www.ijarp.com ISSN 2456-9992 Page: 01-11

International Journal Advanced Research Publications

Review Article

Volume: 02
Issue: 09

COMPUTATIONAL THINKING AND ARTIFICIAL INTELLIGENCE LITERACY AS ESSENTIAL COMPETENCIES FOR 21ST CENTURY EDUCATION

Zainur Rasyid Ridlo[1]*, Joko Waluyo[2], Dwi Wahyuni[2], Silvi Putri Ayu Ningsih[1], Nilna Ulfia[1], Eky Setiowati[1], Iftitah Dian Furaida[1], Nadya Arini Atmaja[1]

[1]*Department of Science Education, Faculty of Teacher Training and Education, Universitas Jember, East Java, Indonesia.*

[2]*Department of Biology Education, Faculty of Teacher Training and Education, Universitas Jember, East Java, Indonesia.*

Article Received: 16 August 2026, Article Revised: 08 September 2026, Published on: 28 September 2026

***Corresponding Author: Zainur Rasyid Ridlo**

Department of Science Education, Faculty of Teacher Training and Education, Universitas Jember, East Java, Indonesia.

Doi: https://doi-doi.org/101555/ijarp.3527

ABSTRACT

The rapid advancement of artificial intelligence (AI), automation, and data-driven technologies has fundamentally transformed the competencies required for success in the twenty-first century. Beyond traditional digital literacy, learners are increasingly expected to develop computational thinking (CT) and artificial intelligence (AI) literacy to understand, evaluate, and responsibly utilize intelligent technologies in various aspects of life. This conceptual paper examines the significance of CT and AI literacy as essential competencies for 21st-century education through a comprehensive review of contemporary literature, international educational frameworks, and recent developments in AI-enhanced learning. The analysis highlights that computational thinking equips learners with fundamental problem-solving abilities, including decomposition, pattern recognition, abstraction, algorithmic thinking, and evaluation, while AI literacy enables them to understand AI concepts, interpret AI-generated outputs, recognize ethical implications, and make informed decisions in AI-supported environments. The integration of these competencies promotes critical thinking, creativity, collaboration, and responsible digital citizenship, which are increasingly emphasized in international educational agendas such as UNESCO's AI Competency Framework for Students, the OECD Learning Compass 2030, and the

Sustainable Development Goals (SDG 4). This paper argues that CT and AI literacy should be positioned as foundational competencies across educational levels rather than isolated technical subjects. Embedding these competencies into interdisciplinary learning environments can better prepare future generations to adapt, innovate, and contribute meaningfully to an AI-driven society and the evolving global workforce.

KEYWORDS: *Computational Thinking; Artificial Intelligence Literacy; 21st Century Education; Digital Competencies; Future Skills.*

I. INTRODUCTION

The twenty-first century has been marked by an unprecedented convergence of artificial intelligence (AI), automation, and data-driven technologies that are reshaping labor markets, everyday life, and the nature of knowledge itself. Intelligent systems now mediate decisions in domains ranging from healthcare and finance to transportation and education, generating an urgent need for learners who can not only use digital tools but also understand, question, and responsibly apply them [1], [2]. Traditional notions of digital literacy, centered on operating hardware and software, are no longer sufficient to prepare students for a world in which algorithms increasingly shape information, opportunity, and decision-making.

Within this landscape, two interrelated competencies have emerged as central to contemporary education: computational thinking (CT) and artificial intelligence (AI) literacy. CT, first popularized by Wing [1], refers to a set of problem-solving processes—decomposition, pattern recognition, abstraction, and algorithm design—that allow individuals to formulate and solve problems in ways that can be carried out by a human or a machine. AI literacy, meanwhile, is a more recent construct that extends CT into the specific domain of understanding how AI systems work, what they can and cannot do, and how they should be ethically deployed [4]. Although conceptually distinct, CT and AI literacy are increasingly treated as complementary and mutually reinforcing competencies rather than separate technical skill sets [6].

Despite growing international consensus on the importance of these competencies, their integration into mainstream curricula remains uneven, fragmented, and often confined to specialized computer science courses [6]. This conceptual paper addresses this gap by synthesizing contemporary literature, international frameworks, and recent empirical findings to argue that CT and AI literacy should be positioned as foundational, cross-disciplinary competencies for all learners rather than isolated technical electives. The paper is organized

as follows: Section II outlines the review methodology; Section III examines CT as a foundational competency; Section IV discusses AI literacy in education; Section V reviews international frameworks that integrate both competencies; Section VI discusses implications for interdisciplinary implementation; Section VII outlines challenges and future directions; and Section VIII concludes the paper.

II. LITERATURE REVIEW METHODOLOGY

As a conceptual literature review, this paper synthesizes peer-reviewed journal articles, conference proceedings, and policy documents published primarily between 2006 and 2026, retrieved through academic databases including Scopus, ERIC, Springer, ScienceDirect, and Google Scholar, alongside primary policy documents issued by UNESCO, the OECD, and the United Nations. Search terms included combinations of "computational thinking," "AI literacy," "21st century skills," "AI education," and "digital competencies." Sources were selected based on relevance to the conceptual integration of CT and AI literacy in educational contexts, methodological credibility, and citation influence within the field. Rather than following a formal systematic-review protocol (e.g., PRISMA), the review adopts a narrative-synthesis approach appropriate for conceptual and theory-building papers, organizing findings thematically around the two core constructs and the frameworks that connect them.

III. COMPUTATIONAL THINKING AS A FOUNDATIONAL COMPETENCY

Wing [1] defines computational thinking as an approach to solving problems, designing systems, and understanding human behavior by drawing on concepts fundamental to computer science. Crucially, Wing emphasizes that CT is a way of thinking, not merely a technical skill tied to programming; it involves choosing appropriate abstractions and understanding the relationships among multiple layers of abstraction. Building on this foundation, subsequent scholarship has operationalized CT into a set of interrelated sub-skills commonly summarized as decomposition (breaking a complex problem into manageable parts), pattern recognition (identifying similarities or trends across problems), abstraction (filtering out unnecessary detail to focus on essential structure), algorithmic thinking (developing step-by-step solutions), and evaluation (assessing the efficiency and correctness of a solution).

Empirical work increasingly links CT to broader twenty-first-century competencies. Student-centered CT curricula have been shown to foster measurable gains in critical thinking, creativity, communication, and collaboration—the so-called "4Cs" identified as core to

future-of-work readiness [9], [10]. A cross-case analysis of CT integration across school subjects further demonstrates that CT need not be confined to computer science classrooms; it can be embedded through modelling, storytelling, and unplugged activities across mathematics, science, and the humanities [7]. This cross-disciplinary applicability positions CT as a transferable cognitive toolkit rather than a narrow technical competency, reinforcing calls to treat it as a basic literacy alongside reading, writing, and numeracy.

A. Assessing and Cultivating Computational Thinking

A recurring challenge in CT scholarship concerns assessment: because CT manifests as a cognitive process rather than a single measurable product, researchers have relied on a mix of approaches, including analysis of programming artifacts, standardized CT assessments, portfolio-based evaluation, and observation of problem-solving behavior during unplugged tasks. This diversity of assessment strategies reflects the fact that CT is context-dependent—its expression in a block-based programming task looks different from its expression in a science inquiry activity or a mathematical modelling exercise, even though the underlying cognitive processes (decomposition, abstraction, algorithmic reasoning) remain consistent. For classroom practice, this suggests that CT is best cultivated through repeated, varied exposure across subjects and grade levels rather than through a single dedicated unit, allowing students to recognize and transfer the same reasoning patterns across different domains of application.

IV. ARTIFICIAL INTELLIGENCE LITERACY IN EDUCATION

AI literacy has emerged as a distinct but closely related construct to CT, addressing the specific competencies needed to understand and interact meaningfully with AI systems. Long and Magerko [4] define AI literacy as a set of competencies that enables individuals to critically evaluate AI technologies, communicate and collaborate effectively with AI, and use AI as a tool at home, at school, and in the workplace. Their widely cited framework synthesizes seventeen core competencies organized around five overarching questions: what is AI, what can AI do, how does AI work, how should AI be used, and how do people perceive AI. This framework has become a foundational reference for subsequent AI-literacy curriculum design across educational levels.

A systematic review of AI literacy in K-12 contexts by Casal-Otero et al. [3] analyzed 179 studies and identified two broad approaches to AI-literacy education: a learning-experience approach, which emphasizes hands-on acquisition of technical, conceptual, and applied AI

skills, and a theoretical-perspective approach, which focuses on conceptual models and frameworks for understanding AI. The review found that most existing initiatives remain fragmented, unevenly distributed across regions, and rarely embedded into mainstream curricula, echoing broader concerns about the uneven institutionalization of digital competencies in schooling.

The rise of generative AI tools since 2023 has further accelerated the urgency of AI literacy, shifting emphasis from understanding AI systems in the abstract toward developing critical, reflective practices for interacting with generative models in learning and assessment contexts. Teacher perceptions research indicates generally positive attitudes toward AI educational tools, but also highlights persistent gaps in teachers' own AI literacy and confidence in translating AI concepts into developmentally appropriate instruction for younger learners [8]. These findings suggest that AI literacy cannot be developed in students alone; it requires parallel investment in educator preparedness.

A. From Passive Use to Critical Engagement

A useful distinction within the AI-literacy literature separates passive use of AI tools from critical engagement with them. Passive use involves operating an AI system to accomplish a task—for example, prompting a chatbot to draft text or using a recommendation engine—without necessarily understanding how the underlying model was trained or why it produces particular outputs. Critical engagement, by contrast, involves interrogating the provenance of training data, recognizing the statistical rather than deliberative nature of AI-generated outputs, identifying potential bias or hallucination, and evaluating the appropriateness of AI use in a given context. Long and Magerko's framework [4] explicitly foregrounds this distinction through its "how should AI be used" and "how do people perceive AI" competency clusters, positioning ethical and reflective judgment as equally important as technical understanding. Embedding this distinction into classroom practice implies that AI-literacy instruction should not stop at tool demonstration but should routinely ask students to question, verify, and critique AI outputs as part of the learning task itself.

V. INTERNATIONAL FRAMEWORKS INTEGRATING CT AND AI LITERACY

A. UNESCO AI Competency Framework for Students

In 2024, UNESCO released the AI Competency Framework for Students, an international reference outlining twelve competencies organized across four dimensions: a human-centered mindset, ethics of AI, AI techniques and applications, and AI system design [2]. Each

competency spans three progression levels—understanding, applying, and creating with AI—providing a developmental pathway from basic awareness to active, ethically grounded engagement with AI systems. Notably, the framework is technology-neutral and human-rights-centered, explicitly positioning ethical reasoning and inclusion alongside technical understanding, and closely mirrors the CT emphasis on abstraction and system design while extending it into questions of fairness, bias, and societal impact.

B. OECD Learning Compass 2030

The OECD Learning Compass 2030 offers a complementary, broader vision for future-oriented education, organized around core foundations, knowledge, skills, attitudes and values, and "transformative competencies" that enable students to navigate novelty, reconcile tensions and dilemmas, and take responsibility [5]. Rather than prescribing a fixed curriculum, the Compass metaphor emphasizes student agency in navigating unfamiliar contexts—a framing highly compatible with CT's emphasis on iterative problem-solving and AI literacy's emphasis on critical evaluation of unfamiliar, opaque technological systems. The Compass explicitly names anticipation-action-reflection cycles as central to learning, aligning with the iterative, evaluative stages of the CT process.

C. Sustainable Development Goal 4

At a global policy level, Sustainable Development Goal 4 (Quality Education) commits nations to ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all, with explicit targets concerning relevant skills for employment and sustainable development [11]. CT and AI literacy align directly with SDG 4's emphasis on future-relevant skills and digital inclusion, positioning these competencies not merely as technical add-ons but as instruments of educational equity—particularly important given documented disparities in access to AI and computing education across regions and socioeconomic contexts [3].

Taken together, these three frameworks converge on a shared premise: CT and AI literacy are not isolated technical subjects but foundational, cross-cutting competencies that intersect with ethics, agency, equity, and lifelong learning. This convergence provides a strong policy rationale for embedding CT and AI literacy across curricula rather than confining them to specialized computing tracks. Table I summarizes the primary focus and structural emphasis of each framework reviewed.

TABLE I. COMPARISON OF INTERNATIONAL FRAMEWORKS RELEVANT TO CT AND AI LITERACY.

Framework	Structure	Core Emphasis
UNESCO AI Competency Framework [2]	4 dimensions x 3 progression levels (12 competencies)	Human-centered mindset, AI ethics, technical design
OECD Learning Compass 2030 [5]	Core foundations, transformative competencies, AAR cycle	Student agency, navigating novelty and dilemmas
SDG 4 [11]	Global development targets	Equitable access, future-relevant skills, lifelong learning

VI. DISCUSSION: TOWARD INTERDISCIPLINARY IMPLEMENTATION

The literature reviewed above suggests that the most effective and equitable path to developing CT and AI literacy is interdisciplinary integration rather than standalone instruction. Weng, Ye, Dai, and Ng [6] conducted a systematic review of instructional designs combining AI and CT in educational contexts and found that integrated approaches—where CT concepts such as abstraction and algorithmic thinking are taught through the lens of AI systems (e.g., training simple classifiers, examining recommendation algorithms, or critiquing chatbot outputs)—produced stronger conceptual understanding and more positive attitudes toward technology than approaches teaching CT and AI as separate units. Similarly, design-based research in mathematics education has demonstrated that CT and AI concepts can be productively embedded within existing subject-matter instruction, provided that curricular design explicitly scaffolds the transfer of computational reasoning into domain-specific problem solving [7].

This integrated model carries several pedagogical implications. First, CT should be introduced early and reinforced across subjects through unplugged and plugged activities alike, ensuring accessibility regardless of technology infrastructure. Second, AI literacy instruction should move beyond tool operation toward critical evaluation—helping students interrogate how training data, model design, and algorithmic bias shape AI outputs, consistent with the ethical dimension emphasized in UNESCO's framework [2]. Third, fostering these competencies supports broader twenty-first-century capacities such as critical thinking, creativity, collaboration, and responsible digital citizenship [9], [10], reinforcing the case for treating CT and AI literacy as general education outcomes rather than domain-specific technical skills reserved for STEM-track students.

A. Illustrative Subject-Area Applications

Concrete integration examples help translate these principles into practice. In science education, students can apply CT's decomposition and pattern-recognition skills to analyze experimental data, then compare their reasoning to an AI-based classifier trained on similar data—surfacing both the power and the limitations of automated pattern detection. In mathematics, algorithmic thinking can be reinforced by having students trace and debug simple algorithms by hand before observing how an AI system solves the same class of problem, developing intuition for computational efficiency and error propagation. In language and social studies classrooms, AI literacy can be cultivated by having students critically evaluate AI-generated text for factual accuracy, bias, and rhetorical framing, directly exercising the "how should AI be used" competency cluster identified by Long and Magerko [4]. These examples illustrate that meaningful integration does not require a dedicated computing curriculum; it requires deliberate instructional design that makes computational and AI-related reasoning visible within existing subject matter.

B. Relevance for Teacher Education Programs

For teacher-education institutions, including faculties of education preparing pre-service science and biology teachers, these findings carry direct implications. Embedding CT and AI-literacy modules within pedagogy courses—rather than treating them as separate technology electives—can help future teachers internalize these competencies as integral to subject-matter pedagogy rather than as an additional burden layered onto an already crowded curriculum. This is particularly relevant in contexts where access to dedicated computer science teacher training remains limited, reinforcing the case for embedding CT and AI literacy within general pedagogical preparation rather than specialized tracks alone.

VII. CHALLENGES AND FUTURE DIRECTIONS

Despite this convergence of policy vision and empirical support, significant implementation challenges remain. Chief among these is teacher readiness: research consistently reports that educators face barriers including limited technological self-efficacy, insufficient pre-service and in-service training, misconceptions about AI capabilities, and inadequate institutional support [8]. Without sustained investment in teacher professional development, ambitious framework-level goals risk remaining aspirational rather than operational. Second, infrastructural and socioeconomic disparities continue to limit equitable access to AI and computing education, particularly in under-resourced regions, raising the risk that CT and AI literacy initiatives could exacerbate rather than narrow existing educational inequities [3].

Third, curricular fragmentation persists: current K-12 AI education often remains tool-oriented and inconsistently sequenced across grade levels, with limited attention to conceptual progression and long-term skill transfer.

Future research and policy efforts should therefore prioritize three directions: (1) developing and validating scalable, low-infrastructure pedagogical models for CT and AI literacy that are viable in resource-constrained settings; (2) embedding AI and CT competencies explicitly within teacher-education curricula and ongoing professional development, rather than treating them as optional add-ons; and (3) establishing shared, cross-nationally comparable assessment instruments to track the developmental progression of CT and AI literacy over time, enabling evidence-based refinement of the frameworks reviewed in this paper.

A. Equity and Contextual Adaptation

A further consideration concerns how global frameworks such as those reviewed in Section V should be contextually adapted rather than adopted wholesale. UNESCO's framework and the OECD Learning Compass are explicitly designed to be globally informed but locally contextualized [2], [5], acknowledging that infrastructure, curricular structures, and teacher-preparation systems vary considerably across national and regional contexts. In many developing-country settings, including much of Southeast Asia, CT and AI-literacy initiatives must contend with uneven internet connectivity, limited device access, and large class sizes, making unplugged CT activities and low-bandwidth AI-literacy resources particularly valuable entry points rather than a reliance on continuous access to advanced computing tools. Contextual adaptation also extends to language and cultural relevance: AI-literacy materials that rely heavily on English-language examples or assume familiarity with specific commercial AI products may inadvertently disadvantage learners in non-English-speaking or lower-resource school systems. Addressing these disparities requires that policymakers and teacher-education institutions treat equity not as an afterthought but as a design principle guiding how CT and AI literacy are introduced, sequenced, and assessed across diverse educational settings.

B. Implications for Curriculum and Assessment Design

The convergence of findings across Sections III through VII points toward several practical implications for curriculum developers and assessment designers. Curricula should sequence CT concepts developmentally, beginning with unplugged decomposition and pattern-recognition activities in early grades before progressing to formal algorithmic reasoning and, eventually, critical engagement with AI systems in upper secondary and tertiary education—

mirroring the progression-level structure already adopted by UNESCO's framework [2]. Assessment design should likewise move beyond multiple-choice measures of factual AI knowledge toward performance-based tasks that require students to decompose an authentic problem, propose an algorithmic or AI-assisted solution, and justify the ethical appropriateness of that solution, thereby jointly assessing CT and AI-literacy competencies rather than treating them as separate testing domains. Finally, curriculum reform efforts should be paired with formative feedback loops between classroom practice and policy, so that the frameworks reviewed in this paper function as living references that are iteratively refined by evidence from implementation, rather than static top-down mandates.

VIII. CONCLUSION

This paper has argued, through a synthesis of contemporary literature and international policy frameworks, that computational thinking and AI literacy constitute essential, complementary, and mutually reinforcing competencies for twenty-first-century education. CT provides the foundational problem-solving processes of decomposition, pattern recognition, abstraction, algorithmic thinking, and evaluation, while AI literacy extends these processes into the specific domain of understanding, evaluating, and ethically engaging with intelligent systems. International frameworks—including UNESCO's AI Competency Framework for Students, the OECD Learning Compass 2030, and SDG 4—converge in positioning these competencies as foundational rather than elective, and cross-disciplinary rather than confined to computer science. Realizing this vision, however, requires deliberate interdisciplinary curriculum design, sustained investment in teacher preparedness, and attention to equity of access. Positioning CT and AI literacy as foundational competencies across all levels of education, rather than isolated technical subjects, represents a necessary step toward preparing learners to adapt, innovate, and participate meaningfully in an AI-driven society and the evolving global workforce.

REFERENCES

1. J. M. Wing, "Computational thinking," Communications of the ACM, vol. 49, no. 3, pp. 33–35, 2006.
2. UNESCO, AI Competency Framework for Students. Paris: UNESCO, 2024.
3. L. Casal-Otero, A. Catala, C. Fernández-Morante, M. Taboada, B. Cebreiro, and S. Barro, "AI literacy in K-12: a systematic literature review," International Journal of STEM Education, vol. 10, no. 1, art. 29, 2023.

4. D. Long and B. Magerko, "What is AI literacy? Competencies and design considerations," in Proc. 2020 CHI Conf. Human Factors in Computing Systems, Honolulu, HI, USA, 2020, pp. 1–16.
5. OECD, OECD Learning Compass 2030: A Series of Concept Notes. Paris: OECD Publishing, 2019.
6. X. Weng, H. Ye, Y. Dai, and O. Ng, "Integrating artificial intelligence and computational thinking in educational contexts: a systematic review of instructional design and student learning outcomes," Journal of Educational Computing Research, vol. 62, no. 6, pp. 1640–1670, 2024.
7. ScienceDirect, "Computational thinking integrated in school subjects: a cross-case analysis of students' experiences," International Journal of Educational Research Open, 2024.
8. I. H. Y. Yim and R. Wegerif, "Teachers' perceptions, attitudes, and acceptance of artificial intelligence (AI) educational learning tools: an exploratory study on AI literacy for young students," Future in Educational Research, 2024.
9. B. Thornhill-Miller, A. Camarda, M. Mercier, J.-M. Burkhardt, T. Morisseau, S. Bourgeois-Bougrine, F. Vinchon, S. El Hayek, M. Augereau-Landais, F. Mourey, C. Feybesse, D. Sundquist, and T. Lubart, "Creativity, critical thinking, communication, and collaboration: assessment, certification, and promotion of 21st century skills for the future of work and education," Journal of Intelligence, vol. 11, no. 3, art. 54, 2023.
10. International Journal of Instruction, "Fostering 21st century competences through computational thinking and active learning: a mixed method study," International Journal of Instruction, vol. 14, no. 3, 2021.
11. United Nations, Transforming Our World: The 2030 Agenda for Sustainable Development, Sustainable Development Goal 4: Quality Education. New York: United Nations, 2015.