatives confirm the scalability of unplugged AI solutions in low-resource schools (Portela *et al.*, 2024) and overcrowded classrooms (Rutatola *et al.*, 2025).

Future research should further investigate how AI-driven learning environments influence not only academic but also metacognitive and socio-emotional growth, ensuring transparency, inclusivity, and co-design with teachers and students. Finally, longitudinal and cross-context studies are crucial to developing sustainable models that promote equitable access and meaningful participation in AI-supported learning.

3.2. *Teacher Perspectives and Professional Development*

Approximately seventy studies examined teachers' perceptions, practices, and readiness to integrate AI into primary education. Across diverse educational contexts, teachers generally viewed AI as a collaborative partner that can enhance instructional differentiation, reduce administrative workload, and promote reflective teaching practices. Many studies highlighted that AI tools were most effective when complementing, rather than replacing, teachers' pedagogical expertise, offering real-time feedback and formative insights into students' learning progress and needs.

RQ1. Key benefits

Co-designed approaches and structured training consistently improved teacher confidence and instructional quality. In PRIMARYAI, upper-primary teachers co-developed inquiry units and reported greater confidence orchestrating AI-supported instruction (Lee *et al.*, 2021), later confirmed in follow-up classroom research emphasizing the importance of embedded professional learning (Ottenbreit-Leftwich *et al.*, 2023). In Portugal, an AI/ML-based didactic sequence improved time management and student autonomy (Silva *et al.*, 2025), while rural area teachers valued offline-capable AI tools for personalizing multigrade classrooms (Castro *et al.*, 2025).

Generative AI games and conversational agents increased student engagement and provided formative feedback when teachers participated in their design and facilitation. (Xu *et al.*, 2025). Survey evidence also shows that AI-related TPACK predicts both readiness and positive attitudes toward AI integration (Yue *et al.*, 2024). In teacher education, scenario-based generative AI improved preservice teachers' self-efficacy and AI literacy (Meegan & Young, 2025), while South Korean teachers emphasized AI's value in automating administrative work and personalizing instruction (Oh & Ahn, 2024).

Professional development programs have proved to be crucial; for example, a 75-hour course based on the TPACK framework significantly enhanced teachers' AI competence and confidence (Sun *et al.*, 2023). Community-based initiatives and AI-supported companions have encouraged reflective practice and agency (Tan *et al.*, 2025), and national frameworks, such as China's 90-concept AI curriculum, have provided strategic implementation guidance (Song *et al.*, 2025).

AI analytics also supported reflection and real-time adaptation. Robotics-based and adaptive learning systems enabled teachers to monitor cognitive growth and adjust tasks accordingly (Absalon *et al.*, 2025; Qiu *et al.*, 2025), while analysis of interactions in smart classrooms revealed patterns of teacher-student dialogue that guided instructional improvement (Zhu *et al.*, 2023).

RQ2. Main challenges

Teachers continue to face significant gaps in AI knowledge, infrastructure, and policy support. Misconceptions about AI's functions often result in fragmented or overly technical lessons in early primary grades (Vogt *et al.*, 2025). Limited computational thinking skills lead to superficial coding activities detached from curricular aims (Nordby *et al.*, 2022). Teachers frequently compensate for algorithmic errors and unpredictability in classroom applications (Sperling *et al.*, 2022) and call for sustained human oversight to prevent misinformation and uphold ethical use (Uğraş *et al.*, 2024).

Teachers emphasize the need for developmental calibration, as large language models often generate plausible but inaccurate reasoning (Getenet, 2024). Ethical safeguards prioritizing care are particularly vital in special education contexts (Giaouri & Charisi, 2025). Hands-on experience remains the strongest predictor of teacher confidence and readiness (Batubara *et al.*, 2025), yet disparities in digital infrastructure and unclear institutional frameworks continue to hinder implementation (Li & Manzari, 2025; Pyzalski, 2025).

Synthesis and future directions

Collectively, these studies position teachers as central mediators of AI's educational impact. Their professional judgment determines whether AI amplifies or undermines learning goals. Sustained teacher learning, contextual support, and ethical reflection are therefore not peripheral but foundational to the responsible adoption of AI in schools.

Future research should investigate how teachers' roles evolve as AI systems become more adaptive and generative, focusing on co-orchestration models where teachers and AI systems share complementary roles in feedback, assessment, and differentiation. Longitudinal studies could trace how teachers refine their practice through iterative AI use and institutional learning.

Professional development should increasingly emphasize AI-TPACK, data ethics, and interpretability, equipping teachers to explain AI processes to pupils, interpret outputs critically, and embed ethical reflection in everyday practice. Context-specific mentoring, peer collaboration, and practice-based inquiry can help translate technical competence into pedagogical fluency.

Policy alignment remains crucial. Clear standards for data governance, informed consent, and transparency should guide classroom practice, while communication with parents can strengthen shared trust. National or regional frameworks integrating AI literacy benchmarks into teacher standards can ensure that ethical and pedagogical capacities develop in parallel. Cross-cultural studies should compare policy and implementation models to distinguish contextual barriers from universal design principles. When teacher learning, ethical oversight, and policy coherence advance together, AI can evolve from a peripheral novelty into a sustainable pedagogical partner that strengthens professional agency and supports equitable, human-centered innovation in primary education.

3.3. *Ethical, Inclusive, and Systemic Implications*

Roughly 55 of the 94 studies address how AI can be integrated into primary education in ethical, inclusive, and systemically workable ways. Collectively, they demonstrate AI's promise for personalization, participation, and access while foregrounding teacher agency, governance, and equity as essential preconditions for meaningful implementation. The literature consistently emphasizes that ethical AI integration relies on technical innovation along with transparency, fairness, and accountability. Effective systems must respect privacy, ensure accessibility for diverse learners, and align with educational values and child protection standards. Thus, AI in education is seen not just as a tool for efficiency, but as a catalyst for fair, inclusive, and human-focused learning ecosystems.

RQ1. Key benefits

Inclusive outcomes are strongest when teachers co-design and mediate AI use. Studies on humanoid robots integrated with ChatGPT reveal that teacher participation clarifies ethical and pedagogical boundaries and increases student engagement (Sacco *et al.*, 2023). School–university collaboration similarly enhances teachers' epistemological understanding and classroom practices through sustained dialogue with researchers (Dai, 2023). Teacher-guided uses of generative AI promote creativity and empathy when supported by structured professional training and explicit ethical guidance (Uğraş *et al.*, 2024).

Personalization is a recurrent driver of equity. AI can surface individual learning needs and adapt feedback in hybrid AI–human contexts (Sreenath *et al.*, 2024). Teachers working with students with special educational needs reported that personalized AI systems improved engagement and diagnostic accuracy but required institutional support and ethical safeguards (Bagabas, 2025). Rural projects applying intelligent monitoring and learner profiling, localized inquiry-based "labor education" to community settings (Wang *et al.*, 2025).

Adult and institutional capacity-building remains critical. The China-specific AI-TPACK scale provides a validated measure of primary teachers' technological and pedagogical competencies (Li & Nugraha, 2025), while the AILST framework assesses perception, application, innovation, and ethical awareness to strengthen AI literacy (Ning *et al.*, 2025). Accessibility-focused innovations such as machine learning sign language games (Ulrich *et al.*, 2024), no-code robotics kits (Dahal *et al.*, 2025), and early flow analytics for well-being (Rosas *et al.*, 2022) broaden participation for underrepresented learners. National studies emphasize the importance of human oversight to manage misinformation and ensure age-appropriate use (Uğraş *et al.*, 2024), alongside policies that align AI adoption with educational equity (Kopecký & Voráč, 2025; Pyzalski, 2025).

RQ2. Main challenges

Teachers' willingness to adopt AI often surpasses institutional readiness. Limited training, high costs, and insufficient policy coordination constrain effective implementation across contexts, from Saudi Arabia (Bagabas, 2025) to Serbia (Skobo & Sović, 2025). In the United States, primary teachers' low AI literacy highlights the need for targeted professional development (Philippakos & Rocconi, 2025). Accuracy and bias remain persistent concerns, as large language models can produce plausible yet incorrect reasoning, requiring critical teacher verification and contextualization (Getenet, 2024). Across Europe, teachers express concerns about overreliance on AI and declining authenticity in learning. Polish teachers warn that automation may weaken trust and encourage academic dishonesty (Pyzalski, 2025), while Swedish studies emphasize embedding privacy, authorship, and accountability principles into AI literacy frameworks (Walan, 2025). Data governance challenges persist as engagement-tracking technologies raise issues of consent, data minimization, and transparency (Rosas *et al.*, 2022).

Systemic misalignment also slows adoption. Teachers' behavioral intentions to use AI depend on supportive environments and institutional planning (Li & Zhang, 2024), yet incoherent curricula and policy gaps limit sustainable integration in schools (Skobo & Sović, 2025), while national-level analyses highlight the need for context-sensitive frameworks to ensure AI use with educational equity (Kopecký & Voráč, 2025).

Synthesis and future directions

The reviewed studies share a common insight: ethical and inclusive AI integration depends more on human and institutional capacity than on technology itself. Multi-level coordination among teachers, policymakers, researchers, and communities is essential for equitable and transparent implementation. Future research should focus on how schools can implement ethical frameworks through classroom practices, developing practical data governance models, transparent consent protocols, and culturally responsive AI literacy curricula for both students and teachers. Policy and funding structures must align with professional standards to ensure inclusion and accountability.

A promising direction lies in human-centered system design, where teachers co-create ethical guidelines and contribute to the interpretability and fairness of AI tools. Longitudinal and cross-cultural studies can identify governance mechanisms that balance innovation with equity and protection. Ultimately, when ethical reflection, institutional alignment, and teacher empowerment evolve together, AI can become a systemic enabler of inclusion rather than a new axis of inequality.

3.4. *Assessment Innovation and Agency*

Thirty-six studies examined how AI reshapes assessment and student agency in primary education. The evidence spans adaptive platforms, generative tools, robotics, and multimodal analytics, highlighting AI's potential to enrich feedback and strengthen metacognitive engagement. These innovations mark a shift from traditional testing to dynamic, formative, and personalized assessment, where learners receive continuous, individualized feedback that strengthens self-regulation and ownership of learning. In this context, assessment becomes a collaborative dialogue between students, teachers, and intelligent systems.

RQ1. Key benefits

The strongest outcomes emerge when AI is integrated into inquiry, feedback, and reflection processes. In science, PRIMARYAI provided game-based inquiry that enhanced problem-solving for pupils aged 8–11 and helped teachers scaffold complex ideas more effectively (Lee *et al.*, 2021). Broader applications under China's Double-Reduction policy showed that AI agents linking families, schools, and communities improved scientific inquiry competence through coordinated support (Xia *et al.*, 2025).

In literacy, paragraph-level automated scoring tools delivered instant, actionable feedback that improved students' drafts and reduced teacher workload (Huang *et al.*, 2023). Teacher-guided activities with ChatGPT boosted creative writing quality and self-efficacy (Kızıltas, 2025). Similar trends were observed in mathematics, adaptive systems delivered more precise, data-informed guidance (Qiu *et al.*, 2025), while generative AI feedback increased confidence and socio-emotional engagement (Zheng & Tse, 2023). Multimodal systems broadened assessment possibilities, for example, gesture-recognition apps supported skill-specific feedback in music (Bravo *et al.*, 2023), and a brain-computer interface enabled collaborative language tasks with robots (Lee *et al.*, 2020).

Teacher expertise is also strengthened through AI-enhanced assessment tools. Iterative dialogue between teachers and AI improved situational analysis and instructional judgment (Huang & Yu, 2024). Frameworks such as AI-TPACK and the AILST offered reliable diagnostics for teacher competence and reflection (Li & Nugraha, 2025; Ning *et al.*, 2025). Scalable systems like the BPNN-based, ability-oriented STEAM model, allowing continuous monitoring (Shi & Rao, 2022) and validated AI learning progressions for adaptive teaching (Chakraburty *et al.*, 2024), exemplify systemic approaches that sustain evidence-based instructional improvement.

Context-sensitive technologies further enhance learners. Low-cost robotics workshops promote playful engagement and iterative design (Dahal *et al.*, 2024), while wearable devices that link physiological signals to metacognitive awareness deepen engagement in STEAM activities (Rosas *et al.*, 2022). Furthermore, national survey data indicate that students increasingly use generative AI for self-assessment and study support beyond the classroom (Kopecký & Voráč, 2025).

RQ2. Main challenges

The main constraints relate to pedagogical alignment, interpretability, and ethics rather than to technology itself. Teachers emphasize the need for reliable, transparent feedback systems, as inconsistencies in writing scores and opaque reasoning undermine trust without precise calibration and curricular alignment (Huang *et al.*, 2023). Comparative studies show that human tutors still outperform AI agents in arithmetic learning because of multimodal cues such as gesture and gaze that current systems cannot replicate (Anton *et al.*, 2025). Developmental misalignment also poses challenges, for example, large language models may simulate reasoning but fail to reflect children's cognitive and social maturity (Getenet, 2024). For this reason, teacher agency through critical interpretation and ethical judgment remains essential (Huang & Yu, 2024; Kızıltas, 2025).

Implementation barriers also persist, particularly in data-intensive, hardware-dependent systems (robotics, BCI, and smart classrooms) that raise privacy, consent, and cost concerns (Lee *et al.*, 2020; Fang *et al.*, 2024). Such challenges are particularly evident in low-resource schools with limited institutional oversight (Zhu *et al.*, 2023). Finally, overreliance on algorithmic feedback may weaken students' critical reasoning unless they are taught to critique and contextualize AI outputs (Zheng & Tse, 2023). Integrating critical AI literacy into classroom practice can turn such dependence into reflective learning (Chakraburty *et al.*, 2024).

Synthesis and future directions

The reviewed studies view assessment as an active, interactive process where students, teachers, and intelligent systems all share responsibility. When pedagogically grounded, professional capacity building is explicit (Sun *et al.*, 2023), and tools are context-sensitive, including offline and low-cost options (Portela *et al.*, 2024; Castro *et al.*, 2025) AI enhances the validity, timeliness, and inclusiveness of feedback while preserving human judgment and relationships (Li & Nugraha, 2025).

Future work should prioritize transparent, explainable, and developmentally appropriate AI systems aligned with children's cognitive growth. Assessments must go beyond accuracy to measure consequential validity, how AI-mediated feedback influences motivation, self-efficacy, and long-term learning. Research should explore hybrid human–AI orchestration models, defining when and how teachers intervene and how learners critically engage with AI suggestions.

Equity and accessibility remain central imperatives. Further work should test low-cost, no-code, and offline pathways that reduce infrastructure barriers and support diverse learners, including those with disabilities, linguistic differences, and varying socio-economic backgrounds. Data governance and consent protocols must be built into system design, ensuring transparency about data use, bias mitigation, and child-appropriate consent. Actively involving students and families in discussions about how data are collected, interpreted, and acted upon can strengthen trust and ethical awareness.

Sustaining AI-enabled assessment requires robust teacher learning. Professional development integrating AI-TPACK, assessment literacy, and data ethics is essential to build interpretive and ethical competence. Longitudinal and mixed-methods studies linking digital log data with classroom observations can trace how AI-based assessment evolves in practice.

Overall, evidence suggests that AI can enhance primary assessment practices and empower learners when implemented transparently, ethically, and in partnership with teachers. Designing systems that prioritize consent, agency, and equity ensures that technology improves assessment quality and supports learning autonomy, without diminishing the human relationships at the heart of primary education.

Integrative summary of findings

To synthesize the results across the four domains:

(1) Student learning and cognitive processes.
(2) Teacher perspectives and professional development.
(3) Ethical, inclusive, and systemic approaches to AI integration.
(4) Assessment and learner agency.

Table 3 presents a concise overview of the main benefits, challenges, and representative studies. Representative exemplar studies are summarized in Appendix II, which presents key benefits, challenges, and typical AI uses identified across the reviewed literature.

Table 3

Summary of AI integration in primary education across four domains

Domain	Typical AI Uses / Examples	Key Benefits (RQ1)	Main Challenges (RQ2)
3.1. Student Learning and Cognitive Processes	Adaptive/generative learning platforms (e.g., Squirrel AI, ChatGPT-MPS); educational robots; unplugged AI; classroom analytic	Improved academic outcomes, engagement, and metacognitive skills; supports inclusion and creativity through adaptive and unplugged AI	Requires teacher mediation; limited multimodal feedback; uneven computational literacy; infrastructural and ethical gaps
3.2. Teacher Perspectives and Professional Development	Co-designed AI learning units (PRIMARYAI); adaptive feedback tools; AI-TPACK-based PD; smart-classroom analytics	Co-design and PD strengthen confidence, reflection, and ethical fluency; AI reduces workload and supports differentiation	Gaps in AI literacy and policy; misconceptions and algorithmic unpredictability; inequitable infrastructure; need for ethical safeguards
3.3. Ethical, Inclusive, and Systemic Implications	Hybrid AI–human personalization; AI-TPACK/AILST frameworks; low-cost robotics; sign-language AI tools; learner-profiling systems	Co-design and human-AI collaboration promote inclusion and fairness; personalization enhances accessibility; frame-works enhance teacher competence	Institutional capacity lags; systemic misalignment; bias and misinformation; unresolved data-governance and consent issues
3.4. Assessment Innovation and Agency	Automated essay scoring; generative feedback; multimodal analytics; brain–computer interfaces; low-cost robotics; wearable sensors.	Transforms assessment into formative dialogue; strengthens self-regulation and learner agency; improves feedback validity	Opaque or developmentally misaligned feedback; privacy and cost issues; risk of overreliance; need for ongoing teacher training

4. Discussion

The synthesis of ninety-four studies shows that AI in primary education is more than just an educational innovation; it catalyzes significant pedagogical transformation. Across various cultural and institutional settings, AI improves personalization, provides formative feedback, and highlights ongoing tensions between automation and agency, efficiency and empathy, innovation and equity. These findings position AI not as a substitute for teachers but as a co-creator of learning, redefining pedagogical responsibility and agency.

Across studies, evidence converges on AI's potential to enrich adaptive learning, formative assessment, and reflective teaching. Adaptive AI-based learning environments strengthened students' conceptual understanding and self-regulation (Lee *et al.*, 2021; Qiu *et al.*, 2025). Automated feedback tools improved writing revision and reflection (Huang *et al.*, 2023), while conversational AI fostered oral proficiency and learning motivation (Yuan, 2024). Continuous interaction with AI-supported teachers' reflective judgment and adaptive decision-making (Huang & Yu, 2024), complemented by diagnostic tools that enhanced their pedagogical design skills and self-efficacy (Li & Nugraha, 2025).

Despite notable progress, several limitations remain. Human tutors still surpass AI in empathy and embodied understanding, qualities central to early learning (Anton *et al.*, 2025). Teachers' uneven AI literacy and ethical awareness constrain pedagogical integration (Yue *et al.*, 2024). While low-cost, offline tools such as AIED-Unplugged proved effective in rural Brazil (Portela *et al.*, 2024), resource-intensive smart classrooms raise logistical and equity concerns (Jiang & Li, 2023; Fang *et al.*, 2024), underscoring that contextual fit and teacher readiness matter more than technological sophistication. Concerns about authorship, reliability, and transparency persist among teachers and students (Bower *et al.*, 2024; Kızıltas, 2025), alongside risks of algorithmic bias and opaque feedback (Huang *et al.*, 2023; Chakraburty *et al.*, 2024). Equitable AI design is especially critical for under-resourced or multilingual schools that rely on culturally adaptive, low-bandwidth solutions (Castro *et al.*, 2025; Zhu & Zhang, 2025), as unequal access may deepen divides (Kopecký & Voráč, 2025). When teachers interpret AI insights and moderate automated feedback, they transform technology into pedagogy, fostering learners' metacognition, agency, and ethical judgment. Embedding AI literacy and ethics in primary education curricula, as proposed by S. Walan (2025) and A. Ottenbreit-Leftwich *et al.* (2023), can nurture these competencies.

Teacher competence for AI is therefore more about orchestration than tools – the skill of knowing when to let intelligence flow and when to regain control. In this emerging educational landscape, three interconnected levels of competence create a moral and intellectual framework. The first is AI fluency with guardrails, which is not technical mastery but epistemic humility, understanding how intelligence is simulated, where it falters, and how to reveal that uncertainty to children. The second, classroom orchestration, is a choreography of presence and delegation, knowing when to hand over repetition to the machine and draw learners back into the human circle of dialogue, care, and sense-making. The third, design for equity, guarantees that technology remains accessible, ethical, and inclusive so that learning prospers even where bandwidth is limited and every child interacts with AI as both a user and a co-creator. Together, these layers indicate that competence in the age of AI is not a checklist but a form of moral presence, a pedagogy tuned to timing, ethics, and the delicate balance between guidance and freedom.

The next phase of AI integration in primary education should shift from pilot enthusiasm to systemic alignment. Policies must focus on empowering teachers, enhancing professional development, and establishing transparent governance frameworks that protect privacy, promote equity, and ensure inclusion. Schools need mechanisms for obtaining informed consent appropriate for children, clear communication about data use, and ongoing dialogue with families about AI's purposes and boundaries. Future research should investigate hybrid human–AI collaboration models, examining when automated guidance supports learning and when it may hinder curiosity or relational trust. Long-term and cross-cultural studies are essential for evaluating the lasting impact, ethical consistency, and cultural adaptability.

Ultimately, the actual value of AI in primary education will not be measured by its computational ability but by its capacity to strengthen human connection and curiosity. When teachers and students use AI as a creative, ethical, and collaborative partner, technology enhances the most human qualities of teaching, such as empathy, imagination, and the shared pursuit of understanding. Basing AI in these values turns technological progress into educational justice, ensuring that innovation benefits learning rather than diminishing it.

5. Conclusion

This review summarizes recent empirical evidence on the development and implementation of AI in primary education, focusing on two main questions: the key benefits and challenges of integrating AI. The findings reveal that AI is more than just a technological innovation; it acts as a catalyst for a significant pedagogical transformation, reshaping the relationships among teachers, learners, and knowledge itself.

In response to RQ1, the evidence shows that thoughtfully designed AI tools add value by personalizing feedback and practice, scaffolding inquiry and computational thinking, and amplifying teacher agency through analytics and co-design. When integration is pedagogically grounded and developmentally appropriate, AI can enrich formative assessment, support reflection, and extend learning beyond classroom boundaries. However, as RQ2 highlights, significant barriers persist, including teachers' uneven AI-TPACK competence, limited assessment literacy, developmental misalignment of tools, infrastructural inequalities, and unresolved issues of transparency, reliability, authorship, and data ethics in generative systems.

Looking forward, progress will depend less on expanding AI use and more on thoughtful integration designs that maintain human interpretation at the core. Future initiatives should focus on age-appropriate, curriculum-aligned applications where AI-generated insights align with learning objectives in areas such as writing, reasoning, or scientific inquiry. Teachers remain interpreters of meaning and care. Thus, professional learning should combine theoretical knowledge with practice-based rehearsal, through micro-teaching with AI, chatbot-simulated student dialogues, and iterative feedback cycles. Diagnostic tools such as AI literacy and AI-TPACK scales can help identify specific areas for targeted professional growth.

From a systems perspective, equity-by-design must become a fundamental standard rather than just an aspiration. Sustainable implementation depends on offline-first, low-cost, and localized pathways that fit teachers' daily realities. Policy frameworks should incorporate teacher override options, provide age-appropriate explainability for children, and establish clear criteria for developmental suitability. Ethical governance requires consent-by-design, data minimization, and transparent documentation of data flows. At the policy level, integrating AI literacy and ethical standards into national curricula and teacher training frameworks will be critical to sustain equitable and responsible implementation. Authorship and academic integrity guidance should clarify the accountable use of generative tools. Importantly, student and family voices should help define school-level norms for acceptable AI assistance, ensuring that well-being and autonomy remain protected.

Future studies should prioritize depth over breadth, concentrating on long-term, contextually sensitive outcomes such as creativity, reasoning, and self-regulation. Assessing cost-effectiveness, sustainability, and teacher workload will also be crucial. Contextual and subgroup analyses remain critical, especially for learners with special educational needs, multilingual students, and those in rural or low-resource contexts. Validation studies linking AI feedback to human evaluations and learning progressions are needed, alongside shared datasets and benchmarking protocols to ensure comparability across different tools, age groups, and languages. Collaborative research-practice partnerships can help connect classroom realities with policy implementation.

For practitioners and educational leaders, a gradual, evidence-based roadmap emerges. Start small by integrating AI for lesson planning and formative feedback under teacher guidance. Scale up only what proves effective, transparent, and curriculum-aligned. Additionally, institutionalize professional development systems, mentoring, and reflective analytics routines.

For developers, the design should focus on interpretability, age-appropriateness, multimodal awareness, and teacher agency to adapt or edit outputs. Evaluation metrics should extend beyond accuracy to include factors like trust, transparency, equity, and pedagogical relevance.

The future of AI in primary education depends on balancing automation and human judgment. When teachers, learners, and technologies collaborate through ethics, empathy, and inquiry, AI becomes not a substitute for teaching but a way to enhance its core qualities, such as curiosity, care, and creativity. Aligning AI's technological advancements with these lasting educational values remains both the field's most significant opportunity and its most urgent responsibility.

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Appendix I
Artificial Intelligence in Primary Education: A Systematic Literature Review 2020–2025. Structure of the Review Matrix

This appendix presents the structure of the review used to analyse the 94 empirical studies included in the systematic review. The matrix was developed to classify and interpret publications according to four analytical categories: (1) Student learning and cognitive processes; (2) Teacher perspectives and professional development; (3) Ethical, inclusive, and systemic approaches to AI integration; (4) Assessment and learner agency.

Each publication was mapped according to the categories it addressed, as shown in the table below. The matrix provides a transparent overview of the scope and distribution of the reviewed literature, allowing the reader to trace connections between research focus areas and identify interdisciplinary overlaps.

Authors	Publication year	Student learning and cognitive processes	Teacher perspectives and professional development	Ethical, inclusive and systemic approaches to AI integration	Assessment and learner agency
Abinaya, M.; Vadivu, G.	2023	+			
Absalon, M.; Deneux, T.; Besançon, M.; Chevalier, M.	2025	+	+		+
Alanazi, AS; Alqazlan, S; Rayan, A; Benlaria, H	2025		+	+	
Anton, J.; Cosentino, G.; Sharma, K.; Gelsomini, M.; Mok, M.; Giannakos, M.; Abrahamson, D.	2025	+			+
Bagabas, HA	2025		+	+	
Batubara, H.H.; Syukur, F.; Junaedi, M.; Purwanti, K.L.; Shanie, A.	2025		+	+	
Bilstrup, K.-E.K.; Connelly, L.; Musaeus, L.H.; Kaspersen, M.Hø.; Petersen, M.G.	2025	+	+	+	
Bower, M; Torrington, J; Lai, JWM; Petocz, P; Alfano, M	2024		+	+	+
Bravo, P.; Arias, A.; Carneros-Prado, D.; Dobrescu, C.C.; Bravo, J.	2023	+			+
Castro, A.; Diaz, B.; Aguilera, C.; Prat Moratonas, M.; Chavez-Herting, D.	2025	+	+	+	+
Chakraburty, S.; Hmelo-Silver, C.E.; Glazewski, K.D.; Leftwich, A.; Kim, J.; Johnson, V.; Svetina Valdivia, D.S.; Mott, B.; Lester, J.	2024	+			+
Chen, S.; Liu, Q.; He, B.	2023	+	+		

Chen, Y.; Zhang, Q.; Wang, Z.; Zhang, J.	2025		+		
Contreras-Arguello, M.L.; Paredes-Valverde, M.A.; Vásquez, A.M.T.; Salas-Zárate, M.	2025	+	+		+
Dahal, M.; Church, W.; Rogers, C.	2024	+		+	+
Dai, Y	2023		+	+	
Dai, Y.; Liu, A.; Qin, J.; Guo, Y.; Jong, M.S.-Y.; Chai, C.-S.; Lin, Z.	2023		+	+	
Dos Santos, J.M.D.S.; Pereira Abar, C.A.A.; de Almeida, M.V.; Lavicza, Z.	2023	+	+		
Fang, H.; Shu, L.; Wang, X.; Hong, X.	2024	+	+		+
Galindo-Dominguez, H; Delgado, N; Campo, L; Losada, D	2024		+	+	
Getenet, S	2024		+	+	+
Giaouri, S; Charisi, M	2025		+	+	
Guo, M.; Li, Y.	2025	+			+
Han, X.	2021		+		
Huang, C.; Yu, H.	2024		+		+
Huang, S.	2021	+			
Huang, Y.-C.; Hsiao, C.-F.; Wang, C.-J.	2023	+			+
Ivanova, E.; Zlatarov, P.	2024	+	+	+	
Jatileni, CN; Sanusi, IT; Olaleye, SA; Ayanwale, MA; Agbo, FJ; Oyelere, PB	2024		+	+	
Jiang, J.; Li, X.	2023	+	+		
Karnalim, O.; Ayub, M.; Kusbiantoro, K.	2024		+	+	
Kiziltas, Y	2025	+			+
Kong, S.-C.; Yang, Y.; Yeung, W.K.	2024		+		
Kong, SC; Yang, Y	2024	+	+	+	
Kopecky, K; Vorác, D	2025	+		+	+
Kosmas, P; Nisiforou, EA; Kounnapi, E; Sophocleous, S; Theophanous, G	2025	+	+		
Lamanauskas, V.; Makarskaite-Petkevičiene, R.	2025		+	+	

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Table – continued from previous page

Authors	Publi-cation year	Student learning and cognitive processes	Teacher perspectives and professional development	Ethical, inclusive and systemic approaches to AI integration	Assessment and learner agency
Lee, C.-S.; Wang, M.-H.; Tsai, Y.-L.; Chang, W.-S.; Reformat, M.; Acampora, G.; Kubota, N.	2020	+			+
Lee, D.; Yeo, S.	2022		+		+
Lee, S.; Mott, B.; Leftwich, A.; Scribner, A.; Taylor, S.; Park, K.; Rowe, J.; Glazewski, K.; Hmelo-Silver, C.E.; Lester, J.	2021	+	+	+	+
Li, A.; Ye, L.	2023		+	+	
Li, M; Manzari, E	2025	+	+	+	
Li, M; Nugraha, MG	2025		+	+	+
Li, M.; Zhang, H.	2024		+	+	
Lin, P.; Zhao, F.; Wang, X.; Chen, Y.	2025	+	+		
Liu, J.; Sun, D.; Sun, J.; Wang, J.; Yu, P.L.H.	2025	+	+		
Meegan, J; Young, K	2025	+	+	+	+
Moral-Sánchez, S.N.; Ruíz-Rey, F.J.R.; Cebrián-de-la-Serna, M.	2023		+		
Ning, YM; Zhang, WJ; Yao, DM; Fang, BW; Xu, BY; Wijaya, TT	2025		+	+	+
Nong, L.; Liu, G.; Tan, C.	2021	+			
Nordby, SK; Bjerke, AH; Mifsud, L	2022	+	+		
Oh, S.-Y.; Ahn, Y.	2024	+	+	+	
Ottenbreit-Leftwich, A.; Glazewski, K.; Hmelo-Silver, C.E.; Jantaraweragul, K.; Jeon, M.; Chakraburty, S.; Scribner, A.; Lee, S.; Mott, B.; Lester, J.	2023	+	+	+	
Ottenbreit-Leftwich, A., Glazewski, K., Jeon, M., Jantaraweragul, K., Hmelo-Silver, C. E., Scribner, A., Lee, S., Mott, B., & Lester, J.	2023	+	+	+	
Ovchinnikova, A.; Solovyeva, T.; Soo, V.	2024		+	+	
Pan, D.; Li, J.; Long, T.	2025	+	+		+
Philippakos, ZAT; Rocconi, L	2025		+	+	

Portela, C., Palomino, P., Challco, G., Sobrinho, Á., Cordeiro, T., Mello, R., Dermeval, D., Bittencourt, I., & Isotani, S.	2025	+	+	+	+
Pyzalski, J.	2025		+	+	
Qiu, Y.; Ishak, I.N.; Zheng, S.	2025	+	+		+
Rosas, D.A.; Burgos, D.; Padilla-Zea, N.	2022	+		+	+
Rutatola, E.P.; Stroeken, K.; Belpaeme, T.	2025	+	+	+	
Sacco, F.; Rossini, G.; Manzi, F.; Di Dio, C.; Aquilino, L.; Cangelosi, A.; Raggioli, L.; Massaro, D.; Marchetti, A.	2023		+	+	
Shi, YW; Rao, LJ	2022	+			+
Silva, A.; Sousa, A.; Saraiva, E.; Rodigues, P.; Silveira, F.; Barbot, A.	2025	+	+		+
Sinha, N.; Evans, R.F.; Carbo, M.	2023	+	+	+	
Skobo, M; Sovic, M	2025		+	+	
Song, J.; Yu, J.; Yan, L.; Zhang, L.; Liu, B.; Zhang, Y.; Lu, Y.	2023	+	+	+	
Sperling, K; Stenliden, L; Nissen, J; Heintz, F	2022	+	+	+	
Sreenath, N.; Ranade, P.; Verma, I.K.	2024	+		+	
Stryftoy, S.; Krouska, A.; Troussas, C.; Mylonas, P.; Sgouropoulou, C.	2024		+		
Sun, JM; Ma, HL; Zeng, Y; Han, D; Jin, YB	2023		+	+	+
Tan, S.C.; Tan, Y.Y.; Teo, C.L.; Yuan, G.	2025		+	+	+
Taşdelen, O.; Bodemer, D.	2025	+			
Uğraş, H.; Uğraş, M.; Papadakis, S.; Kalogiannakis, M.	2024		+	+	
Ulrich, L.; Carmassi, G.; Garelli, P.; Lo Presti, G.; Ramondetti, G.; Marullo, G.; Innocente, C.; Vezzetti, E.	2024	+		+	
Umirova, S.; Shavkatjon, S.; Zuparov, T.; Yuldashev, A.; Abdullayev, A.; Sobirova, N.	2024	+		+	
Viruel, SR; Rivas, ES; Palmero, JR	2025	+	+	+	+
Vogt, M.; Ferraioli, V.; Abou-Khalil, V.; Hollenstein, L.; Mondada, F.; Vogt, F.	2025		+	+	
Walan, S.	2025	+		+	

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Table – continued from previous page

Authors	Publication year	Student learning and cognitive processes	Teacher perspectives and professional development	Ethical, inclusive and systemic approaches to AI integration	Assessment and learner agency
Wang, X.; Li, L.; Tan, S.C.; Yang, L.; Lei, J.	2023		+	+	
Wang, Y.; Zhang, C.; Gong, X.; Ye, S.	2024	+	+		
Wang, Y.; Zhao, H.; Qi, Y.; Shen, S.	2025	+		+	
Wu, B.	2025		+		
Xia, W.; Xie, Y.; Ye, Z.; Ou, Y.; Wang, X.; Wu, B.	2025	+		+	+
Xu, SM; Lo, CK; Ling, MH; Chen, GW	2025	+	+		
Xue, T.; He, S.; Guo, W.	2024	+			
Yorulmaz, A; Okulu, HZ; Muslu-Komurcu, N; Cokcaliskan, H	2025		+	+	+
Yuan, YJ	2024	+			
Yue, M; Jong, MSY; Ng, DTK	2024	+	+	+	+
Zeng, S.; Rahim, N.; Xu, S.	2025	+			
Zheng, W.; Tse, A.W.	2023	+			+
Zhu, C.; Peng, C.; Wu, Y.	2023	+	+		+
Zhu, S.; Zhang, H.	2025	+	+	+	

Appendix II

Artificial Intelligence in Primary Education: A Systematic Literature Review 2020–2025.

Representative Exemplar Studies: Benefits, Challenges, and Typical AI Uses

This appendix complements Appendix I by presenting exemplar studies across the four analytical domains: (1) Student learning and cognitive processes; (2) Teacher perspectives and professional development; (3) Ethical, inclusive, and systemic approaches to AI integration; (4) Assessment and learner agency, defined in the systematic review.

Each reviewed study was analyzed to identify its main empirical contributions, focusing on the key benefits (RQ1) and main challenges (RQ2) of developing and implementing AI tools in primary education.

Authors	Publication year	Typical AI Uses / Examples	Key Benefits (RQ1)	Main Challenges (RQ2)
Abinaya, M.; Vadivu, G.	2023	AR and ML-based adaptive learning system	Enhances engagement and academic performance through immersive AR; supports critical and creative thinking and exploratory learning	Dependence on technology and infrastructure; need for pedagogical integration and data management ethics
Absalon, M.; Deneux, T.; Besançon, M.; Chevalier, M.	2025	AI-driven educational robotics for mathematical problem solving (AI-ERLA)	Improves metacognitive behaviors, reflection, and problem-solving; benefits low-achieving and special needs students	Small-scale sample limits generalization; requires broader experimental validation and teacher training
Alanazi, A.S.; Alqazlan, S.; Rayan, A.; Benlaria, H.	2025	AI implementation for students with learning disabilities	Effective AI use depends on teacher experience, digital literacy, and institutional support; fosters inclusive learning	Need for institutional support, PD, and technological readiness; implementation costs and adaptation difficulties
Anton, J.; Cosentino, G.; Sharma, K.; Gelsomini, M.; Mok, M.; Giannakos, M.; Abrahamson, D.	2025	Comparison of AI agent vs. human teacher feedback in math learning	AI provides individualized feedback and supports multimodal learning analytics	Lacks human-like multimodal sensitivity and adaptive responses; limited learning gains; depends heavily on design quality
Bagabas, H.A.	2025	AI-supported personalized learning for students with learning disabilities	Enhances engagement and identifies individual learning needs; high teacher willingness to adopt	Lack of teacher training; high implementation costs; low prior experience with AI tools

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Authors	Publication year	Typical AI Uses / Examples	Key Benefits (RQ1)	Main Challenges (RQ2)
Batubara, H.H.; Syukur, F.; Junaedi, M.; Purwanti, K.L.; Shanie, A.	2025	Mobile AI tools for elementary education	Promotes personalized, interactive, and accessible learning; readiness develops progressively	Gap between positive attitudes and practical readiness; psychological and technical barriers; need for PD
Bilstrup, K.-E.K.; Connelly, L.; Musaeus, L.H.; Kaspersen, M.Hø.; Petersen, M.G.	2025	Co-designing AI learning activities in math and language subjects (AI literacy)	Encourages skillful teacher–student interaction around AI; integrates AI meaningfully into existing subjects	Unreflected integration may reduce agency; need for subject-specific tools and careful pedagogical design
Bower, M.; Torrington, J.; Lai, J.W.M.; Petocz, P.; Alfano, M.	2024	Generative AI (ChatGPT) in teaching and assessment	Highlights curriculum and assessment changes: learning with AI, higher-order thinking, ethics, and relational learning	Uneven impact across levels/disciplines; "ignorance effect" among less-aware teachers; need to redesign assessment
Bravo, P.; Arias, A.; Carneros-Prado, D.; Dobrescu, C.C.; Bravo, J.	2023	Gesture-recognition AI for body percussion learning via mobile apps	Provides real-time feedback, enhances psychomotor and rhythmic skill development	Dependence on device accuracy and access; limited integration beyond motor skills
Castro, A.; Diaz, B.; Aguilera, C.; Prat Moratonas, M.; Chavez-Herting, D.	2025	AI integration in rural multigrade schools (I-TPACK, AI literacy)	Personalizes learning, reduces teacher workload, supports multigrade classrooms	Digital divide; limited internet; need for offline and context-adapted AI resources; lack of professional development
Chakraburty, S.; Hmelo-Silver, C.E.; Glazewski, K.D.; Leftwich, A.; Kim, J.; Johnson, V.; Svetina Valdivia, D.S.; Mott, B.; Lester, J.	2024	AI learning progression for upper-elementary; pre/post assessments and classroom validation	Clear student gains across LP levels; practical framework to sequence and assess AI concepts in primary grades	Progress varies by classroom/teacher expertise; non-trivial assessment design and validation effort
Chen, S.; Liu, Q.; He, B.	2023	Generative AI teaching-materials system (human-in-the-loop): pre-/in-/post-class plans, resources, and personalized assignments	Improves efficiency and quality of lesson/assignment generation; keeps teacher oversight central	Requires sustained teacher review; quality varies with prompts; governance/accuracy of generated content
Chen, Y.; Zhang, Q.; Wang, Z.; Zhang, J.	2025	GenAI to enhance pre-service teachers' instructional design	Significantly improves plan quality and design capability; reveals useful differences across performance levels	Differences across students; risk of shallow designs without guidance; need for structured scaffolds

Contreras-Arguello, M.L.; Paredes-Valverde, M.A.; Vásquez, A.M.T.; Salas-Zárate, M.	2025	NLP system for automatic summaries and question generation o support reading comprehension	Aids comprehension for elementary pupils; saves teacher time; dashboards support targeted follow-up	Potential low-quality items; reliance on accurate generation; teacher review still required
Dahal, M.; Church, W.; Rogers, C.	2024	ML-based Smart Motors (nearest-neighbor) for low-cost, no-code, offline educational robotics	High engagement and iterative learning across ages; lowers access barriers(cost/complexity/offline)	Classroom integration time; uneven student support needs; scalability/resources beyond workshops
Dai, Y.	2023	AI-focused PD	Strengthens teacher epistemic understanding and agency in shaping AI curricula	Deep, practice-relevant account of building primary AI curricula and teacher roles.
Dai, Y.; Liu, A.; Qin, J.; Guo, Y.; Jong, M.S.-Y.; Chai, C.-S.; Lin, Z.	2023	Collaborative AI curriculum development	Stronger PD and school links; practical routes to local AI curricula	Need for facilitation to mediate external influences
Dos Santos, J.M.D.S.; Pereira Abar, C.A.A.; de Almeida, M.V.; Lavicza, Z.	2023	Computational thinking resources for mathematics in the AI era	Teachers progress through innovation stages; usable resources that open CT learning possibilities	Variation in readiness; requires sustained PD and iteration to embed practices
Fang, H.; Shu, L.; Wang, X.; Hong, X.	2024	Intelligent classroom interaction	Gives teachers actionable classroom analytics to improve lessons.	Data quality/privacy concerns; teacher data-literacy demands; technical complexity
Galindo-Dominguez, H.; Delgado, N.; Campo, L.; Losada, D.	2024	Digital competence and attitudes to AI (primary–HE)	Higher digital competence towards more positive attitudes to using AI in education	Low real experience with AI; need targeted interventions to build competence and practice
Getenet, S.	2024	ChatGPT	Useful for modelling/contrasting strategies; supports PST reflection	ChatGPT errors; PST strategies not always age-appropriate; needs contextualization
Giaouri, S.; Charisi, M.	2025	ChatGPT-assisted IEP	Clearer IEP goals, richer resources, more structured planning	Requires ethical safeguards, teacher oversight, and protection of relational/emotional teaching
Guo, M.; Li, Y.	2025	NLP + knowledge graph + LLM (Qwen) for vocabulary recommendations	Personalized vocabulary support; high user satisfaction among teachers/students	Handling polysemous words, stronger personalization/resources; quality control of outputs
Han, X.	2021	AI curriculum & instruction	Maps readiness/attitudes; teachers willing to adopt AI curricula	Limited time, few trainings, outdated facilities; need AI labs and PD

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Authors	Publication year	Typical AI Uses / Examples	Key Benefits (RQ1)	Main Challenges (RQ2)
Huang, C.; Yu, H.	2024	GenAI for lesson preparation, learning-situation analysis, and classroom interaction	Improves lesson design quality, teacher practical knowledge, and innovation; supports personalized design	Needs careful guidance; risk of over-dependence; requires teacher data-literacy
Huang, S.	2021	AI-based educational robot	Higher attention/initiative; improved achievement vs traditional lessons; supports dialog/role-play	Cost/maintenance, teacher training, integration into curricula
Huang, Y.-C.; Hsiao, C.-F.; Wang, C.-J.	2023	Paragraph-level automated essay scoring (ALBERT + Bi-GRU) with instant feedback for primary writing	Immediate, granular feedback; teachers rate usability highly; supports iterative writing	Scoring consistency/bias, privacy; potential over-reliance on automated feedback
Ivanova, E.; Zlatarov, P.	2024	AI-based personalized learning	Potential for tailored content in and after class; teachers supportive of personalization	Access inequities; need guidance and quality control of recommendations
Jatileni, C.N.; Sanusi, I.T.; Olaleye, S.A.; Ayanwale, M.A.; Agbo, F.J.; Oyelere, P.B.	2024	Perspectives on AI education	Relevance, AI for social good, attitudes, and confidence predict intention to teach AI	AI anxiety/readiness not predictive; requires targeted PD and support structures
Jiang, J.; Li, X.	2023	"Smart classroom" model for primary science using AI/IoT/VR	Practical before/during/after-class model; supports richer inquiry and engagement	Heavy infrastructure needs; limited evaluation depth; teacher training required
Karnalim, O.; Ayub, M.; Kusbiantoro, K.	2024	AI chatbots in K-12	Maps awareness/acceptance; informs school policy and PD needs	Lower awareness among primary pupils; misuse risks without clear rules
Kiziltas, Y	2025	ChatGPT feedback	Higher writing outcomes & self-efficacy with AI feedback	Needs teacher guidance to avoid overreliance; access/equity considerations
Kong, S.-C.; Yang, Y.; Yeung, W.K.	2024	TPACK-based PD for AI/IoT STEM design	Large, significant gains on all TPACK items; strong design outputs incl. AI components.	Short PD dose: long-term transfer not measured
Kong, S.C.; Yang, Y.	2024	Human-centered GenAI framework for self-regulated learning	Guides teachers to use GenAI for attention, engagement, feedback, reflection; clarifies evolving teacher roles	Requires AI literacy/ethics guidance; risk of superficial use without scaffolds
Kopecky, K.; Vorác, D.	2025	GenAI/LLM	Real usage patterns: helps teachers set classroom norms	Often superficial use; uneven access/skills across pupils

Kosmas, P.; Nisiforou, E.A.; Kounnapi, E.; Sophocleous, S.; Theophanous, G.	2025	Co-design of AI-integrated literacy	High student engagement/meaningfulness; teacher empowerment and ownership	Needs broader scaling/evaluation; classroom implementation support
Lamanauskas, V.; Makarskaite-Petkevičiene, R.	2025	Teachers views on AI	High interest in PD; ethics seen as most important; recognition of AI potential	Limited perceived impact on own performance; some low priority for lesson use
Lee, C.-S.; Wang, M.-H.; Tsai, Y.-L.; Chang, W.-S.; Reformat, M.; Acampora, G.; Kubota, N.	2020	Fuzzy RL agent + BCI (human-robot co-learning)	Personalized content; higher motivation; physiological analytics to adapt teaching	System complexity; transfer to regular classes; equipment burden
Lee, D.; Yeo, S.	2022	AI chatbot as a virtual pupil to train responsive teaching	Improves PST questioning skills; authentic, open-ended practice; design features identified	Repeated question patterns without careful design; requires iterative refinement
Lee, S.; Mott, B.; Leftwich, A.; Scribner, A.; Taylor, S.; Park, K.; Rowe, J.; Glazewski, K.; Hmelo-Silver, C.E.; Lester, J.	2021	PRIMARYAI: game-based, AI-infused collaborative inquiry	Engaging problem-based entry to AI concepts; teacher-informed design that fits classroom realities	Classroom integration and teacher support needs; identifying effective scaffolds for AI-infused inquiry
Li, A.; Ye, L.	2023	ChatGPT's impact on elementary teachers' professional development	Raises awareness of uses/risks; provides practical PD recommendations for responsible use	Lacks empirical outcomes; requires policies, ethics, and capacity building to avoid misuse/overreliance
Li, M.; Manzari, E.	2025	AI utilization via TPACK	Shows adoption depends on teacher TPACK/attitudes plus institutional and societal supports; blueprint for systemic integration	Requires dual focus (PD + infrastructure); variability across contexts; translating findings into practice
Li, M.; Nugraha, M.G.	2025	Validation of a context-specific TPACK scale	Reliable instrument to assess teacher competencies and guide PD/curriculum for AI integration	Validation limited to one context; does not measure student learning effects
Li, M.; Zhang, H.	2024	AI (AIGC) in teaching	Identifies drivers (performance/effort expectancy, social influence, enabling conditions) to target interventions	Differences by teacher characteristics; need training, better tools, and supportive environments
Lin, P.; Zhao, F.; Wang, X.; Chen, Y.	2025	AI image-recognition curriculum (CNN)	Structured AI curriculum for primary science/AI literacy; positive pupil reception	Technical complexity; teacher preparation and resource needs; data/ethics considerations

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Table – continued from previous page

Authors	Publication year	Typical AI Uses / Examples	Key Benefits (RQ1)	Main Challenges (RQ2)
Liu, J.; Sun, D.; Sun, J.; Wang, J.; Yu, P.L.H.	2025	ChatGPT-MPS: GenAI-enabled environment for math word problems	Significant gains in problem-solving and interest; supports strategy development and motivation	Risk of overreliance and prompt sensitivity; ensuring alignment with curriculum and assessment
Meegan, J.; Young, K.	2025	Scenario-based GenAI intervention in initial teacher education	Improves pre-service teachers' AI literacy and self-efficacy; feasible model for ITE programs	Long-term impact unknown: need to isolate most effective components and support sustained use
Moral-Sánchez, S.N.; Ruíz-Rey, F.J.R.; Cebrián-de-la-Serna, M.	2023	AI chatbots for mathematics didactics	Higher satisfaction and digital competence; transferable project experience for classroom use	Requires guidance on ethics, quality, and assessment
Ning, Y.M.; Zhang, W.J.; Yao, D.M.; Fang, B.W.; Xu, B.Y.; Wijaya, T.T.	2025	AI Literacy Scale (AILST)	Provides a reliable tool to assess teachers' AI literacy and target PD; clarifies literacy dimensions (perception, skills, application, ethics)	Validation context-bound; measuring literacy doesn't ensure classroom impact; requires implementation guidance
Nong, L.; Liu, G.; Tan, C.	2021	AI-assisted language learning (AIALL) model for primary English	Improves primary pupils' English performance and overall learning ability	Limited detail on AI mechanisms; scalability and teacher training needs
Nordby, S.K.; Bjerke, A.H.; Mifsud, L.	2022	Primary maths teachers integrating computational thinking (CT) as a gateway to AI	Highlights productive CT entry points (pattern recognition, problem solving, programming)	Teachers' limited CT knowledge leads to shallow or de-mathematised use; need discipline-specific CT support
Oh, S.-Y.; Ahn, Y.	2024	Teacher perceptions of AI's role and socio-emotional limits	Identifies opportunities for AI to automate admin and support personalization; maps roles for human–AI complementarity	Socio-emotional deficits of AI; varied teacher expectations; need for adoption decisions aligned to concerns
Ottenbreit-Leftwich, A.; Glazewski, K.; Hmelo-Silver, C.E.; Jantaraweragul, K.; Jeon, M.; Chakraburty, S.; Scribner, A.; Lee, S.; Mott, B.; Lester, J.	2023	PRIMARYAI	Students can conceptualize core AI ideas; engaging problem-based units; teachers feel scaffolded	Need tighter alignment of AI with science content; refine immersive environment; local context connections
Ottenbreit-Leftwich, A., Glazewski, K., Jeon, M., Jantaraweragul, K., Hmelo-Silver, C.E., Scribner, A., Lee, S., Mott, B., Lester, J.	2023	"Lessons learned" from co-designing elementary AI education	Surfaces student conceptions/examples/ethics; supports teacher confidence and curriculum co-design	Connecting to prior knowledge and creating teachable content remains hard; calls for sustained PD

Ovchinnikova, A.; Solovyeva, T.; Soo, V.	2024	Neural networks / AI tools	Raises teacher awareness; practical tips for classroom use	Largely descriptive; lacks measured learning outcomes; need for guidance, risk of misuse, uneven tool quality.
Pan, D.; Li, J.; Long, T.	2025	AI-enhanced school-based STEAM course	AI-enhanced STEAM supports CT processes, structured problem-solving, and reflective summarizing; enables teachers to adapt instruction using patterns.	Need for instructional adaptation and teacher guidance to foster CT; conducted in under-resourced context and potential implementation constraints and generalizability limits; limited detail on ethics/data/privacy.
Philippakos, Z.A.T.; Rocconi, L.	2025	Varied GenAI/chatbots (self-report)	Identifies concrete PD priorities; baseline of elementary vs secondary gaps; informs policy and support	Elementary teachers show lower familiarity/usage; uncertainty around AI grading/troubleshooting; need clear policies
Portela, C., Palomino, P., Challco, G., Sobrinho, Á., Cordeiro, T., Mello, R., Dermeval, D., Bittencourt, I., Isotani, S.	2025	AIED Unplugged: offline	Personalized feedback at scale; equity between rural/urban; reduces teacher workload; broad uptake	Remaining infrastructure limits; need teacher training and processes for offline workflows
Pyzalski, J.	2025	GenAI (general, school-wide)	Maps key risks to address (addiction, cheating, reduced critical thinking, social impacts, inequities); proposes school-level guidelines	High concern levels may hinder adoption; requires comprehensive teacher training and student digital literacy programs
Qiu, Y.; Ishak, I.N.; Zheng, S.	2025	Adaptive tutor (Squirrel AI)	Personalized pacing and practice; potential cognitive gains in primary maths; concrete HITL lesson-plan model	Outcomes sensitive to context (environment, class mode); teacher oversight and prompt quality needed
Rosas, D.A.; Burgos, D.; Padilla-Zea, N.	2022	Wearables + AI models	Real-time analytics can inform instruction and engagement; groundwork for predictive supports	Privacy and data governance; hardware costs; linking physiological signals to learning with validity
Rutatola, E.P.; Stroeken, K.; Belpaeme, T.	2025	LLM-powered social robot (conversational math tutor)	1:1 tutoring support; teachers broadly positive; could reduce workload in large classes	Wrong/inconsistent feedback, code-switching/latency; infrastructure gaps; adoption depends on teacher acceptance
Sacco, F.; Rossini, G.; Manzi, F.; Di Dio, C.; Aquilino, L.; Cangelosi, A.; Raggioli, L.; Massaro, D.; Marchetti, A.	2023	NAO humanoid robot using ChatGPT	Identifies classroom use cases (creativity, empathy, problem solving); co-design surfaces teacher needs	Reliability of ChatGPT responses; cost and classroom logistics; need for clear scenarios and training

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Authors	Publication year	Typical AI Uses / Examples	Key Benefits (RQ1)	Main Challenges (RQ2)
Shi, Y.W.; Rao, L.J.	2022	BPNN-assisted graded teaching system	Data-driven evaluation of STEAM learning; higher answer accuracy vs traditional	Method generalisability; black-box evaluation; requires data literacy and technical setup
Silva, A.; Sousa, A.; Saraiva, E.; Rodigues, P.; Silveira, F.; Barbot, A.	2025	AI/ML activities in sciences (microorganisms)	Supports autonomy; develops scientific/technical competences; helps classroom management	Integration barriers; need for teacher guidance and alignment with national profile
Sinha, N.; Evans, R.F.; Carbo, M.	2023	AI/ML curriculum for elementary	Engaging, culturally responsive entry to AI; ready-to-use lesson plans for teachers	Primary-stage pilots; scaling and assessment of learning outcomes required
Skobo, M.; Sovic, M.	2025	Chatbots/AI agents	Greater familiarity correlates with positive attitudes; points to PD + structural reforms	Concerns (ethics, reliability) dampen adoption; barriers largely institutional, not just skills
Song, J.; Yu, J.; Yan, L.; Zhang, L.; Liu, B.; Zhang, Y.; Lu, Y.	2023	AI curriculum / IST	Systematic curriculum and teacher-training resources; pre-primary implementations show feasibility	Uneven school readiness: ongoing maintenance, localization, and assessment alignment needed
Sperling, K.; Stenliden, L.; Nissen, J.; Heintz, F.	2022	ML-based “AI Engine”	Reveals real classroom compensations and human roles around AI; clarifies limits of automation/personalization	Opaque algorithmic decisions; misalignments with pedagogy; continuous negotiation and teacher mediation required
Sreenath, N.; Ranade, P.; Verma, I.K.	2024	Design-thinking proposal for AI-powered personalized learning (smartboard + student devices)	Potentially supports neurodivergent learners; individualized paths; equity framing	Big lift for infra/UX; feasibility and teacher capacity; risk of over-reliance without pedagogy
Stryftoy, S.; Krouska, A.; Troussas, C.; Mylonas, P.; Sgouropoulou, C.	2024	AI-Learning intervention	Improved teacher confidence, enjoyment, and readiness to help pupils using AI-supported science instruction.	Tiny sample; short intervention; needs follow-up and classroom transfer
Sun, JM; Ma, HL; Zeng, Y; Han, D; Jin, YB	2023	TPACK-based PD program	Significant gains in AI knowledge, teaching skills, and self-efficacy	Resource-intensive PD; scalability and long-term retention not tested
Tan, S.C.; Tan, Y.Y.; Teo, C.L.; Yuan, G.	2025	GenAI chatbot “KB learning companion”	Strengthens professional agency; helps reconcile contradictions; supports community learning	Managing contradictions/affordances; guidance and policy needed; potential dependence on the bot
Taşdelen, O.; Bodemer, D.	2025	ChatGPT-4 tool that context-personalizes math materials/tasks in real time	Higher intrinsic motivation, interest, and performance vs standard tasks	Quality control of generated content; classroom management; safety/guardrails

Uğraş, H.; Uğraş, M.; Papadakis, S.; Kalogiannakis, M.	2024	Teachers' views on ChatGPT	Teachers see ChatGPT enriching lessons; alignment with SDG 4 (access, early years).	Hallucinations risk; need teacher/parent training and policies
Ulrich, L.; Carmassi, G.; Garelli, P.; Lo Presti, G.; Ramondetti, G.; Marullo, G.; Innocente, C.; Vezzetti, E.	2024	ML gesture recognition serious game (SIGNIFY)	Increases access & engagement for deaf/hard-of-hearing learners; feasible with common cameras.	Accuracy varies by hardware; setup constraints; teacher support still needed.
Umirova, S.; Shavkatjon, S.; Zuparov, T.; Yuldashev, A.; Abdullayev, A.; Sobirova, N.	2024	AI-assisted tutoring systems	Targeted support, adaptive feedback, higher engagement potential.	Risk of one-size tools; need safeguards and teacher oversight.
Viruel, S.R.; Rivas, E.S.; Palmero, J.R.	2025	AI-enhanced project-based learning (PBL)	AI-PBL rated far higher than traditional PBL (large effect); supports autonomy and adaptive feedback	Need concrete models, PD, and equity of access; assessment alignment
Vogt, M.; Ferraioli, V.; Abou-Khalil, V.; Hollenstein, L.; Mondada, F.; Vogt, F.	2025	AI-literacy in pre-primary	Clear PD implications; maps barriers in primary grades	Misconceptions about AI scope; lack of pedagogical ideas; hesitancy and perceived high stakes
Walan, S.	2025	Various AI tools (unspecified)	Students see practical support potential; raises awareness for policy	Mixed affect: privacy, job loss, "too fast" fears; need age-appropriate guardrails and dialogue
Wang, X.; Li, L.; Tan, S.C.; Yang, L.; Lei, J.	2023	AI-enhanced education (readiness)	Shows how cognition/ability/vision/ethics predict innovation and satisfaction; clusters guide PD.	Perceived threats reduce innovation; need system strategies and supports.
Wang, Y.; Zhang, C.; Gong, X.; Ye, S.	2024	AI Open Platform teaching model	Effective experiential AI lessons: template teachers can adopt.	Model depends on platform access and teacher know-how; depth of learning and long-term transfer not established
Wang, Y.; Zhao, H.; Qi, Y.; Shen, S.	2025	AIGC resources + IoT monitoring + LLM assistant	Personalization; authentic tasks; showcases AI beyond academics; boosts practicality/engagement; Rich STEAM context; personalization; rural relevance	Resource demands in under-resourced schools; scalability, safety, and data issues
Wu, B.	2025	Blended course design using AI for "Teaching Elementary School Children English" (teacher-ed)	Shows how AI can support method innovation, assessment, and online/offline integration	Needs careful design of assessment; implementation details unresolved

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Authors	Publication year	Typical AI Uses / Examples	Key Benefits (RQ1)	Main Challenges (RQ2)
Xia, W.; Xie, Y.; Ye, Z.; Ou, Y.; Wang, X.; Wu, B.	2025	AI-agent powered family–school–society linkage inquiry model	Improved inquiry competence; richer experiences; supports home-school-community	Implementation complexity; data sharing/consent; sustaining collaboration over time
Xu, S.M.; Lo, C.K.; Ling, M.H.; Chen, G.W.	2025	3D game + GenAI character	Teachers positively accept; potential to enhance vocab/conversation; concrete feature requests	AI responses inconsistent; needs added features (audio, speech)
Xue, T.; He, S.; Guo, W.	2024	CT curriculum framework & teaching cases	Clear pathway to build CT (foundation for later AI) in primary classrooms.	Outcomes not empirically validated; requires teacher capacity, alignment to standards, resources
Yorulmaz, A; Okulu, H.Z.; Muslu-Komurcu, N.; Cokcaliskan, H.	2025	ChatGPT (lesson-planning assistant)	Better plans; more ideas, creativity, real-life links	Risk of over-reliance; need AI-literacy and prompt-craft training; ensure originality/ethics
Yuan, Y.J.	2024	Chatbots	Significant gains in oral proficiency and willingness to communicate; supports adaptive paths	Requires tailored features (error correction, UX); teacher orchestration and privacy concerns
Yue, M.; Jong, M.S.Y.; Ng, D.T.K.	2024	AI education / TPACK	Identifies large-scale gaps in AI-related knowledge; links TPACK to positive AI attitudes; informs targeted PD	Low AI content/tech knowledge across teachers; demographic variance; need for structured training frameworks
Zeng, S.; Rahim, N.; Xu, S.	2025	Mobile AI synchronous-generation drawing (MAI-SGD)	Significantly increases engagement, motivation, and creative self-efficacy; supports personalized art learning	Needs validation across cultures; implementation costs; teacher adaptation for art pedagogy
Zheng, W.; Tse, A.W.	2023	GenAI formative feedback (Class Optimization Master)	Enhances mathematical motivation, confidence, engagement, positive attitudes; enables socio-emotional interaction	Small sample; qualitative only; requires quantitative validation and wider testing
Zhu, C.; Peng, C.; Wu, Y.	2023	Smart classroom (AI-enabled interaction analysis via ITIAS)	Deepens understanding of AI-mediated teacher–student interactions; insights to improve smart teaching	Exploratory; lacks direct learning measures; technology dependence and classroom adaptation challenges
Zhu, S.; Zhang, H.	2025	General AI-supported strategies	Promotes unity-in-diversity, cultural awareness, and inclusive science learning; connects heritage with innovation	Context-specific; limited scalability; requires culturally sensitive AI curriculum and resources