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Unlocking the algorithmic mind: a systematic review of AI's role in cultivating computational thinking in primary education

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Abstract

This systematic literature review (SLR) synthesizes research published between 2020 and 2025 to examine the utilization of Artificial Intelligence (AI) to explore and enhance Computational Thinking (CT) skills in primary school students. The review analysed empirical and systematic review studies focusing on various AI methodologies, including Generative AI (e.g., ChatGPT), Explainable AI (XAI), adaptive learning systems, and interdisciplinary robotics platforms. Findings consistently demonstrate a positive, moderate-to-significant impact of AI-based interventions on core CT components such as problem decomposition and algorithmic thinking, alongside crucial 21st-century skills like Critical Thinking, Communication, Collaboration, and Creativity (4Cs). The most effective approaches are characterized by personalized and project-based learning. However, the review identifies significant implementation challenges, including the imperative need for substantial investment in equitable technological infrastructure, the scarcity of comprehensive teacher training programs focusing on both AI literacy and CT pedagogy, and the complexity of ethical issues surrounding data privacy and algorithmic bias. A critical research gap persists in the lack of long-term longitudinal studies and standardized, validated CT assessment tools for this age group. The conclusion advocates for policy actions to establish clear ethical guidelines, support scalable teacher professional development, and prioritize research into sustained impact and reliable assessment to ensure the responsible and equitable integration of AI for fostering computational thinkers.

Introduction

The global integration of Artificial Intelligence (AI) into primary education has significantly increased since 2020. This trend is largely fueled by the acknowledgment that Computational Thinking (CT) is a critical 21st-century skill, foundational for problem-solving, creativity, and digital literacy. AI offers compelling potential to revolutionize learning by enabling personalization, delivering adaptive feedback, and nurturing advanced cognitive skills, resulting in a proliferation of research and practical tools aimed at young learners. However, this swift adoption of AI brings forth complex challenges regarding its actual effectiveness, ensuring equitable access, addressing ethical implications, and guaranteeing that educators and institutions are adequately prepared to genuinely support meaningful CT skill development in primary students (Al Husaeni et al., 2025; Rizvi et al., 2023).

The integration of Artificial Intelligence (AI) in primary education is rapidly advancing, with a range of methodologies, including generative models (e.g., ChatGPT), intelligent tutoring systems, and robotics, being deployed to foster Computational Thinking (CT) skills. These tools are specifically utilized to support core CT components such as Problem Decomposition and Algorithm Design, facilitated by AI-powered platforms and block-based programming environments (e.g., Scratch, Machine Learning for Kids) (Li et al., 2025; Mung et al., 2025; Saputra et al., 2024; Tian, n.d.).

Furthermore, AI enhances learning through Personalized Feedback and Assessment, where gamified intelligent tutoring systems and learning analytics deliver real-time, individualized feedback, boosting student motivation and learning efficiency (Akintolu & Oyekunle, 2025; Joshi & Ramnath, 2025; Saputra et al., 2024). The advent of Generative AI Tools offers dynamic, personalized support, fostering critical thinking and problem-solving, although concerns about potential over-reliance and originality remain (Al-Karasneh et al., 2025; Matobobo et al., 2025; Wang et al., 2025).

Empirical evidence largely supports these interventions, indicating that AI-based approaches significantly improve CT skills, particularly in algorithmic thinking and creative problem-solving (Arkoumanis et al., 2025; Moreno-León et al., n.d.; Mung et al., 2025; Omeh et al., 2025; Peng et al., 2025; Tian & Zheng, 2025). Meta-analyses consistently report large positive effects on learning outcomes, with adaptive and personalized systems proving exceptionally effective (Arkoumanis et al., 2025; Tian & Zheng, 2025).

Despite the promising outcomes, the effective and equitable integration of AI for CT education faces several critical hurdles and research gaps. A major challenge lies in Teacher Training and Professional Development, as many educators lack sufficient AI literacy and CT pedagogy training. Professional development programs are often fragmented, with insufficient attention paid to ethical AI integration and interdisciplinary collaboration (Kong et al., 2023; Moudgalya & Allen, n.d.; Ortuño Meseguer & Serrano Sánchez, 2024), while teachers' attitudes and access to support are crucial mediators of success (Kazmaci et al., 2025; Kong et al., 2023).

Persistent Ethical and Equity Issues are also a concern, encompassing data privacy, algorithmic bias, and the equitable distribution of AI resources. Disparities in infrastructure, digital literacy, and resource allocation widen the digital divide, limiting the reach and effectiveness of AI-enhanced CT education (Abulibdeh, 2025; Fombona et al., 2025; Katona & Gyonyoru, 2025; van Leeuwen et al., 2024), underscoring the urgent need for ethical frameworks and policy guidelines to ensure responsible and inclusive AI adoption (Alawneh et al., n.d.; Curi et al., 2025; Yan et al., 2025).

Furthermore, research on the Longitudinal Impact and Sustainability of these interventions is sparse, with most studies focusing on short-term gains, leaving a dearth of knowledge on the sustained effect of AI-based tools on long-term CT skills and autonomous problem-solving (Ibrahim et al., 2025; Labrague et al., 2025; Lai & Lee, 2024). A concern also exists that an over-reliance on AI might inadvertently impede the development of independent learning and critical thinking (Tamimi et al., 2024). The Scalability and Contextualization of AI-driven CT programs are further constrained by infrastructural inequities, resource disparities, and contextual differences across varied educational systems (Funa & Gabay, 2025; Katona & Gyonyoru, 2025; Zhao et al., 2025).

Consequently, significant research gaps persist, particularly the need for rigorous, Long-term and Large-scale Studies on the sustainability and transferability of interventions (Ibrahim et al., 2025; Labrague et al., 2025; Lai & Lee, 2024), as well as insufficient research on scalable, equity-focused Teacher Professional Development models (Kong et al., 2023; Ortuño Meseguer & Serrano Sánchez, 2024). Limited empirical evaluation of Ethical Frameworks in real-world settings (Alawneh et al., n.d.; Curi et al., 2025) and a need for studies addressing Equity and Access barriers in under-resourced contexts (Abulibdeh, 2025; Funa & Gabay, 2025) highlight critical areas for future investigation.

This systematic review analyzes journal articles published between 2020 and 2025 to comprehensively examine the intersection of Artificial Intelligence (AI) and the development of Computational Thinking (CT) skills in primary students. The focus is four-fold: scrutinizing the AI methodologies and tools utilized to explore and enhance CT skills; evaluating the reported outcomes and effectiveness of these AI-based educational interventions; identifying associated challenges, ethical considerations, and necessary teacher training issues; and pinpointing critical research gaps and future directions for AI-supported CT education. This structure ensures a thorough synthesis of the current state of research.

Method

Search strategy and data sources

The systematic literature review was grounded in a rigorous search strategy to ensure comprehensive coverage of relevant scholarship concerning the intersection of Artificial Intelligence (AI) and Computational Thinking (CT) in primary education. To achieve this, a multi-database approach was employed, meticulously searching five prominent academic resources: Scopus, Web of Science, ERIC, Google Scholar, and various discipline-specific institutional repositories. This wide net was cast to capture both peer-reviewed research and high-quality gray literature, ensuring that the final corpus of included studies was as exhaustive and representative as possible. The selection of these databases was intentional, focusing on major indexes known for their breadth in educational technology, computer science, and pedagogical research, which are the core domains of this review. The initial scoping searches were iterative, refining the database selection based on preliminary results to maximize relevance and minimize the inclusion of tangentially related studies. This foundation of robust database selection, reliability, and validity of the entire systematic review process.

The search query itself was constructed using a comprehensive and systematic combination of keywords, designed to accurately map the specific research focus. The core terms used included “artificial intelligence” and “computational thinking,” which were then intersected with context-specific terms like “primary education” and “elementary students” to narrow the focus to the appropriate age group. Furthermore, the search incorporated a range of related concepts crucial to the AI-in-education landscape, such as “AI literacy,” which addresses the students' understanding of AI; “adaptive learning,” which covers how AI personalizes instruction; and specialized AI types like “generative AI” and “explainable AI,” which represent emerging research frontiers. The systematic inclusion of terms like “teacher training” and “ethics” ensured that the pedagogical, professional development, and societal implications of deploying AI for CT skills were also considered. This detailed keyword strategy was fundamental in retrieving a highly relevant set of articles for subsequent screening.

To maintain contemporary relevance and reflect the rapid advancements in AI technologies, a strict time frame was enforced for the inclusion of studies. Only research published between 2020 and 2025 was considered for the review. This five-year window was strategically chosen to capture the most recent and cutting-edge literature, as the field of AI in education, particularly for younger students, has seen significant and transformative growth in this period. The exclusion of older studies helps to ensure that the findings and conclusions of the systematic review are based on current pedagogical and technological practices, avoiding reliance on research that may be outdated due to the swift evolution of AI tools and educational standards. This temporal constraint adds a layer of focus and currency to the resulting body of evidence.

The article selection process followed a stringent, multi-stage screening protocol to ensure both relevance and methodological rigor, reducing the risk of bias in the final study set. The initial stage involved a title review, where articles were quickly assessed for their basic relevance to the topic of AI and CT in primary education. This was followed by a more detailed abstract evaluation, where the abstract's content was scrutinized to confirm that the study directly addressed the research questions and met the preliminary inclusion criteria. The final and most critical stage was the full-text assessment, where the complete article was retrieved and thoroughly analyzed for methodological soundness, data quality, and definitive relevance to the review's objectives. Only articles that successfully navigated all three stages were included in the final synthesis. This staged screening process, supported by established systematic review methodologies (Abulibdeh, 2025; Rizvi et al., 2023), ensured that the final evidence base was of the highest quality and directly applicable to the review's scope.

Inclusion and Exclusion Criteria

The inclusion criteria for this systematic literature review focused on identifying peer-reviewed journal articles essential to the research scope. Specifically, the included studies had to concentrate on primary or elementary students, ensuring the relevance of the findings to the target age group. A core requirement was that the interventions described must specifically utilize Artificial Intelligence (AI) and target the development of Computational Thinking (CT) skills. Furthermore, only empirical research (such as experiments, quasi-experiments, or correlational studies) or systematic review studies were considered, guaranteeing a high level of evidence. All selected publications were also required to be in the English language to ensure accessibility for a thorough content analysis.

Conversely, a set of stringent exclusion criteria was applied to filter out irrelevant or less rigorous publications. Studies solely focusing on secondary or tertiary education were excluded, as their findings might not be generalizable to primary students. Interventions that did not explicitly utilize AI, even if they addressed CT skills, were also excluded to maintain the focus on the role of AI. Non-empirical reports, such as conceptual papers, opinion pieces, or theoretical discussions, were systematically excluded due to their lack of original data. Finally, conference abstracts were excluded unless accompanied by a full, peer-reviewed paper to ensure the quality and completeness of the research data (Paraskevopoulou-Kollia et al., 2025; Rizvi et al., 2023).

Data extraction and synthesis

The systematic literature review will include a detailed Extraction phase, focusing on gathering specific data points from each selected study. This includes identifying the AI methodologies or tools utilized in the interventions, the design of the intervention itself, and the characteristics of the student samples (e.g., age, grade level). Crucially, we will extract information on the specific Computational Thinking (CT) outcomes measured by the researchers and the assessment methods they employed to gauge these outcomes. Furthermore, the extraction process will capture any challenges reported during the study and any ethical considerations the researchers addressed. This comprehensive data extraction ensures that all relevant aspects of how AI is being used to foster CT skills in primary students are systematically recorded for subsequent analysis.

Following the data extraction, the Synthesis phase will employ a combination of thematic analysis and meta-synthesis across the body of selected literature. The findings will be structured and organized around a set of core themes to provide a coherent and insightful overview of the field. These key themes include an examination of the various AI methodologies implemented, the observed impacts on specific CT outcomes, the persistent barriers or challenges encountered during the implementation of AI-supported CT education, and the identification of promising directions for future research (Abulibdeh, 2025; Rizvi et al., 2023). This systematic synthesis approach will allow for the identification of patterns, contradictions, and gaps in the current research landscape, ultimately contributing valuable insights for educators and researchers.

Findings

AI methodologies and tools in primary education

AI tools are increasingly integrated into educational settings to enhance Computational Thinking (CT) skills in students, particularly through innovative approaches that leverage natural language processing and code generation. Generative AI tools such as ChatGPT, GitHub Copilot, Claude 3, and DeepSeek offer significant support for programming and problem-solving activities. These platforms provide personalized feedback and can generate content, effectively supporting foundational CT elements like problem decomposition and algorithmic thinking. Furthermore, their application extends to fostering metacognitive skills, as students must reflect on and refine the AI-generated outputs, prompting deeper understanding and critical evaluation of the code or content. The efficacy of Generative AI in these roles is well-documented, positioning them as powerful aids in developing sophisticated computational and reflective capabilities in learners (Jauhiainen & Guerra, 2023; Matobobo et al., 2025; Mung et al., 2025).

Another critical area of AI application in CT education involves Explainable AI (XAI) and systems designed for adaptive and personalized learning. XAI frameworks, like MetaCoXAI, are crucial for enhancing the transparency of AI processes. By providing real-time visualization and explicit explanations, XAI helps students understand how an AI reached a particular conclusion or solution, which directly supports metacognitive reflection. This transparency reduces cognitive load and, crucially, builds trust in the technology, making the learning process more accessible and meaningful (Golrang & Sharma, 2025; Xiao et al., 2025; Zhong et al., 2025). Concurrently, adaptive/personalized systems, including AI-powered tutoring robots, intelligent learning platforms, and sophisticated feedback mechanisms, have demonstrated superior educational outcomes compared to traditional teaching methods. These systems dynamically adjust to individual student needs and pace, leading to marked improvements in student engagement and overall learning efficiency (Solihat et al., 2024; Tian & Zheng, 2025). The synergy between transparent explanation and tailored instruction creates a highly effective environment for mastering CT concepts.

The integration of CT goes beyond pure programming, finding fertile ground in interdisciplinary STEM tools and curricula. Robotics platforms, such as AMIGO and HuskyLens, along with visual programming environments like MakeCode, serve as tangible interfaces where students can apply abstract CT concepts to real-world physical systems. Furthermore, tools like Machine Learning for Kids democratize complex AI principles, allowing primary students to train and deploy their own machine learning models. This hands-on approach reinforces skills like pattern recognition, data representation, and abstraction. Crucially, several nations, including Estonia and Uruguay, have begun implementing national AI curricula that purposefully weave CT into core STEM subjects. This systemic integration promotes not only technical proficiency but also essential collaborative and ethical reasoning skills, preparing students for a technologically driven future (Jauhiainen & Garagorry Guerra, 2024; Lu et al., n.d.).

Project-Based Learning (PBL) provides a highly effective pedagogical framework for integrating AI and CT, moving the learning experience from theoretical knowledge to practical application. AI-driven projects, such as the creative and socially relevant “AI Recycling Bin,” require students to apply a range of CT skills—from decomposing the recycling process to designing and implementing an AI-powered solution. This approach naturally encourages a blended learning environment where computational problem-solving is mixed with creative design and ethical considerations. The nature of these projects inherently enhances creativity as students prototype novel solutions and refine their understanding through iterative design. Evidence shows that these AI-infused PBL environments are particularly successful in boosting students’ CT proficiency and fostering a strong sense of ethical awareness regarding the societal impact of AI (Ahmad et al., 2025; Mung et al., 2025).

The landscape of AI in primary CT education is rich and multifaceted, employing a diverse set of tools and methodologies. From the personalized support offered by Generative AI in coding and reflection, to the trust-building transparency of XAI, and the efficiency of adaptive systems, AI is transforming how CT is taught and learned. When combined with interdisciplinary STEM tools that make CT tangible and the holistic, real-world application of Project-Based Learning, students are provided with a comprehensive and engaging educational experience. This strategic deployment of AI tools does not just teach technical skills; it cultivates critical thinking, metacognition, ethical understanding, and creativity, ensuring that primary students develop the foundational competencies required to navigate and shape the future digital world.

Outcomes and effectiveness of AI-based interventions

The integration of Artificial Intelligence (AI) in education, particularly for primary school students, has demonstrated a significant and positive impact on various facets of learning. One of the most notable outcomes is the moderate but consistent improvement in Computational Thinking (CT) skills. This enhancement is not limited to a single aspect but encompasses a range of core competencies, including problem decomposition—the ability to break down complex problems into smaller, manageable parts—and algorithmic thinking, which involves developing step-by-step procedures to solve a problem. Furthermore, AI-supported learning environments have been shown to foster the development of the 4C skills: critical thinking, which is essential for analyzing and evaluating information; communication, for articulating ideas and solutions; collaboration, for working effectively in teams; and creativity, for generating novel solutions (Lee & Kwon, 2024; Tian & Zheng, 2025). These foundational CT and 4C skills are increasingly recognized as crucial for success in the 21st century, making AI a valuable tool for early-stage skill development. The observed gains suggest that AI offers a compelling pathway to cultivate the necessary cognitive tools that primary students will rely on throughout their academic and professional lives.

A key advantage that AI brings to the educational landscape is a demonstrable improvement in learning efficiency. AI-assisted programming tools, for example, have been shown to contribute to a notable reduction in the time students require to complete specific tasks. This efficiency gain is often accompanied by a simultaneous increase in performance scores, indicating that students are not merely completing work faster but are also achieving a higher level of mastery. Beyond just speed and accuracy, the introduction of AI tools tends to enhance student engagement. The interactive and often gamified nature of AI-driven educational applications can make the learning process more appealing and motivating for young students (Alanazi et al., 2025; Senanayake et al., n.d.). This heightened engagement is critical, especially in primary education, as it can foster a positive attitude towards learning and complex subjects like programming and computational thinking, laying the groundwork for sustained interest and achievement in STEM fields.

Perhaps one of the most powerful capabilities of educational AI is its capacity for deep personalization. Adaptive AI systems are specifically designed to tailor both the content presented to the student and the feedback provided in real-time. This dynamic adjustment is based on the student's current performance, learning pace, and individual needs. Such personalized learning pathways lead to a cascade of positive effects, including higher motivation, as the material is neither too easy nor too frustratingly difficult. Crucially, studies indicate that this personalized approach results in enhanced student engagement and, most importantly, significantly higher knowledge retention when compared to more traditional, one-size-fits-all teaching methods (Chakkaravarthy et al., n.d.; Kumaresan et al., 2025). By continuously adapting to the individual learner, AI transforms the educational experience from a passive reception of information into an active, bespoke journey that maximizes each child's potential.

The scope of AI's educational benefit extends beyond purely cognitive gains to encompass important ethical and metacognitive outcomes. The development and implementation of AI curricula are increasingly incorporating elements designed to promote ethical AI literacy. This involves teaching students about the responsible use of technology, understanding issues like data privacy, and recognizing potential biases in algorithms. Furthermore, the use of Explainable AI (XAI) frameworks in educational settings helps to demystify the technology, encouraging students to understand why an AI system makes a certain suggestion or decision. This process inherently promotes metacognitive awareness—the ability to reflect on one's own thinking and learning processes. By engaging with these concepts, primary students are being prepared not just as users of technology, but as informed, ethical, and responsible digital citizens (Choi & Bae, 2025; Curi et al., 2025).

The evidence for AI's effectiveness is particularly compelling when considering its impact on students with special needs. AI interventions have demonstrated exceptionally large effect sizes in this demographic, indicating a profound positive influence on learning outcomes. This is particularly true in foundational areas of literacy and numeracy. For instance, AI-driven tools have proven highly effective in improving arithmetic fluency, allowing students with learning disabilities to practice and master basic math facts at their own pace with targeted, immediate feedback. Similarly, AI applications have shown significant success in boosting reading comprehension, often by providing adaptive text and scaffolded support that caters precisely to the unique challenges faced by these learners (Paglialunga & Melogno, 2025). These results underscore the potential of AI as a powerful inclusive technology, capable of breaking down learning barriers and providing equitable access to education for all students.

The research firmly establishes AI as a multifaceted and highly effective tool in primary education. It fosters critical CT and 4C skills, dramatically increases learning efficiency and student engagement, and provides deeply personalized learning experiences that boost knowledge retention. Moreover, it instills crucial ethical and metacognitive awareness necessary for the digital age and offers specialized, high-impact support for students with special educational needs. The body of evidence suggests that AI is not a fleeting educational trend but a transformative technology that is fundamentally reshaping how primary students learn, offering a pathway toward a more efficient, equitable, and effective educational future.

Challenges and limitations in implementation

The integration of Artificial Intelligence (AI) to foster Computational Thinking (CT) skills in primary education is fraught with several significant challenges, many of which can be grouped into distinct yet interconnected areas. One of the most foundational obstacles lies in the Technological Infrastructure. For AI to be successfully deployed, schools require reliable, high-speed internet access, up-to-date hardware, and robust technical support. Unfortunately, many educational settings, particularly those in resource-constrained regions, face limited access to the necessary technology. Furthermore, the high initial and maintenance costs associated with AI systems and specialized educational software often make widespread adoption financially prohibitive. System reliability and the lack of consistent technical support also present practical barriers, causing disruptions that hinder effective, sustained use of AI-powered CT tools in the classroom. Addressing these infrastructural and financial disparities is a crucial first step toward equitable AI integration (Huang et al., 2025; Wilson et al., 2024).

A second, equally critical area of concern revolves around Teacher Training. The successful integration of AI into the curriculum depends heavily on educators who are knowledgeable, confident, and enthusiastic about the technology. Currently, there is an acute lack of sufficient professional development programs specifically designed to equip primary school teachers with the necessary AI literacy and pedagogical strategies for integrating AI with CT instruction. Many teachers feel unprepared to use these new tools effectively or to troubleshoot technical issues. Moreover, pre-existing negative attitudes, fear of technology displacement, or a lack of understanding regarding the potential benefits of AI can impede effective adoption. Without targeted, ongoing training that addresses both the technical and pedagogical aspects, and fosters positive teacher buy-in, the potential of AI to enhance CT skills will remain largely untapped (Galindo-Domínguez et al., 2024; Lucas et al., 2025; Wilson et al., 2024).

The rapid deployment of AI in education has amplified a host of Ethical Concerns that need comprehensive frameworks for mitigation. Data privacy is a paramount issue, as AI tools collect vast amounts of sensitive student data, raising questions about storage, security, and consent. Equally important are issues related to algorithmic bias, where embedded biases in AI models can lead to unfair or inequitable learning experiences and assessment outcomes, particularly for students from marginalized backgrounds. The 'black box' nature of some AI systems also raises issues of transparency and fairness. Teachers and students should be able to understand how an AI tool reaches a certain conclusion or provides a specific recommendation. Currently, few comprehensive ethical frameworks are in place within educational contexts to adequately address these complex issues, leaving schools and developers to navigate a challenging and often unregulated landscape (Huang et al., 2025; Matos et al., 2025; Solihat et al., 2024).

A more subtle, pedagogical risk is the potential for Overreliance on AI. While AI tools can provide personalized instruction and automate certain tasks, there is a genuine risk that excessive dependence on these systems could diminish the development of crucial cognitive skills, including critical thinking, problem-solving, and independent reasoning—the very skills CT aims to cultivate. Students might rely on the AI to provide immediate answers or solutions, rather than engaging in the productive struggle essential for deep learning. Furthermore, the availability of advanced AI tools, such as generative AI, presents significant challenges to academic integrity, raising concerns about how to authenticate student work and ensure that the learning process remains focused on genuine intellectual effort and not simply on manipulating AI output. Managing this balance between leveraging AI's benefits and mitigating the risk of reduced learner autonomy and intellectual rigor is vital for maintaining the integrity of the educational process (Anders & Dux Speltz, 2025; Salih et al., 2025; Tian & Zhang, 2025).

A key challenge to evaluating the true impact of AI on CT skills lies in the pervasive Assessment Gaps. Computational thinking, as a skill set, is notoriously difficult to measure accurately and consistently, especially in younger students. There is a demonstrable lack of standardized, validated CT assessment tools that are specifically tailored for the primary school level and suitable for use in conjunction with AI-based learning environments. Without reliable and consistent instruments, it is challenging for researchers, educators, and policymakers to gather robust evidence on whether and how AI interventions truly improve students' CT abilities over time. Compounding this issue is the prevalence of short study durations in much of the current research, which limits the evidence base on the long-term impact and sustainability of AI-enhanced CT instruction. Addressing this gap requires a concerted effort to develop and validate appropriate assessment methodologies (Abulibdeh, 2025; Hamed et al., 2025; Paraskevopoulou-Kollia et al., 2025).

The journey toward utilizing AI as a transformative tool for primary students' CT skill development is complicated by a multifaceted array of obstacles. These challenges span technological readiness, teacher preparedness, complex ethical and privacy considerations, potential pedagogical pitfalls, and significant gaps in assessment and research methodology. Successfully navigating these limitations demands a holistic, collaborative approach involving policymakers, educators, researchers, and technology developers. Only through strategic investment in infrastructure, comprehensive teacher development, the establishment of clear ethical guidelines, a balanced pedagogical approach, and the creation of rigorous assessment tools can the full, equitable potential of AI in fostering the next generation's computational thinkers be realized.

Discussion

AI-driven personalized and adaptive learning systems demonstrate consistent superiority over traditional educational approaches in developing essential skills such as Computational Thinking (CT) and the 4C skills (critical thinking, communication, collaboration, and creativity) among primary school students. These sophisticated systems tailor the learning experience to each student's pace and style, ensuring a more effective and engaging educational journey. By offering immediate feedback and dynamically adjusting the difficulty of tasks, AI not only solidifies foundational knowledge but also cultivates the complex cognitive processes inherent in CT and the 4Cs. This personalized approach addresses the diverse learning needs within a primary classroom, maximizing individual student potential in a manner that traditional, one-size-fits-all methodologies often cannot achieve. The integration of AI thus marks a significant advancement in educational technology for this age group, directly contributing to the cultivation of future-ready skills (Choi & Bae, 2025; Matobobo et al., 2025).

Furthermore, the strategic application of contemporary AI tools, specifically Generative AI models like ChatGPT and Copilot, alongside Explainable AI (XAI) frameworks, plays a crucial role in supporting the development of higher-order thinking skills. These technologies actively enhance metacognitive abilities, allowing students to better understand and regulate their own learning processes. They provide robust support for complex problem-solving scenarios by offering sophisticated scaffolding and encouraging systematic inquiry. Moreover, these tools are instrumental in fostering ethical reasoning, particularly when embedded within curricula that emphasize project-based learning and interdisciplinary connections. Such integration ensures that students are not merely consuming information but are actively engaging in the application of knowledge, collaborating on complex tasks, and grappling with the societal and ethical implications of technology, thereby rounding out their skill development in a holistic and meaningful way (Ahmad et al., 2025).

Despite the clear and compelling benefits of integrating these advanced AI technologies into primary education, their widespread and effective adoption is met with significant practical and systemic hurdles. Primary among these challenges is the necessity for comprehensive teacher readiness. Educators require substantial training and ongoing professional development to effectively integrate, manage, and leverage AI tools within their pedagogical frameworks. Furthermore, reliable and equitable technological infrastructure is a prerequisite; disparities in access to high-speed internet and necessary hardware can exacerbate existing educational inequalities. Finally, the implementation must navigate complex ethical considerations, particularly concerning data privacy, algorithmic bias, and ensuring responsible use by young learners. Overcoming these interconnected challenges is essential to fully realize the transformative potential of AI in enhancing the CT and 4C skills of primary students, ensuring that the benefits are accessible to all and implemented in a manner that is both responsible and sustainable (Kurniawan et al., 2025).

Metacognitive and ethical considerations

AI tools and curricula are increasingly integrating features designed to enhance student self-awareness and responsible use of technology. This includes incorporating metacognitive prompts that encourage critical reflection on the learning process, explainability features that demystify how AI arrives at its outputs, and ethical literacy frameworks that promote understanding of the societal implications of AI. These components are vital for fostering self-regulation, enabling students to become more effective learners, and preparing them to be responsible digital citizens. However, the successful implementation of these advanced features requires careful consideration of pedagogical strategies that are age-appropriate for primary students. Furthermore, robust and specialized teacher training is essential to equip educators with the necessary skills to effectively integrate these complex concepts into their daily teaching practices (Choi & Bae, 2025; Curi et al., 2025; Ma et al., 2025a, 2025b).

Various global and interdisciplinary frameworks offer models for a holistic approach to AI education. For instance, initiatives in Uruguay and Estonia, alongside models like ED-AI Lit and ABCE, provide exemplary structures for integrating AI literacy, computational thinking, and ethical considerations into the curriculum. These models demonstrate a commitment to comprehensive AI education that goes beyond mere tool usage. Nevertheless, despite the promise and innovative design of these frameworks, there remains a critical need for more extensive empirical research to rigorously evaluate their long-term effectiveness in improving primary students' computational thinking skills and their scalability across diverse educational contexts. Future studies must focus on providing evidence-based insights to guide the widespread and successful adoption of these comprehensive AI education frameworks.

Barriers, enablers, and equity issues

The successful integration of AI for fostering primary students' computational thinking (CT) skills is critically shaped by a distinct set of barriers that impede progress. Chief among these are negative or hesitant teacher attitudes toward adopting new technologies, often stemming from a lack of confidence or perceived complexity. Insufficient and inadequate teacher training is another significant hurdle, leaving educators unprepared to effectively utilize AI tools or integrate CT concepts into their existing curricula. Furthermore, infrastructural limitations, such as unreliable internet access, insufficient hardware, or a lack of technical support within schools, can make the practical implementation of AI technologies impossible. Cultural or institutional resistance to change, where traditional teaching methods are deeply entrenched, presents a psychological barrier. Finally, a growing concern surrounds ethical considerations, including data privacy, algorithmic bias, and the appropriate age for exposure to advanced AI tools, which must be addressed proactively to ensure responsible deployment. Overcoming these multifaceted barriers requires a strategic, holistic approach that addresses pedagogical, technical, and ethical dimensions simultaneously to clear the path for AI's beneficial role in primary education.

Conversely, a clear set of enablers can significantly accelerate the adoption and successful application of AI for CT skill development in primary schools. High-quality, targeted professional development programs are paramount, focusing not just on technical proficiency but also on pedagogical strategies for integrating AI and CT into the primary curriculum. These programs should be continuous, collaborative, and tailored to the specific needs and contexts of primary school teachers. Developing integrated and interdisciplinary curricula is another key enabler, embedding CT and AI concepts naturally across subjects like mathematics, science, and language arts, making learning more relevant and holistic. Robust policy support from educational authorities is essential, providing clear guidelines, necessary funding for infrastructure upgrades, and incentives for schools and educators who embrace innovation. Finally, fostering collaborative professional networks among teachers, researchers, and technology providers creates a vital ecosystem for sharing best practices, troubleshooting challenges, and collectively advancing the field. By capitalizing on these enablers, educational systems can create a supportive and dynamic environment that maximizes the potential of AI to enhance primary students' CT skills.

A critical dimension that underpins both the barriers and enablers is the issue of equity in AI integration. Current trends indicate that disparities in access to necessary AI technologies, such as reliable devices and high-speed internet, and access to quality training disproportionately affect schools in low-resource communities or those serving socio-economically disadvantaged populations. These disparities do not merely reflect existing educational inequalities but actively worsen them, creating a significant "digital divide" where some students are prepared for a future driven by AI and others are left behind. The promise of AI to personalize learning and democratize access to high-quality education risks being undermined if equity is not made a foundational principle of its deployment. Simply introducing AI tools is not enough; the context of implementation must be fair.

Therefore, targeted strategies are absolutely essential to ensure the equitable and inclusive integration of AI in primary education for CT development. These strategies must involve deliberate policies to bridge the resource gap, such as subsidized technology access and focused infrastructural investment in underserved areas. Furthermore, professional development must be universally accessible and culturally responsive. Crucially, ethical frameworks must be established to continuously audit AI tools for inherent bias that could disadvantage certain student groups, as AI is only as impartial as the data it is trained on (Adabor et al., 2025; Clorion et al., 2025; Gómez-Rodríguez et al., 2024; Joshi & Ramnath, 2025). An intentional commitment to equity ensures that AI integration serves as a powerful catalyst for closing achievement gaps and providing every primary student with the opportunity to develop essential computational thinking skills for the 21st century.

Research gaps and future directions

The current body of research on AI for enhancing Computational Thinking (CT) skills in primary students presents several critical avenues for future investigation and development. One significant gap lies in the scarcity of Longitudinal Studies that track the enduring impact and sustained retention of CT skills acquired through AI-driven interventions. Most existing studies are short-term, offering limited insights into whether the observed gains are transient or indicative of deep, lasting learning. Future research must, therefore, embrace rigorous longitudinal designs, preferably employing a mixed-methods approach, to provide a comprehensive understanding of the long-term efficacy and impact of AI in this educational context (Abulibdeh, 2025; Matobobo et al., 2025; Paraskevopoulou-Kollia et al., 2025; Zhang et al., n.d.). Such studies are essential to inform the development of sustainable, effective curricula and ensure that resources are invested in interventions that yield genuine, long-term educational benefits for young learners.

A second, equally pressing challenge is the urgent need for robust and standardized Assessment Tools specifically designed to measure CT skills in primary school children. The field currently suffers from a lack of universally accepted, validated instruments, making it difficult to compare findings across different studies and accurately gauge student progress. While tools like TechCheck, CTt-LP, and the Critters Puzzle represent promising steps, their broader validation and standardization are critically required (Geng et al., 2025; Relkin et al., 2020; Zhang et al., n.d.). The development and rigorous psychometric testing of new assessment instruments are paramount to ensure that educators and researchers can reliably identify CT proficiencies, diagnose specific learning challenges, and accurately measure the effectiveness of various AI-based teaching strategies. Without reliable, standardized assessments, the progress of this research area will remain fragmented and its practical application limited.

Furthermore, the successful and sustainable integration of AI into the primary school classroom hinges on effective and scalable Teacher Training initiatives. Teachers are the linchpin of educational reform, yet many lack the necessary competencies to effectively integrate AI tools and teach CT concepts. Therefore, the development of scalable, competency-based professional development programs is an absolute necessity (Gómez-Rodríguez et al., 2024; Kong et al., 2023). These programs must not only equip teachers with the pedagogical skills to use AI for CT instruction but also integrate essential modules on AI ethics and responsible technology use. A well-trained teaching workforce is crucial for overcoming resistance to change, ensuring high-fidelity implementation of AI-enhanced curricula, and ultimately, translating research findings into meaningful educational outcomes for students.

In parallel with teacher preparedness, the development of robust frameworks for Ethical AI Literacy among primary students is increasingly critical. As AI tools become more ubiquitous, even young students must be equipped with the knowledge to understand the implications of these technologies. Current curricula often fall short in addressing complex issues such as data privacy, algorithmic bias, and the responsible and ethical use of AI. There is an imperative need to develop and rigorously evaluate more comprehensive frameworks and curricula that embed these ethical considerations directly into CT education (Ma et al., 2025a, 2025b). This proactive approach will foster a generation of digitally literate citizens who can not only use AI tools but also critically evaluate their societal impact, ensuring they become responsible creators and consumers of technology.

The future direction of AI-enhanced CT education for primary students must focus on addressing these systemic challenges through a concerted and coordinated effort. This includes a commitment to long-term Longitudinal Studies to understand lasting impacts, the creation and validation of Assessment Tools for reliable measurement, the implementation of scalable Teacher Training programs for sustainable integration, and the proactive development of Ethical AI Literacy frameworks. By prioritizing these areas, researchers and educators can move beyond fragmented pilot studies to establish a robust, ethical, and effective pedagogical foundation for integrating AI to cultivate the critical thinking skills essential for the 21st century.

Conclusions

Artificial Intelligence (AI) methodologies, encompassing generative and explainable AI, adaptive learning systems, and interdisciplinary STEM tools, have demonstrated a positive impact on enhancing computational thinking (CT) skills in primary school students. Key findings indicate moderate but significant improvements in specific CT components, notably problem decomposition, algorithmic thinking, and the "4C" skills: Critical Thinking, Communication, Collaboration, and Creativity. The most effective interventions leverage personalized and project-based AI learning strategies, suggesting that active, student-centered approaches maximize the benefits of AI integration. However, the successful implementation of these technologies is hampered by persistent challenges, including the need for substantial investments in infrastructure, comprehensive and ongoing teacher training, the establishment of clear ethical guidelines for AI use, and the development of robust, validated assessment tools to accurately measure CT skill development.

To effectively translate these research insights into practice, several key recommendations for educators and policymakers are necessary. Educators should integrate AI tools using project-based and adaptive learning frameworks, specifically focusing on fostering ethical reasoning and metacognitive skills alongside core CT competencies. Crucially, they must commit to continuous professional development to stay abreast of rapidly evolving AI technologies and pedagogical best practices [6] [49]

[50]. Concurrently, curriculum designers must develop interdisciplinary and age-appropriate AI curricula that seamlessly embed CT, ethical considerations, and metacognitive prompts. This requires moving beyond traditional content delivery to a more holistic approach and utilizing validated assessment tools to ensure learning outcomes are accurately measured. Policymakers have a fundamental role in creating an environment conducive to successful AI integration by investing in the necessary technological infrastructure, supporting comprehensive teacher training initiatives, and establishing clear guidelines to ensure ethical AI use and equitable access for all students.

Future research should focus on several critical areas to build upon the existing evidence base. The field urgently requires large-scale, long-term longitudinal studies to investigate the sustained effects of AI integration on students' Computational Thinking (CT) and 4C skills, moving beyond short-term intervention results. Another paramount area is assessment development, where researchers must create and rigorously validate standardized and culturally sensitive CT assessment tools specifically tailored for the primary education level, ensuring they accurately capture the nuances of young children's cognitive development. Addressing the implementation gap, a significant focus must be placed on teacher training; this involves designing, implementing, and evaluating scalable, competency-based professional development programs to equip primary school teachers with the practical knowledge and pedagogical skills required to effectively integrate both AI and CT instruction into their classrooms.

Finally, a dedicated effort must be made in establishing robust ethical frameworks for AI education at the primary level. This involves developing and empirically testing ethical AI literacy curricula for young students. Such curricula should focus on integrating essential, age-appropriate concepts like data privacy, understanding algorithmic bias, and promoting responsible AI use. By proactively addressing these ethical dimensions, the educational system can prepare students to be informed, critical, and responsible digital citizens in an increasingly AI-driven world, ensuring that the integration of AI tools is both powerful and principled.

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