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STEM Education in Early Childhood: A Systematic Literature Review of Trends and Practices

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Abstract

Despite expanding global interest in early childhood Science, Technology, Engineering, and Mathematics (STEM) education, empirical evidence regarding pedagogical integration, teacher belief systems, and early cognitive outcomes remains conceptually fragmented and geographically asymmetric. To address this gap, this systematic literature review applies PRISMA 2020 guidelines and the SPIDER eligibility framework to synthesize a primary empirical corpus of N = 20 studies within a broader 30-source academic foundation. Grounded in Vygotsky's sociocultural theory and Papert's constructionism, this review evaluates early childhood STEM instructional mechanics including Engineering Design Process (EDP) cycles, screen-free tangible robotics, digital manipulatives, and arts-integrated storybooks for learners aged 3 to 8 years. Synthesized findings reveal a clear developmental continuum: toddler learning (ages 3-4) relies primarily on open-ended sensory discovery, whereas kindergarten settings (ages 5-6) require structured teacher scaffolding to guide children from initial prototyping toward systematic testing, spatial reasoning, and failure optimization. Furthermore, teacher pedagogical belief structures significantly moderate curriculum execution; educators holding discrete beliefs regarding play and academics achieve higher technical coding gains through structured modules, whereas those with integrated beliefs prioritize open-ended exploration without diminishing computational thinking or debugging skills. Methodological quality appraisal via the Mixed Methods Appraisal Tool (MMAT 2018) confirms high overall rigor (M = 84.5%), though geographic distributions reveal severe imbalances favoring Asian and European research hubs over African and South American contexts. Ultimately, this review offers actionable theoretical, policy, and practical frameworks for curriculum designers and teacher education programs seeking to establish equitable, developmentally aligned early STEM learning environments.

Keywords: Early childhood STEM education; Engineering Design Process; Tangible robotics; Computational thinking; Teacher pedagogical beliefs

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1. Introduction

In contemporary educational research and social humanities, early childhood Science, Technology, Engineering, and Mathematics (STEM) education has emerged as an integrated pedagogical framework for young children aged 3 to 8 years (Alvita et al., 2026; Wan et al., 2021) Global early learning policy reforms increasingly emphasize early exposure to scientific inquiry and technological reasoning as foundational drivers of lifelong learning, cognitive agency, and socio-emotional competence (RAND Corporation, 2016) Rather than treating STEM disciplines as isolated academic subjects, contemporary policy frameworks position integrated STEM and STEAM incorporating the arts and humanities as a multidisciplinary vehicle designed to nurture 21st-century problem-solving abilities, spatial reasoning, and critical thinking skills during formative developmental stages (RAND Corporation, 2016; Wan et al., 2021). By engaging young learners in authentic, real-world inquiry and collaborative experimentation, early STEM initiatives seek to establish cognitive flexibility and inclusive learning habits that support sustainable educational development across diverse demographic contexts (Alvita et al., 2026; Wan et al., 2021).

Recent empirical scholarship demonstrates significant pedagogical evolution in the design and delivery of early childhood STEM experiences across diverse learning environments. A prominent development involves the adaptation of simplified Engineering Design Process (EDP) cycles such as think, try, fix, share that enable young children to act as emergent engineers by defining human problems, constructing physical models, and engaging in iterative trial-and-error problem-solving (Ata-Aktürk & Demircan, 2019; Reuter & Leuchter, 2022; Risnawati, 2025). In parallel, play-based inquiry supported by Technology-Enhanced Toys (TETs) and screen-free tangible robotics promotes emergent computational thinking, spatial manipulation, and peer collaboration in early learning environments (Bourha et al., 2026; Levinson et al., 2024). Computational thinking is further expanded through unplugged, arts-integrated STEAM frameworks, such as pop-up storybook engineering, where young learners apply algorithmic logic, modularity, and debugging during physical paper construction (Li et al., 2024). Furthermore, storybook scaffolding and explicit-reflective Nature of Engineering (NOE) instruction utilize narrative contexts to connect abstract physical science concepts with human-centered engineering challenges (Deniz et al., 2021; Kapoor, 2023). Empirical trials confirm that combining structured curriculum modules with hands-on play yields measurable gains in early coding knowledge and mechanical problem-solving (Levinson et al., 2024; Reuter & Leuchter, 2022).

Despite these pedagogical advancements, widespread classroom implementation encounters substantial operational friction within early childhood settings. A principal systemic barrier is the documented gap in early childhood educators' Pedagogical Content Knowledge (PCK) and physical science subject confidence, which frequently manifests as instruction-related anxiety (Kewalramani et al., 2025; Leung, 2023; Yang et al., 2022). Research indicates that teachers' underlying pedagogical belief systems significantly moderate curriculum delivery and learning mastery; specifically, educators holding discrete beliefs regarding play and academic learning adhere strictly to structured instructional sequences, whereas those holding integrated beliefs often prioritize open-ended exploration at the expense of complete module coverage (Hurme et al., 2026; Levinson et al., 2024). Furthermore, early childhood practitioners struggle to align market-driven commercial STEM kits with established early learning standards, as proprietary packages often promote isolated activities rather than sustained, inquiry-driven problem-solving (RAND Corporation, 2016; Leung, 2023). Institutional constraints including low educator compensation, inadequate planning time, restrictive scheduling, and administrative pressure to prioritize basic literacy further impede educators from enacting their reflective professional vision during classroom play sessions (RAND Corporation, 2016; Kewalramani et al., 2025; Leung, 2023).

An analysis of published literature reviews and empirical evaluations highlights three overarching gaps within the current research corpus. First, existing scholarship exhibits conceptual fragmentation, where empirical findings remain divided across isolated disciplinary silos such as digital technology tools versus outdoor nature-based play without a unified typology of pedagogical practices (Wan et al., 2021; Pellas, 2025). Second, systematic literature reviews reveal severe contextual and geographical imbalances across global bibliographic databases; instructional model evaluations remain overwhelmingly concentrated in secondary education and specific Northern hemisphere research hubs, leaving early childhood education significantly underrepresented (Alvita et al., 2026; Ching & Hsu, 2024). Third, empirical research is constrained by methodological limitations, as the evidence base relies predominantly on short-term intervention studies and brief qualitative observations that lack multi-year longitudinal tracking to evaluate the retention of early engineering habits of mind (RAND Corporation, 2016; Wan et al., 2021). Consequently, a rigorous systematic synthesis across the active N = 20 empirical corpus is urgently required to consolidate fragmented findings, appraise study quality, and establish an evidence-based taxonomy of early STEM instruction (Alvita et al., 2026; Wan et al., 2021). To address these empirical gaps, this systematic literature review synthesizes the active N = 20 empirical corpus in accordance with PRISMA 2020 guidelines and SPIDER eligibility criteria. The

study is structured around three primary research questions: RQ1 (Trends): What structural, temporal, geographical, and methodological trends characterize research on STEM education in early childhood? RQ2 (Practices): What STEM educational practices, pedagogical frameworks, learning environments, technology tools, and teacher roles are reported in early childhood settings? RQ3 (Emerging Horizons): What emerging themes, underexplored areas, and research gaps exist within the early childhood STEM literature?

The analytical novelty of this review lies in its multi-layered synthesis pipeline, which combines Mixed Methods Appraisal Tool (MMAT 2018) quality assessment with Thomas & Harden (2008) thematic synthesis to establish a rigorous, source-locked typology of early STEM instruction. By bridging theoretical frameworks with empirical classroom evidence, this study provides actionable insights for educational policy makers, curriculum developers, and early childhood teacher educators seeking to implement developmentally appropriate STEM instruction.

2. Methodology

This systematic literature review applies the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) statement (Page et al., 2021) in conjunction with the Sample, Phenomenon of Interest, Design, Evaluation, Research type (SPIDER) eligibility framework (Cooke et al., 2012). A systematic literature review design was selected to establish a transparent, auditable, and reproducible methodology for synthesizing fragmented empirical evidence across early childhood STEM education. To operationalize study selection, the SPIDER framework was defined across five specific criteria: Sample, focusing on young children aged 3 to 8 years, early childhood educators, preservice teachers, or early learning centers; Phenomenon of Interest, encompassing integrated STEM or STEAM education, play-based inquiry, engineering design process models, educational robotics, or technology-supported STEM learning; Design, including qualitative case studies, quantitative experimental and quasi-experimental designs, mixed-methods evaluations, and design-based research; Evaluation, addressing implementation mechanics, pedagogical strategies, teacher belief systems, child cognitive or social skill outcomes, and institutional barriers; and Research Type, restricted to peer-reviewed empirical journal articles and official research reports. Because this investigation relies exclusively on secondary synthesis of published, open-access academic literature, direct institutional review board approval was not required; nevertheless, strict standards of citation integrity, data accuracy, and transparent reporting were maintained throughout the review process.

Systematic literature retrieval was executed across six electronic databases and indexing platforms: Scopus, Web of Science, ERIC, IEEE Xplore, Semantic Scholar, and publisher repositories. The search strategy was restricted to peer-reviewed empirical studies published in English between 2016 and 2026. Search strings were constructed using Boolean operators combining three core keyword blocks: sample terms, including early childhood, kindergarten, preschool, or young children; phenomenon terms, including STEM education, STEAM, engineering design process, educational robotics, or computational thinking; and pedagogical terms, including play-based, inquiry, teacher beliefs, or pedagogy. Multi-stage screening followed a systematic protocol comprising initial record identification, automated and manual deduplication, title and abstract screening against predefined criteria, and full-text eligibility appraisal. To ensure selection rigor and minimize selector bias, two independent reviewers performed dual-screening at both title/abstract and full-text stages, resolving eligibility discrepancies through structured consensus discussions. The complete selection pipeline, from initial database retrieval to final study inclusion (N = 20), is illustrated in Figure 1.

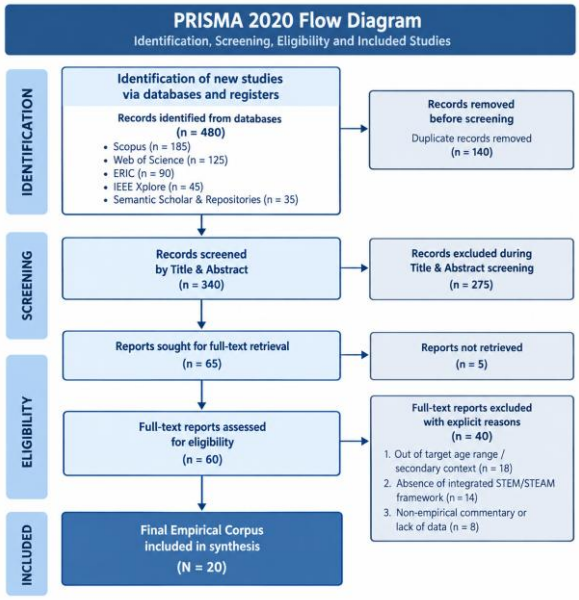


Figure 1
PRISMA 2020 Flow Diagram of the Literature Identification, Screening, Eligibility, and Selection Process (N = 20).

Methodological quality and risk of bias across the included empirical corpus (N = 20) were evaluated using the Mixed Methods Appraisal Tool (MMAT 2018) criteria (Hong et al., 2018). The MMAT framework was selected because it accommodates diverse research designs within a unified appraisal architecture: qualitative studies were appraised for qualitative approach appropriateness, data collection methodology, data-to-interpretation coherence, and researcher reflexivity; quantitative non-randomized and experimental studies were evaluated for sample representativeness, measurement instrument validity, outcome completeness, and control of confounding variables; and mixed-methods and design-based research studies were assessed for integration rationale, component methodological quality, and effective resolution of divergent findings. Criterion-level judgments were recorded as compliance percentages to determine methodological trustworthiness and inform cross-study synthesis without arbitrarily excluding lower-scoring studies.

Data extraction was executed using a standardized matrix recording study identifiers, author names and publication year, country context, design and sample characteristics, primary research question alignment, MMAT score, and core empirical focus. Qualitative and empirical text extraction followed Thomas & Harden's (2008) three-stage thematic synthesis pipeline: Stage 1 involved line-by-line open coding of extracted findings, observational records, and author interpretations from full-text papers; Stage 2 involved grouping primary codes into descriptive sub-themes based on conceptual and empirical commonalities; and Stage 3 involved generating higher-order analytical themes explicitly aligned with RQ1 (Trends), RQ2 (Practices Typology), and RQ3 (Emerging Horizons). To maintain complete auditability and coding reliability, reference management was conducted via Zotero, record screening was tracked in Rayyan, and qualitative coding matrices were structured in Microsoft Excel.

One of the studies included in this review, Martino et al. (2025) (Study 15 in Table 1), was authored by the corresponding author of the present review, Jastin Martino. This relationship is disclosed to ensure transparency regarding potential conflicts of interest. To minimize the potential for author-related inclusion bias, the eligibility screening and inclusion decision for Martino et al. (2025) were independently conducted by another reviewer who was not an author of the included study. The study was assessed using the same predefined eligibility criteria and screening procedures applied to all

other records. Its inclusion was therefore determined solely on the basis of its eligibility for the present review.

3. Results

3.1. Research Characteristics and Research Trends (RQ1)

Bibliometric and geographical analysis of the active N = 20 empirical corpus demonstrates a temporal concentration of publications between 2016 and 2026, reflecting accelerated global research on early childhood integrated STEM and educational technologies. Geographically, empirical classroom evaluations are distributed across East and Southeast Asian research hubs (n = 7)significant regional disparities where African, Australia and South American early learning contexts remain underrepresented (Alvita et al., 2026; Nyaaba et al., 2024). Methodological distributions across the corpus reveal a predominance of qualitative designs (n = 9), followed by systematic evidence syntheses and policy reviews (n = 5), mixed-methods and design-based research paradigms (n = 4), and quantitative experimental or quasi-experimental trials (n = 2). Quality appraisal using the Mixed Methods Appraisal Tool (MMAT 2018) yielded compliance scores ranging from 75% to 95% (M = 84.5%). Systematic reviews within the corpus confirm that early childhood education (ages 3-8) accounts for a minor fraction of global instructional model evaluations compared to secondary education levels (Alvita et al., 2026; Wan et al., 2021; Misirli & Komis, 2023). For studies examining broader age bands, synthesis focuses strictly on primary-level sub-data and foundational competencies to preserve SPIDER eligibility criteria. The complete sy nthesis of study-level metadata, geographical distributions, research designs, MMAT appraisal scores, and core trends across all twenty included papers is presented in, European jurisdictions (n = 6), North America (n = 4), Africa (n = 1), Australia (n = 1), and South America (n = 1), confirming Table 1.

Table 1
Master Empirical Corpus Matrix (N = 20)

Study ID	Author(s) & Year	Country Context	Design & Sample	Primary RQ Alignment	MMAT Score (%)	Core Empirical Focus & Key Variables
Study 01	Bourha., et al (2026)	Greece	Qualitative observational design; N = 37 children aged 3-4 across 4 ECEC settings	RQ2	90%	Play-based STEM using Technology-Enhanced Toys (Bee-Bot, Coko robot); examines problem-solving, computational thinking, and peer collaboration.
Study 02	Reuter & Leuchter (2022)	Germany	Quantitative task analysis & observational study; N = 41 kindergarten children aged 4-7	RQ2	85%	Gear engineering task; measures goal awareness, self-evaluation, spatial skills, task persistence, testing, and design optimization.
Study 03	Levinson., et al (2024)	United States & Argentina	Sequential mixed-methods RCT design; N = 35 teachers and kindergarten students aged 5–6	RQ1, RQ2	90%	Coding as Another Language ScratchJr curriculum; compares Discrete Beliefs versus Integrated Beliefs teachers regarding student coding gains ($\beta = 1.81, p < 0.05$) and computational thinking.
Study 04	Ata-Aktürk & Demircan (2019)	Turkey	Design-Based Research across 3 prototyping cycles; N = 20 children aged 4–5, 20 parents, 2 teachers	RQ2, RQ3	95%	Development of a STEM Engineering Design Curriculum for Parental Involvement (EDCPI); measures parental scaffolding, EDP stages, and home-school educational continuity.
Study 05	Li., et al (2024)	China (Hong Kong)	Arts-Based Educational Research; N = 12 talented children aged 6–11 (primary sub-sample analyzed)	RQ2, RQ3	80%	Arts-integrated STEAM through pop-up storybooks; evaluates seven computational thinking concepts including algorithms, modularity, control structures, and debugging.

Study 06	Leung (2023)	China (Hong Kong)	Sequential qualitative interview design; N = 24 kindergarten teachers	RQ2	85%	Teacher pedagogical strategy shifts; evaluates composite cooperative approaches versus traditional instruction and identifies professional development needs.
Study 07	Yuan., et al (2022)	United States	Qualitative verbal protocol analysis; N = 12 preservice elementary teachers	RQ2, RQ3	80%	Collaborative educational robotics project; analyzes design discourse, idea generation, evaluation, and the absence of modeling and feasibility analysis.
Study 08	Putra., et al (2025)	Indonesia	Mixed-methods investigation; N = 68 primary/junior pupils (early inquiry tools sub-data)	RQ2	85%	Implementation of Engineering Design Process (EDP) tools; measures progression in scientific communication skills, technical expression, and academic literacy.
Study 09	Alvita., et al (2026)	Indonesia / Global Corpus	Systematic Literature Review using PRISMA 2020; N = 282 empirical articles (2020–2026)	RQ1	90%	Global trends in Problem-Based Learning and Project-Based Learning; documents geographical imbalances and level-specific underrepresentation in early childhood education.
Study 10	Deniz., et al (2021)	United States	Qualitative classroom design study; primary elementary students (Grades 3–5) & 2 teachers	RQ2	80%	Explicit-reflective Nature of Engineering (NOE) instruction using children's picture books during soda can crusher design challenges.
Study 11	Risnawati (2025)	Indonesia	Qualitative classroom action research; N = 20 kindergarten children aged 5–6	RQ2	80%	Engineering Design Process (EDP) integration into project-based learning within an Islamic kindergarten; evaluates critical thinking, problem definition, and spiritual-cognitive alignment.
Study 12	Nyaaba., et al (2024)	Ghana	Critical discourse analysis & allegory case study; early primary educators & policy stakeholders	RQ1, RQ3	75%	Early STEAM foundation reform; analyzes structural barriers, gender stereotype dismantling, and resource equity in primary education.
Study 13	Kapoor (2023)	International Context	Qualitative synthesis & observational design; 25 early childhood classrooms	RQ2	80%	Integration of STEM with loose-parts play and Conceptual PlayWorld models; examines teacher facilitation and 21st-century skill acquisition.
Study 14	Kewalramani, Devi, & Ng (2025)	Australia	Qualitative multi-case study; N = 11 early childhood preservice teachers	RQ2, RQ3	85%	STEM pedagogical content knowledge (PCK) development, mentoring, play-based placement integration, and reduction of science teaching anxiety.
Study 15	Martino., et al (2025)	Global Corpus	PRISMA 2020 systematic evidence synthesis; N = 25 empirical studies (2022–2026)	RQ1, RQ3	90%	Generative AI integration in pre-service teacher training; identifies prompt-assisted lesson design, technological agency, and evaluative vigilance gaps.
Study 16	Gavrilas & Kotsis (2025)	Greece / Global Context	Systematic integrative review; N = 45 empirical studies (2010–2025)	RQ2	85%	Eight core STEM teaching practices including scaffolding inquiry and equity; evaluates teacher role transition from instructor to facilitator.
Study 17	RAND Corporation (2016)	United States	Empirical policy analysis & observational benchmark; 50 early childhood centers	RQ1, RQ3	80%	Infrastructure and training barriers in early childhood STEM; addresses socioeconomic disparities, educator wage gaps, and literacy-STEM alignment.
Study 18	Wan., et al (2021)	Global Context	Systematic review of empirical literature; N = 62 peer-reviewed articles	RQ1, RQ2	85%	Mapping empirical early childhood STEM literature; categorizes child learning outcomes, pedagogical frameworks, and methodological limitations.
Study 19	Hurme., et al (2026)	Finland	Qualitative case analysis; pre-service early childhood education teachers during play sessions	RQ2, RQ3	85%	Professional vision of early childhood pre-service teachers; analyzes enacted and unaddressed pedagogical opportunities during play-based STEM sessions.
Study 20	Ribarić & Novoselić, 2025	Croatia	Quasi-experimental longitudinal design; N = 650 primary school	RQ1, RQ2	85%	STEM inquiry-based intervention; evaluates longitudinal STEM interest trends ($F(2,1278) =$

	students aged 10 across 5 schools	$73.65, p < 0.001$) and gender parity.

Note. Corpus matrix summarizing metadata, methodology, and MMAT quality appraisal

3.2. Typology of Early Childhood STEM Practices (RQ2)

Synthesis of reported instructional practices across the N = 20 corpus identifies four core pedagogical frameworks in early childhood settings (ages 3-8): (1) simplified Engineering Design Process (EDP) cycles (think, try, fix, share), (2) play-based and inquiry-driven STEM, (3) unplugged computational thinking, and (4) narrative and picture book scaffolding (Ata-Aktürk & Demircan, 2019; Bourha et al., 2026; Deniz et al., 2021; Li et al., 2024; Reuter & Leuchter, 2022). Learning environments deploy screen-free tangible robotics (Bee-Bot, Coko, KIBO), Technology-Enhanced Toys (TETs), pop-up storybooks, and nature-based loose parts (Bourha et al., 2026; Levinson et al., 2024; Li et al., 2024). Operational mechanics vary by age group: while 3- to 4-year-old children demonstrate emergent problem-solving and peer collaboration during unstructured play (Bourha et al., 2026), 5- to 6-year-old children engaged in gear engineering tasks require direct teacher questioning to execute systematic testing and design optimization (Reuter & Leuchter, 2022). Regarding teacher scaffolding, Discrete Beliefs (DB) educators who separated play from formal lessons achieved higher post-curriculum student coding scores (β=1.81, $p<0.05$) due to strict lesson completion, whereas Integrated Beliefs (IB) educators allocated time to open-ended exploration that limited curriculum coverage without reducing overall computational thinking gains ($p > 0.10$; Levinson et al., 2024). Longitudinal inquiry-based interventions yielded sustained increases in primary student STEM interest ($F(2, 1278) = 73.65$, $p < 0.001$; Ribarić & Novoselić, 2025). The structured typology of pedagogical frameworks, tools, age-based mechanics, and scaffolding behaviors is detailed in **Table 2**.

Table 2
Typology of Early Childhood STEM Practices

Practice Dimension	Ages 3-4 (Toddler / Early Preschool)	Ages 5-6 (Kindergarten / Early Primary)	Teacher Scaffolding & Role Dynamics
Pedagogical Frameworks	Play-based inquiry, open-ended exploration, sensory discovery, and emergent problem-solving (Bourha et al., 2026).	Simplified EDP cycles (think, try, fix, share), project-based learning, and explicit Nature of Engineering instruction (Ata-Aktürk & Demircan, 2019; Deniz et al., 2021).	Transition from traditional knowledge transmitter to inquiry co-investigator and facilitator (Gavrilas & Kotsis, 2025; Leung, 2023).
Technology Tools & Environments	Screen-free Technology-Enhanced Toys (Bee-Bot, Coko robot), physical blocks, and loose parts (Bourha et al., 2026; Kapoor, 2023).	Tangible robotics (KIBO), ScratchJr block coding, gear manipulation, pop-up storybooks, and Augmented Reality (Levinson et al., 2024; Li et al., 2024; Reuter & Leuchter, 2022).	Scaffolding boundary management; providing explicit questioning during testing and optimizing phases to prevent satisfaction with non-functional prototypes (Reuter & Leuchter, 2022).
Cognitive & Behavioral Focus	Basic cause-and-effect reasoning, spatial manipulation, emergent social interaction, and peer collaboration (Bourha et al., 2026).	Algorithmic logic, sequencing, debugging, modularity, goal awareness, task persistence, and technical communication (Li et al., 2024; Putra et al., 2025).	Belief system alignment; Discrete Beliefs teachers drive technical content mastery ($\beta = 1.81, p < 0.05$), while Integrated Beliefs teachers foster open exploration (Levinson et al., 2024).

Note. Synthesis of early childhood STEM practices comparing pedagogical frameworks, technology tools and learning environments, age-based learning mechanics, cognitive and behavioral focuses, and teacher scaffolding across ages 3–4 and 5–6.

3.3. Emerging Horizons and Empirical Literature Gaps (RQ3)

Synthesizing emerging trajectories across the corpus reveals three key research horizons: (1) STEM-based Engineering Design Curricula for Parental Involvement (EDCPI) that enhance home-school educational continuity (Ata-Aktürk & Demircan, 2019), (2) prompt-assisted Generative AI

lesson design among preservice educators (Martino et al., 2025), and (3) inclusive eco-STEAM initiatives that address early gender stereotypes and environmental sustainability (Kapoor, 2023; Nyaaba et al., 2024). Conversely, the corpus highlights three persistent empirical gaps: (1) a lack of multi-year longitudinal tracking to evaluate the retention of early engineering habits of mind (RAND Corporation, 2016; Wan et al., 2021), (2) an over-reliance on adult-directed verbal assessments that fail to capture non-verbal problem-solving in children under age 5 (Wan et al., 2021), and (3) widespread teacher content anxiety and limited Pedagogical Content Knowledge (PCK) regarding physical science principles (Kewalramani et al., 2025; Leung, 2023). A categorized breakdown of emerging thematic horizons, systemic barriers, and research gaps is presented in **Table 3**.

Table 3
Emerging Horizons, Literature Gaps, and Systemic Barriers

Analytical Dimension	Synthesized Corpus Findings	Representative Source Evidence
Emerging Horizons	Structured parent-training models (EDCPI) that extend engineering design activities into home learning ecologies; Integration of Generative AI for prompt-assisted lesson design and digital manipulative authoring among preservice teachers; Inclusive, nature-based eco-STEAM initiatives designed to dismantle early gender stereotypes and promote environmental agency.	Ata-Aktürk & Demircan (2019); Martino et al. (2025); Kapoor (2023); Nyaaba et al. (2024)
Methodological & Empirical Gaps	Dominance of short-term intervention windows lacking multi-year longitudinal tracking of cognitive retention; Over-reliance on adult-directed, verbal assessment instruments unsuited for children under age 5; Severe geographical underrepresentation of ECE data in global bibliographic databases compared to secondary education.	RAND Corporation (2016); Wan et al. (2021); Alvita et al. (2026)
Systemic & Workforce Barriers	Teacher physical science content anxiety and limited Pedagogical Content Knowledge (PCK) in engineering design; Misalignment between commercial, market-driven STEM packages and developmental ECE curriculum standards; Institutional infrastructure constraints, low educator compensation, and administrative prioritization of basic literacy over STEM.	Kewalramani et al. (2025); Leung (2023); RAND Corporation (2016)

Note. Matrix mapping emerging research horizons, methodological and empirical gaps, and systemic and workforce barriers identified across the synthesized literature on early childhood STEM education.

4. Discussion

The empirical findings synthesized in this review illustrate the underlying sociocultural and cognitive mechanisms that determine the success of early childhood STEM instruction. The effectiveness of simplified Engineering Design Process (EDP) cycles, tangible educational robotics, and storybook-integrated engineering can be understood through Vygotsky's sociocultural learning theory and Papert's constructionist framework. Children construct scientific understandings through mediated social interaction and the physical manipulation of concrete artifacts. In early preschool settings (ages 3-4), open-ended play with screen-free Technology-Enhanced Toys functions as a social mediator, enabling toddlers to observe cause-and-effect relationships and engage in collaborative problem-solving without direct adult instruction (Bourha et al., 2026). However, an explicit cognitive boundary emerges between ages 3-4 and 5-6 regarding testing and optimization. While older kindergarten children (ages 5-6) demonstrate heightened goal awareness and independently construct physical prototypes, they frequently exhibit a cognitive limitation characterized by premature satisfaction with non-functional designs, rarely executing systematic failure analysis or iterative design adjustments without targeted teacher questioning (Reuter & Leuchter, 2022). Narrative scaffolding and picture book authoring address this developmental gap by embedding abstract physical science concepts and engineering constraints within human-centered story structures, providing the contextual scaffolding necessary for children to practice algorithmic sequencing, modularity, and debugging (Deniz et al., 2021; Li et al., 2024).

The operational friction observed across classroom implementations originates from an interplay between teacher pedagogical content knowledge (PCK), subject-matter confidence, and underlying pedagogical belief structures. Early childhood educators frequently report physical science content anxiety, which leads to pedagogical hesitation or over-reliance on rigid, direct-instruction methods (Kewalramani et al., 2025; Leung, 2023). The divergence between Discrete Beliefs (DB) and Integrated Beliefs (IB) teachers illuminates how pedagogical philosophies shape curricular implementation in computer science and engineering contexts. Educators holding discrete beliefs maintain a formal boundary between play and academic instruction, ensuring complete curriculum delivery that drives higher technical skill acquisition, such as post-curriculum coding gains ($\beta = 1.81, p < 0.05$; Levinson et al., 2024). Conversely, educators holding integrated beliefs view play and academic learning as deeply intertwined, prioritizing open-ended student exploration at the expense of lesson completion, which limits technical coverage while preserving overall computational thinking gains ($p > 0.10$; Levinson et al., 2024; Hurme et al., 2026). Furthermore, comparative analysis highlights a structural contrast between resource-rich and resource-constrained learning environments. Commercial STEM kits utilized in high-resource settings often induce curricular fragmentation because proprietary hardware emphasizes isolated technological tricks rather than continuous scientific inquiry (Leung, 2023; RAND Corporation, 2016). In contrast, empirical evidence from emerging educational settings demonstrates that low-cost loose parts, recyclable materials, and nature-based play yield equivalent or superior problem-solving engagement when guided by intentional EDP structuring (Ata-Aktürk & Demircan, 2019; Kapoor, 2023; Nyaaba et al., 2024). This confirms that instructional quality depends primarily on pedagogical scaffolding rather than expensive technology hardware.

Translating these synthesized findings into actionable policy frameworks requires addressing the dynamics of reciprocal policy borrowing and curricular misalignment. Educational policy initiatives frequently adopt Western or commercial STEM frameworks without adapting them to local early learning ecologies, resulting in administrative overload and fragmented classroom enactment (Nyaaba et al., 2024; RAND Corporation, 2016). To build sustainable early STEM infrastructure, policy makers and teacher education programs must implement two evidence-based workforce development models. First, preservice teacher education must incorporate prompt-assisted Generative AI literacy, enabling candidate teachers to design customized instructional manipulatives and differentiated learning activities while cultivating the critical evaluative vigilance required to detect AI-generated factual errors (Martino et al., 2025). Second, educational systems must formalize parental involvement structures, such as the Engineering Design Curriculum for Parental Involvement (EDCPI) framework, which trains parents to scaffold engineering design challenges within home environments (Ata-Aktürk & Demircan, 2019). Systematically engaging families bridges the gap between home and school learning ecologies, reduces intrusive adult over-intervention, and sustains child interest in scientific fields across early primary education (Ata-Aktürk & Demircan, 2019; Ribarić & Novoselić, 2025).

This systematic literature review is subject to methodological limitations inherent to the secondary synthesis of published literature. The review focused exclusively on peer-reviewed, English-language empirical studies indexed across major bibliographic databases, potentially omitting relevant gray literature, policy briefs in non-English languages, and localized community practices (Alvita et al., 2026; Wan et al., 2021). Additionally, the synthesized corpus relies heavily on short-term intervention windows and single-session observational tasks, restricting the ability to make definitive claims regarding the long-term cognitive retention of early engineering habits of mind (RAND Corporation, 2016; Wan et al., 2021). To address these limitations, a future research agenda must prioritize three methodological directions. First, researchers must establish multi-year longitudinal designs that track children from preschool through upper primary grades to measure the sustained impact of early STEM experiences on problem-solving persistence, spatial reasoning, and academic trajectories (Ribarić & Novoselić, 2025; RAND Corporation, 2016). Second, the field requires the development and

psychometric validation of non-verbal, task-based observational assessment instruments capable of evaluating emergent computational thinking and failure analysis in children under age 5 without confounding cognitive performance with verbal fluency (Wan et al., 2021). Third, empirical research must expand into Global South and socioeconomically disadvantaged contexts to address global evidence asymmetries and establish contextually grounded early childhood STEM models (Alvita et al., 2026; Nyaaba et al., 2024).

5. Conclusion

This systematic literature review synthesizes the empirical evidence base (N = 20) to map global trends, pedagogical typologies, and emerging research horizons in early childhood STEM education across ages 3 to 8 years. In response to RQ1, the evidence demonstrates an expansion of integrated STEM scholarship between 2016 and 2026, accompanied by significant geographical disparities marked by a concentration of empirical studies in Asian and European research hubs and a pronounced underrepresentation of early learning contexts in global bibliographic databases. Answering RQ2, the review establishes that early childhood STEM instruction evolves along a developmental continuum, transitioning from open-ended, play-based inquiry supported by screen-free technology-enhanced toys in toddler settings to structured Engineering Design Process (EDP) cycles, tangible robotics, and storybook-integrated engineering in kindergarten classrooms. Crucially, while young children demonstrate emergent problem-solving and prototype construction capabilities, teacher scaffolding boundaries define the transition from superficial trial-and-error to systematic testing and design optimization. Addressing RQ3, emerging trajectories emphasize parent-led scaffolding frameworks, pre-service Generative AI prompt literacy, and nature-based eco-STEAM initiatives, while persistent empirical gaps highlight a reliance on short-term intervention windows and adult-directed verbal assessment instruments.

The theoretical and practical significance of this review lies in its multi-layered synthesis pipeline, which bridges fragmented disciplinary sub-fields into a unified, source-locked taxonomy of early STEM instruction grounded in constructionist and sociocultural learning theories. By demonstrating that effective early childhood STEM education depends primarily on intentional pedagogical structuring rather than expensive commercial technology hardware, this study offers a framework for reciprocal educational policy borrowing, particularly within resource-constrained learning ecologies. To realize sustainable and equitable early childhood STEM learning environments, future educational policy reforms and research initiatives must prioritize multi-year longitudinal tracking, validate non-verbal observational assessment tools for pre-literate children, and expand contextually grounded empirical evaluations across Global South contexts.

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