ETHICAL AI LITERACY IN STEM EDUCATION: A SCOPING REVIEW OF COMPETENCIES, PEDAGOGICAL APPROACHES, AND RESEARCH DIRECTIONS

Jade C. Colegado, Rebysarah T. Delector
Bukidnon State University, Malaybalay City, Bukidnon, 8700 Philippines
jadecolegado@buksu.edu.ph, rebysarahdelector@buksu.edu.ph
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ABSTRACT: *The increasing integration of artificial intelligence (AI) in STEM education has highlighted the need for ethical AI literacy that enables learners and educators to use AI responsibly, critically, and ethically. This scoping review synthesizes the emerging landscape of ethical AI literacy in STEM, mapping core competencies, pedagogical approaches, and research directions. Using the PRISMA-ScR framework, 6,066 Scopus-indexed records (2020–2026) were screened, with 67 studies meeting eligibility criteria; a STEM-specific subset of 24 informed the final analysis. Three themes emerged: (1) Ethical AI literacy as a foundation for STEM competencies, emphasizing the integration of AI knowledge, ethical reasoning, critical thinking, and responsible AI use; (2) Pedagogical integration of ethical AI in STEM learning, highlighting inquiry-based, learner-centered, and AI-assisted instructional practices that cultivate ethical decision-making; and (3) Institutional readiness and future directions, which shows the need for curriculum integration, teacher professional development, assessment frameworks, governance policies, and longitudinal research. The findings reveal a transformation from technology-centered AI adoption toward human-centered STEM education where AI literacy is framed not merely as technical proficiency but a balance with ethical responsibility. This review provides an evidence-informed foundation for curriculum development, teacher preparation, educational policy, and future research on ethical AI literacy in STEM education.*

Keywords: ethical AI literacy; STEM education; artificial intelligence; AI literacy; scoping review

1. INTRODUCTION

Artificial intelligence (AI) has become one of the most transformative technologies shaping education in the twenty-first century. The rapid advancement of intelligent tutoring systems, machine learning, learning analytics, educational robotics, and, more recently, generative artificial intelligence (GenAI) has expanded opportunities for enhancing teaching and learning, particularly in science, technology, engineering, and mathematics (STEM) education. AI-powered technologies increasingly support personalized learning, adaptive assessment, scientific inquiry, collaborative problem-solving, and data-driven instruction, making AI an integral component of contemporary STEM education. Consequently, research on AI in education has grown substantially, with recent reviews documenting a marked increase in AI-related educational studies following the emergence of generative AI technologies [1][2]. While these developments promise significant educational benefits, they also present complex ethical challenges that extend beyond technical implementation.

Several studies have shown that the widespread adoption of AI has intensified concerns regarding algorithmic bias, transparency, explainability, data privacy, intellectual property, accountability, academic integrity, and equitable access to technology [3]. These concerns are particularly relevant in STEM education, where learners are expected not only to use AI tools but also to design, evaluate, and innovate AI-enabled systems that influence society. STEM education increasingly requires learners to develop ethical reasoning alongside technical competence. This expectation has led to the growing recognition of ethical AI literacy, which extends beyond operational AI skills to encompass the knowledge, critical thinking, values, and dispositions needed to evaluate AI systems responsibly and make informed ethical decisions [4]. Ethical AI literacy therefore positions learners as responsible participants capable of balancing technological innovation with human values such as fairness, transparency, inclusivity, privacy, accountability, and social responsibility.

This shift has been reinforced by international AI competency frameworks and educational initiatives advocating the integration of ethical awareness, civic responsibility, and critical engagement into AI education [4]. However, despite the rapid expansion of AI research in STEM education, existing studies have largely focused on technological innovation, learning analytics, computational thinking, and instructional effectiveness [1]. Comparatively fewer studies have examined how ethical competencies can be intentionally developed within STEM learning environments. Existing reviews also suggest that ethical principles, including fairness, explainability, transparency, equity, and responsible AI, are often discussed as future considerations rather than explicitly embedded within curricula, pedagogy, or assessment [5]. Furthermore, studies employ diverse but overlapping concepts such as AI literacy, AI ethics, responsible AI, trustworthy AI, digital ethics, and algorithmic literacy without clearly distinguishing their conceptual boundaries, resulting in fragmented understandings of ethical AI literacy and inconsistent identification of the competencies required for STEM learners [6].

Methodological limitations further constrain the current evidence base. Previous reviews have reported geographical concentration of studies, limited longitudinal investigations, underrepresentation of diverse learner populations, and insufficient evidence on authentic classroom implementation of ethical AI education [7]. Moreover, although several reviews acknowledge ethics as an emerging priority, none provides a comprehensive synthesis focused specifically on ethical AI literacy within STEM education by examining its conceptualizations, pedagogical approaches, and future research directions. Given the accelerating integration of generative AI into scientific inquiry, engineering design, mathematical problem solving, and technology education, ethical AI literacy has become a foundational competency for preparing learners to engage responsibly with AI while ensuring that technological innovation aligns with human values and sustainable development [1].

To address these gaps, this scoping review systematically maps the literature on ethical AI literacy in STEM education. Guided by the PRISMA-ScR framework, the review synthesizes evidence from peer-reviewed studies to examine three interrelated dimensions: (1) the concepts and competencies that define ethical AI literacy in STEM education, (2) the pedagogical approaches used to develop these competencies, and (3) the future research directions needed to strengthen ethical AI literacy in STEM contexts. By integrating fragmented evidence across these dimensions, this review provides a comprehensive understanding of ethical AI literacy as an emerging field and offers evidence-informed implications for curriculum development, teacher education, educational policy, and future research. The review contributes a conceptual foundation for responsible, human-centered AI integration within STEM education.

2. METHODS

Research Design

This study employed a scoping review methodology to systematically map and synthesize the existing body of literature on ethical AI literacy in STEM education. Scoping reviews are particularly appropriate for emerging and interdisciplinary fields because they enable researchers to examine the breadth, characteristics, and knowledge gaps within a body of evidence rather than evaluating intervention effectiveness alone. Following the framework proposed by [8] later refined by [9], the review sought to identify how ethical AI literacy has been conceptualized, the competencies emphasized, the pedagogical approaches employed, the educational contexts represented, and the future directions proposed in the literature.

The review was conducted and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) [10]. PRISMA-ScR provides a transparent and rigorous framework for identifying, screening, selecting, and synthesizing evidence while accommodating the broad objectives typical of scoping reviews.

Search Strategy

A systematic literature search was undertaken to identify peer-reviewed studies addressing ethical AI literacy within STEM education. Search terms were developed through an iterative process guided by preliminary searches and existing AI literacy frameworks. The search strategy combined controlled vocabulary and free-text keywords related to artificial intelligence, ethics, AI literacy, responsible AI, STEM education, computational thinking, and educational technology using Boolean operators. Representative search terms included: ("artificial intelligence" OR AI OR "generative AI" OR ChatGPT OR "machine learning") AND ("ethical AI literacy" OR "AI ethics" OR "responsible AI" OR "AI literacy" OR "ethical competence") AND (STEM OR science OR technology OR engineering OR mathematics OR education). The search strategy was developed and refined iteratively to maximize the identification of relevant studies while maintaining consistency with the review objectives.

Inclusion and Exclusion Criteria

Studies were eligible for inclusion if they were published between 2020 and 2026, indexed in the Scopus database, published in peer-reviewed journals, written in English, available in full-text, and focused on ethical AI literacy, AI ethics education, responsible AI, or related ethical dimensions of artificial intelligence within STEM education contexts. Eligible studies included empirical research (qualitative, quantitative, or mixed methods), conceptual papers, framework development studies, and review articles that provided substantial empirical or conceptual contributions to the review objectives. Studies were excluded if they were published before 2020, conducted outside STEM education, did not explicitly address ethical AI literacy or AI ethics education, were duplicate records, were non-English publications, had inaccessible full texts, or consisted of publication types with insufficient empirical or conceptual contribution, such as editorials, letters, book reviews, notes, news articles, conference abstracts, or other non-peer-reviewed publications.

Data screening and Selection Process

The study selection process followed the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines to ensure a transparent and systematic identification, screening, and selection of relevant studies. An initial search of the Scopus database yielded 6,066 records. After removing 345 duplicate records, 5,721 unique studies remained for title and abstract screening. This stage excluded 5,483 records that did not meet the predefined inclusion criteria, resulting in 238 articles for full-text eligibility assessment. Following a comprehensive review, 171 articles were excluded because they were outside the scope of STEM education (n = 67), did not explicitly address ethical AI literacy or AI ethics education (n = 32), represented ineligible publication types or lacked sufficient empirical or conceptual contribution (n = 45), or failed to satisfy other inclusion criteria such as language, accessibility, or duplicate publication (n = 27). Consequently, 67 studies met all eligibility criteria and were included in the final scoping review and qualitative synthesis.

The screening and selection process is summarized in Table 1 below.

Table 1. PRISMA-ScR Summary of the Study Selection Process

PRISMA Stage	Selection Process	Records (n)
Identification	Records identified through Scopus database searching	6,066
	Duplicate records removed	345
Screening	Records screened (title and abstract)	5,721
	Records excluded during title and abstract screening	5,483
Eligibility	Full-text articles assessed for eligibility	238
	Full-text articles excluded	171
	• Outside the scope of STEM education	67
	• Did not address ethical AI literacy or AI ethics education	32
	• Ineligible publication type or insufficient empirical/conceptual contribution	45
	• Failed to satisfy other inclusion criteria (e.g., non-English, inaccessible full text, duplicate publication)	27
Included	Studies included in the final scoping review	67

Data Analysis and Synthesis

The extracted data were synthesized using descriptive mapping and qualitative thematic synthesis. Descriptive analysis summarized the characteristics of the included studies, including publication year, country of origin, educational level, participant groups, STEM disciplines, research design, and key focus areas related to artificial intelligence and ethical AI literacy. This mapping provided an overview of the current research landscape represented by the 67 included studies.

For the qualitative synthesis, an analytical subset of 24 core STEM-focused studies was examined in greater depth because these studies explicitly investigated ethical AI literacy, AI-related competencies, pedagogical practices, or AI integration within STEM education. Thematic synthesis followed an inductive approach in which extracted findings were systematically coded, compared, and refined through constant comparison. Initial codes representing recurring concepts, instructional practices, competency frameworks, and research implications were iteratively consolidated into broader thematic categories.

The analysis generated three overarching themes that addressed the objectives of this scoping review: (1) AI Literacy as a Multidimensional Competency for Ethical STEM Practice; (2) Transformative Pedagogies for Ethical AI Integration in STEM Learning; and (3) Building Ethical AI Ecosystems through Policy, Teacher Capacity, and Future Research. Rather than quantitatively aggregating findings, the synthesis emphasized conceptual convergence, variations across educational contexts, and emerging evidence regarding the ethical integration of AI in STEM education. Representative studies were used to illustrate each theme while preserving the breadth and diversity of perspectives characteristic of scoping review methodology.

Ensuring Rigor and Trustworthiness

Several strategies were employed to enhance the rigor and transparency of the review. First, a comprehensive search strategy and predefined eligibility criteria minimized selection bias. Second, adherence to the PRISMA-ScR reporting guidelines ensured transparent documentation of the identification, screening, eligibility, and inclusion processes. Third, the use of a standardized data extraction protocol promoted consistency across studies. Finally, thematic synthesis was conducted through iterative comparison of extracted evidence to ensure that themes accurately reflected the diversity of conceptualizations, competencies, pedagogical approaches, and educational contexts represented in the literature.

3. RESULTS AND DISCUSSIONS

The scoping review synthesized evidence from the core studies identified across the selected literature on ethical AI literacy in STEM education. Three overarching themes emerged from the analysis: (1) AI Literacy as a Multidimensional Competency for Ethical STEM Practice, (2) Transformative Pedagogies for Ethical AI Integration in STEM Learning, and (3) Building Ethical AI Ecosystems through Policy, Teacher Capacity, and Future Research. These themes collectively demonstrate that ethical AI literacy extends beyond technical proficiency, encompassing pedagogical innovation, institutional support, and responsible governance necessary for preparing STEM learners and educators for AI-enabled environments.

Theme 1. AI Literacy as a Multidimensional Competency for Ethical STEM Practice

A dominant finding across the reviewed studies is the evolving conceptualization of AI literacy from a technology-oriented skill to a multidimensional competency integrating knowledge, skills, attitudes, and ethical dispositions. Rather than emphasizing only the operational use of AI applications, recent literature positions AI literacy as encompassing critical evaluation, responsible decision-making, prompt engineering, verification of AI-generated information, and awareness of ethical issues such as bias, privacy, transparency, and accountability.

Several studies emphasized that AI literacy should be viewed as a continuum of competencies rather than a single technical ability. AI adoption among accounting students was found to be significantly influenced by perceived usefulness, AI literacy, facilitating conditions, technology readiness, and social influence, suggesting that conceptual understanding and confidence are equally important for meaningful AI utilization [11]. Similarly, teachers who demonstrated stronger prompt engineering competencies exhibited more sophisticated classroom integration of generative AI despite having limited institutional support, indicating that meaningful AI literacy depends more on interaction competence than access alone [12]. Ethical AI behavior also emerged from learners' ability to critically evaluate AI-generated outputs before using them, as verification intentions and perceived risks significantly predicted responsible AI use among university students [13]. Furthermore, a systematic review of AI governance frameworks identified fairness, accountability, explainability, transparency, and sustainability as universal ethical principles underpinning responsible AI implementation across sectors, including education [14].

Assessment of AI literacy likewise emerged as an important area of development. A validated Knowledge–Attitudes–Practices (KAP) instrument demonstrated that AI literacy extends beyond knowledge acquisition to include ethical attitudes and responsible classroom practices among pre-service teachers [15]. Likewise, AI literacy among ASEAN library and information science researchers was generally satisfactory, although deficiencies remained in ethical understanding, AI concepts, and programming competencies, highlighting the need for structured AI literacy development [16].

Hence, findings suggest that ethical AI literacy in STEM education should be conceptualized as an integrated competency framework combining technical knowledge, critical thinking, ethical reasoning, and responsible AI engagement. Such a perspective aligns with the demands of STEM disciplines, where learners are increasingly expected not only to use AI effectively but also to evaluate its limitations and societal implications.

Theme 2. Transformative Pedagogies for Ethical AI Integration in STEM Learning

Pedagogical transformation likewise emerged as a defining characteristic of ethical AI literacy in STEM education. Across the reviewed studies, AI was consistently described as a cognitive partner that supports inquiry, creativity, personalized learning, and problem-solving rather than replacing teachers or conventional instruction [17][18]. One recurring pedagogical approach is inquiry-oriented learning, wherein students actively engage with AI-generated outputs through questioning, verification, reflection, and evidence-based reasoning. Although teachers frequently used generative AI to support lesson preparation, substantially fewer integrated AI into student-centered classroom activities, indicating that AI implementation remains largely teacher-oriented and highlighting the need for instructional approaches that encourage learners to critically engage with AI technologies [12].

The reviewed studies also emphasized active learning strategies that integrate ethical reasoning into AI-supported instruction. An Educational Design Research study proposed the AI–Pedagogical Civic Design (AI-PCD) model, which combines adaptive learning, digital civic literacy, ethical AI governance, and reflective participation. Although developed within civic education, its emphasis on learner agency, ethical reasoning, and responsible technology use has direct implications for STEM education, where inquiry, experimentation, and evidence-based decision-making are essential instructional practices [19]. Generative AI likewise emerged as an effective learning scaffold when integrated responsibly. University students reported that ChatGPT supported conceptual understanding, independent learning, and reduced academic stress while also recognizing the importance of maintaining ethical use and critical judgment [18]. Similarly, students viewed ChatGPT and Gemini as valuable tools for brainstorming, organizing ideas, and improving academic writing but remained aware of concerns related to plagiarism, academic integrity, and overreliance. Many students demonstrated responsible AI practices by paraphrasing, verifying, and cross-checking AI-generated content before submission [17].

Teacher preparation also represents an essential component of effective AI pedagogy. Assessing teachers' knowledge, attitudes, and practices toward AI provides an important basis for designing interventions that promote responsible classroom integration of AI technologies within STEM education[20]. Thus, reviewed evidence suggests that ethical AI integration requires pedagogies that position AI as a learning partner while simultaneously cultivating critical thinking, reflective judgment, and responsible technology use. Rather than emphasizing AI efficiency alone, STEM instruction should encourage learners to question AI outputs, evaluate evidence, recognize algorithmic limitations, and apply human reasoning in decision-making.

The evidence suggests that ethical AI integration requires learner-centered pedagogies that position AI as a learning partner while cultivating critical thinking, reflective judgment, and responsible technology use. Rather than emphasizing efficiency alone, STEM instruction should encourage learners to question AI-generated outputs, evaluate evidence, recognize algorithmic limitations, and apply human reasoning throughout the learning process.

Theme 3. Building Ethical AI Ecosystems through Policy, Teacher Capacity, and Future Research

The third theme extends beyond classroom practice by emphasizing the systemic conditions necessary to sustain ethical AI literacy. The reviewed studies consistently indicate that responsible AI integration depends not only on individual competencies but also on institutional policies, curriculum reform, teacher professional development, and research-informed governance.

Teacher capacity emerged as one of the strongest determinants of responsible AI implementation. Faculty preparedness, assessment redesign, and institutional policy development were identified as essential prerequisites for integrating AI responsibly into higher education, with implications that readily extend to STEM education where rapid technological advances require continuous curriculum adaptation and professional learning [21]. At the institutional level, coherent AI legislation, educational investment, and sustained public awareness were identified as critical factors supporting national AI implementation [22]. Likewise, effective AI governance should be grounded in ethics-by-design principles emphasizing transparency, accountability, human oversight, and equitable access throughout the AI lifecycle [14].

Research trends likewise demonstrate an important shift in the educational landscape. Bibliometric evidence shows that AI research in higher education has evolved rapidly from emphasizing technological applications toward instructional innovation, assessment reform, digital ethics, and institutional governance. This evolution reflects growing recognition that AI literacy should be embedded within broader educational ecosystems rather than taught solely as technological content [23].

Despite these advances, several research gaps remain. Empirical investigations focusing specifically on ethical AI literacy within STEM disciplines remain limited, with many studies examining higher education broadly without distinguishing discipline-specific pedagogical needs. Longitudinal investigations evaluating the long-term impact of AI literacy interventions are scarce, and relatively few validated instruments currently measure ethical AI competencies beyond general AI literacy. Furthermore, evidence remains limited regarding instructional models that explicitly integrate ethical reasoning, AI literacy, and STEM inquiry into coherent pedagogical frameworks [20].

The findings suggest that advancing ethical AI literacy in STEM education requires a systems-level approach in which learner competencies, innovative pedagogies, institutional governance, teacher professional development, and ongoing research function as interconnected components. Such an ecosystem provides the foundation for preparing ethically responsible STEM graduates capable of critically engaging with AI technologies while addressing complex scientific and societal challenges.

4. CONCLUSION

This findings of the study demonstrate that ethical AI literacy has emerged as a foundational component of STEM education, extending beyond technical AI knowledge to encompass ethical reasoning, responsible decision-making, critical evaluation, and the capacity to apply AI in socially beneficial ways. Analysis of the core STEM-focused studies revealed three interrelated themes: (1) ethical AI literacy as a multidimensional STEM competency, (2) learner-centered pedagogies for ethical AI literacy, and (3) advancing ethical AI literacy through assessment, policy, and future research. These findings highlight a shift from technology-centered AI education toward human-centered approaches that integrate ethical principles with STEM learning. The review further highlights the need for validated assessment instruments, curriculum frameworks, teacher professional development, longitudinal and interdisciplinary research, and coherent institutional policies to support the responsible integration of AI in STEM education. By synthesizing current evidence, this review provides a conceptual foundation to guide curriculum development, educational practice, and future scholarship aimed at preparing ethically responsible and AI-literate STEM learners.

5. LIMITATIONS

This study utilizing scoping review has several limitations that should be considered when interpreting the findings. First, the review included only peer-reviewed studies indexed in the Scopus database and published between 2020 and 2026, which may have excluded relevant studies from other databases, grey literature, conference proceedings, and earlier foundational works on AI literacy and ethics. Second, although 67 studies met the eligibility criteria, the thematic synthesis was derived from a subset of 24 studies that explicitly examined ethical AI literacy within STEM education. Consequently, the proposed themes reflect the current evidence specific to STEM contexts rather than the broader AI-in-education literature. Finally, as a scoping review, this study aimed to map and synthesize existing evidence rather than evaluate the methodological quality or effectiveness of the included studies. Future systematic reviews and meta-analyses are needed to assess the strength of evidence and examine the impact of ethical AI literacy interventions on teaching and learning outcomes.

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