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Transforming Early Childhood Science Learning in the 21st Century: A Systematic Review of Developmentally Appropriate Instructional Strategies

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Abstract

The demands of 21st-century education require early childhood science learning to move beyond content exposure toward the development of curiosity, early scientific literacy, creativity, and problem-solving dispositions. Science learning in early childhood education (ECE) plays a foundational role in shaping children's attitudes toward learning and their readiness to engage in scientific practices in later stages of schooling. This conceptual review synthesizes and compares international research on instructional strategies for early childhood science education that align with 21st-century learning principles. Using a qualitative systematic literature review approach, this study analyzes peer- reviewed international journal articles published between 2015 and 2025. The review focuses on developmentally appropriate instructional strategies, including play-based guided inquiry, early STEM activities, scientific talk and explanation, concrete model-based exploration, and foundational computational thinking. The findings indicate that effective early childhood science learning is characterized by guided exploration, authentic contexts, social interaction, explicit scaffolding of early scientific practices, and purposeful but limited technology integration. Comparative analysis reveals that no single instructional strategy independently addresses all dimensions of early scientific literacy. Instead, integrated use of multiple strategies yields the most robust outcomes when aligned with children's developmental needs and learning contexts. The study provides pedagogical implications and practical recommendations for early childhood educators, curriculum developers, and policymakers seeking to strengthen science learning in the 21st century.

Keywords: 21st-Century Skills; Early Scientific Literacy; Inquiry-Based Learning; Science Learning; STEM In Early Childhood

Introduction

Early Childhood Education (ECE) plays a foundational role in shaping children's cognitive, social, emotional, and epistemic development. During this critical period, learning is not oriented toward the mastery of formal academic content, but toward the cultivation of curiosity, exploration, communication, and meaning-making through interaction with the physical and social environment. In the 21st century, rapid developments in science, technology, and society have significantly reshaped expectations for education, including science learning in early childhood contexts (OECD, 2019).

Science education in early childhood is increasingly recognized as essential for fostering early scientific literacy. Early scientific literacy refers to children's emerging abilities to observe phenomena, ask questions, recognize patterns, construct simple explanations, and engage meaningfully with their environment (National Research Council (NRC), 2012). Research consistently demonstrates that early experiences with science influence children's long-term attitudes toward learning, their confidence in engaging with scientific ideas, and their readiness for later formal science instruction (Osborne et al., 2016). Consequently, the quality of instructional strategies used in early childhood science learning has long-term implications for educational trajectories.

Contemporary early childhood learners are growing up in an increasingly complex and digitally mediated world. Many young children today are exposed to digital technologies, visual media, and interactive platforms from an early age, shaping how they perceive, process, and engage with information (Chardonnens, 2025). These conditions have prompted educators and researchers to reconsider how instructional strategies should be designed to remain developmentally appropriate while responding to 21st-century learning demands. Importantly, early exposure to technology does not imply readiness for formal or abstract scientific reasoning. Instead, it highlights the need for carefully mediated learning environments that balance exploration, play, and guided inquiry.

International educational frameworks emphasize the importance of foundational competencies in early learning. The OECD Learning Compass 2030 highlights curiosity, agency, creativity, and responsibility as essential dispositions that should be nurtured from an early age (OECD, 2019). Similarly, the Framework for K–12 Science Education positions scientific practices such as asking questions, developing models, and constructing explanations as central to science learning across the lifespan, including early childhood when adapted to developmental levels (NRC, 2012). These perspectives underscore the need for instructional strategies that actively engage children in scientific practices rather than passive exposure to information.

Play-based learning has long been established as the pedagogical foundation of early childhood education. Through play, children actively explore their environment, manipulate objects, negotiate meaning with peers, and develop language and reasoning skills (Hmelo-Silver et al., 2007). In science learning, play-based inquiry allows children to investigate natural phenomena through hands-on experiences that align with their cognitive and socio-emotional development. Research indicates that inquiry-oriented approaches enhance engagement and conceptual understanding when supported by appropriate scaffolding and adult guidance (Urdanivia Alarcon et al., 2023).

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In parallel, early STEM education has gained increasing attention in international research and policy discourse. STEM in early childhood does not involve formal disciplinary instruction, but rather integrated, play-based experiences that encourage problem-solving, creativity, and collaboration (English, 2016). Activities such as building structures, sorting objects, observing changes, and designing simple solutions provide meaningful contexts for early science learning. Meta- analytic and review studies suggest that developmentally appropriate STEM experiences support motivation and foundational cognitive skills when learning goals are clearly defined (Kwon & Lee, 2025).

Another important dimension of early childhood science learning is the development of scientific talk and explanation. Although formal scientific argumentation may be developmentally inappropriate, research demonstrates that young children are capable of explaining observations, comparing ideas, and justifying simple claims when supported through dialogic interaction (Berland & McNeill, 2010; Jin, 2022). These early explanatory practices form the foundation for later scientific reasoning and epistemic understanding, highlighting the importance of classroom discourse in early science learning.

Model-based exploration further supports children's conceptual development by encouraging them to represent phenomena through drawings, physical constructions, gestures, and simple simulations. Models function as cognitive tools that help children connect concrete observations with emerging explanations (Schwarz et al., 2009). Despite the growing consensus on the value of early STEM and inquiry-based learning, the field faces significant conceptual and empirical tensions that complicate its implementation. A primary problem lies in the conflicting results between studies regarding the actual efficacy of these interventions; while some research highlights substantial cognitive gains, others suggest that without highly specialized teacher training, such approaches fail to produce measurable improvements in scientific reasoning. Furthermore, the limitations of the STEM approach in early childhood are increasingly evident, as the push for integrated "disciplinary" thinking can inadvertently overshadow the holistic, play-based nature of ECE, potentially imposing rigid structures on a developmental stage that requires fluid exploration. This issue is compounded by a frequent over-generalization of global findings, where frameworks developed in Western, high-resource contexts are applied as universal solutions without accounting for the cultural, linguistic, and material realities of diverse educational settings. Consequently, the challenge is not merely identifying "what works," but addressing the misalignment between idealized global STEM models and the practical, pedagogical limits of early childhood environments.

More recently, the integration of computational thinking (CT) into early childhood science education has emerged as an area of growing interest. Computational thinking in early childhood does not involve programming or coding, but rather foundational practices such as sequencing, pattern recognition, decomposition, and logical reasoning (Wing, 2006). Research indicates that CT can be meaningfully embedded in early science activities through unplugged tasks and representational work that align with children's developmental levels (Arık & Topçu, 2022; Yang et al., 2024).

Despite the growing body of international research on early childhood science learning, the literature remains fragmented. Many studies focus on a single instructional strategy without examining how multiple approaches can be combined coherently. Furthermore, some instructional strategies are adapted from elementary contexts without sufficient consideration of developmental appropriateness in early childhood settings. These gaps highlight the need for integrative reviews that synthesize international research on instructional strategies for early childhood science learning within a 21st-century framework.

Addressing these gaps, the present study conducts a comparative conceptual review of international research on instructional strategies for early childhood science education. The purpose of this study is threefold: (1) to identify dominant instructional strategies highlighted in recent international research; (2) to examine how these strategies support early scientific literacy and 21st-century competencies; and (3) to synthesize implementation considerations for developmentally appropriate science learning in ECE.

By providing a comprehensive synthesis of international research, this study aims to contribute to the ongoing discourse on early childhood science education reform. The findings are expected to inform educators, curriculum developers, and policymakers seeking to design science learning environments that are engaging, equitable, and responsive to the demands of the 21st century while remaining firmly grounded in early childhood pedagogical principles.

Method

This study employed a qualitative systematic literature review design to synthesize and compare international research on instructional strategies for early childhood science education aligned with 21st-century learning demands. A systematic review approach was selected to ensure methodological rigor, transparency, and replicability in identifying, analyzing, and synthesizing relevant studies (Boote & Beile, 2005; Snyder, 2019). Given the conceptual nature of the study, the review focused on identifying dominant instructional patterns, pedagogical rationales, and implementation considerations rather than conducting statistical meta-analysis.

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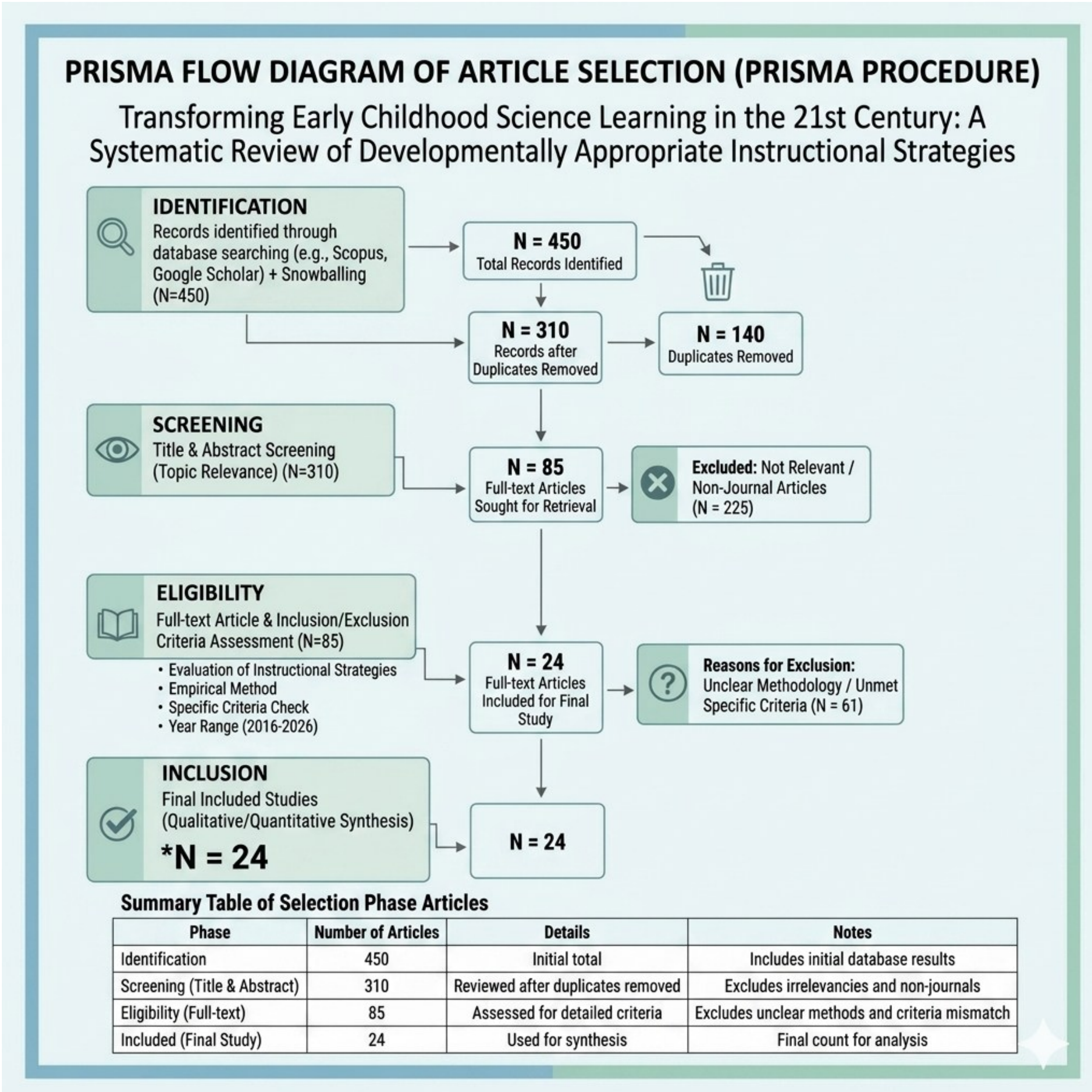

Phase	Number of Articles	Details	Notes
Identification	450	Initial total	Includes initial database results
Screening (Title & Abstract)	310	Reviewed after duplicates removed	Excludes irrelevancies and non-journals
Eligibility (Full-text)	85	Assessed for detailed criteria	Excludes unclear methods and criteria mismatch
Included (Final Study)	24	Used for synthesis	Final count for analysis

Figure 1. Prisma Procedure

Peer-reviewed journal articles were retrieved from major international academic databases, including Scopus, Web of Science, ERIC, ScienceDirect, and Google Scholar. These databases were selected to ensure broad coverage of high-quality research in early childhood education, science education, and educational technology.

The search process was conducted using combinations of keywords related to early childhood science learning and instructional strategies. Core search terms included early childhood science education, early scientific literacy, inquiry-based learning, play-based learning, STEM in early childhood, scientific explanation, model-based inquiry, and computational thinking. Boolean operators (AND/OR) were used to refine searches and capture studies addressing multiple instructional dimensions. Reference lists of relevant review articles were also examined to identify additional studies not captured through database searches.

To ensure relevance and quality, studies were selected based on the following inclusion criteria: 1) published between 2015 and 2025, reflecting contemporary research and policy contexts; 2) focused on early childhood education or primary-level contexts with clear conceptual transferability to PAUD/ECE; 3) examined instructional strategies related to science learning, early scientific literacy, or 21st-century competencies; and 4) reported empirical findings, systematic reviews, or meta-analyses published in peer-reviewed journals.

Studies were excluded if they: 1) focused exclusively on secondary or higher education without developmental relevance to early childhood; 2) addressed science learning solely as content transmission without pedagogical analysis; or 3) lacked sufficient methodological transparency.

The selected studies were analyzed using thematic coding and comparative synthesis. Each article was coded according to: 1) instructional strategy (e.g., play-based inquiry, STEM activities, modeling, scientific talk, computational thinking); 2) pedagogical rationale and theoretical grounding; 3) targeted learning outcomes related to early scientific literacy and 21st-century competencies; and (4) reported implementation conditions, including teacher scaffolding, learning context, and developmental considerations. The analysis process involved iterative reading and comparison across studies to identify recurring themes, convergent findings, and points of divergence. Rather than treating instructional strategies as isolated methods, the synthesis emphasized how different approaches interact and complement one another in early childhood contexts.

To guide synthesis, an analytical framework was developed that positioned play- based guided inquiry as the foundational pedagogical approach, with early STEM activities, scientific talk and explanation, model-based exploration, and foundational computational thinking functioning as complementary practices. This framework enabled systematic comparison across studies and supported the identification of best-practice principles for developmentally appropriate early childhood science learning.

To enhance trustworthiness, the review followed transparent selection procedures and relied on peer-reviewed sources. However, as a conceptual systematic review, the study does not provide effect-size estimates or causal claims. Additionally, while the review prioritizes early childhood contexts, some findings are drawn from elementary-level studies with clear developmental relevance. These limitations are acknowledged and addressed through careful interpretation of results.

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Results

The systematic literature review revealed a consistent pattern of instructional strategies emphasized in international research on early childhood science education aligned with 21st-century learning demands. Across the reviewed studies published between 2016 and 2026, five major instructional approaches repeatedly emerged as dominant and developmentally appropriate for early childhood contexts: play-based guided inquiry, early STEM activities, scientific talk and explanation, concrete model-based exploration, and foundational computational thinking.

These strategies were examined across diverse geographical contexts, including North America, Europe, and Asia-Pacific regions, indicating their broad applicability. Although the studies varied in research design and learning context, a high level of convergence was observed regarding the pedagogical principles underlying effective early childhood science learning.

Overall, the reviewed literature consistently reported positive outcomes related to children's engagement, curiosity, early scientific literacy, and learning dispositions when these instructional strategies were implemented with appropriate scaffolding and alignment to developmental needs. However, the findings also indicated that effectiveness was strongly mediated by instructional design quality, teacher facilitation, and contextual readiness, rather than by the instructional strategy alone.

Dominant Instructional Strategies and Learning Outcomes

Play-based guided inquiry emerged as the most frequently cited foundational strategy. Studies consistently highlighted that inquiry in early childhood is most effective when embedded in play and supported by adult guidance. Children engaged in guided inquiry demonstrated higher levels of curiosity, sustained attention, and ability to make simple observations and explanations. Inquiry activities that were overly open or lacked scaffolding were reported to result in unfocused exploration.

Early STEM activities, often implemented through design-based play and simple problem-solving tasks, were found to support creativity, collaboration, and early problem-solving skills. The reviewed studies emphasized that STEM in early childhood should prioritize process over product, with learning goals centered on exploration and experimentation rather than completed artifacts.

Scientific talk and explanation represented another critical instructional dimension. While formal scientific argumentation is not developmentally appropriate for young children, the literature consistently demonstrated that children can engage in meaningful explanation, comparison, and justification when supported through dialogic interaction. These practices were found to contribute to early epistemic awareness and language development.

Concrete model-based exploration was frequently reported as effective in supporting conceptual coherence. Through drawings, physical constructions, gestures, and simple representations, children were able to externalize their thinking and revise their ideas based on experience. Studies emphasized that modeling should be iterative and grounded in concrete experiences.

Finally, foundational computational thinking (CT) emerged as an emerging but increasingly prominent instructional approach. CT in early childhood was conceptualized as pattern recognition, sequencing, decomposition, and logical reasoning embedded within play and inquiry. The reviewed studies suggested that CT enhances structured thinking and problem-solving when integrated naturally into science activities.

Table 1. Comparative Summary of Instructional Strategies for Early Childhood Science Learning

Instructional Strategy	Core Pedagogical Focus	Targeted Early Scientific Competencies	Reported Learning Outcomes	Key Implementation Considerations
Play-Based Guided Inquiry	Exploration through play with adult scaffolding	Curiosity, observation, questioning	Increased engagement and early inquiry habits	Structured guidance, open-ended prompts
Early STEM Activities	Integrated problem-solving through play	Creativity, collaboration, experimentation	Improved motivation and applied understanding	Process-focused design, clear learning goals
Scientific Talk & Explanation	Dialogic interaction and meaning-making	Explanation, comparison, justification	Enhanced language and epistemic awareness	Teacher facilitation, supportive discourse
Concrete Model-Based Exploration	Representation of phenomena through models	Conceptual coherence, systems awareness	Deeper understanding and idea revision	Iterative modeling, connection to experience
Foundational Computational Thinking	Patterning and logical reasoning in context	Structured thinking, problem-solving	Improved reasoning and engagement	Developmentally appropriate, often unplugged

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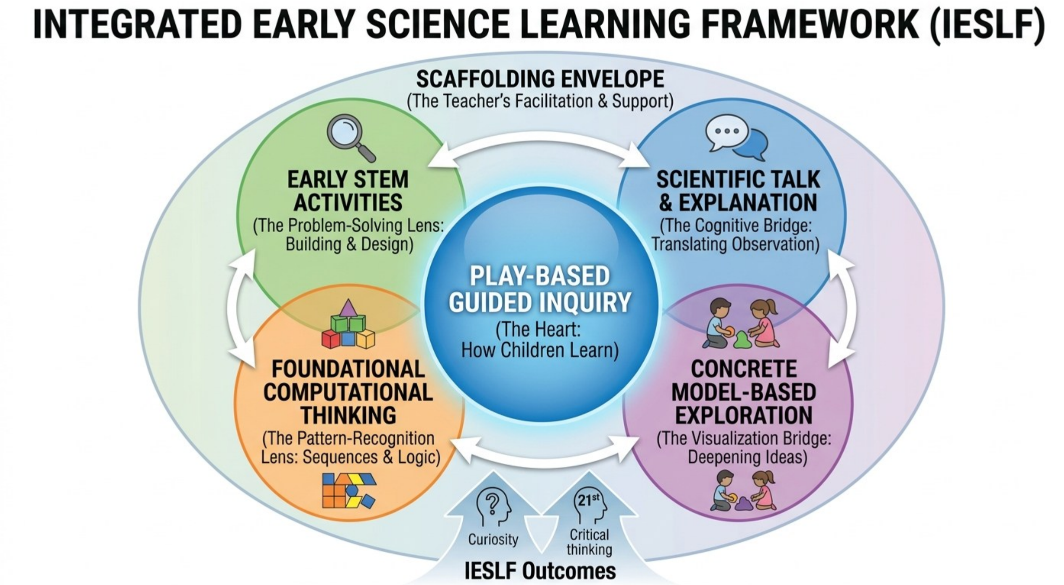

Figure 1. IESLF Model

To address the current theoretical gap, this study proposes the Integrated Early Science Learning Framework (IESLF), a novel conceptual model that synthesizes the five identified pillars into a cohesive pedagogical ecosystem. Rather than viewing these strategies as independent tools, the IESLF positions Play-Based Guided Inquiry as the central nucleus, serving as the primary vehicle through which all other scientific practices are mobilized. Within this framework, Scientific Talk and Concrete Modeling act as the internal cognitive bridges that allow children to articulate and visualize their explorations, while Early STEM and Foundational Computational Thinking provide the structured problem-solving lenses and logical patterns necessary for 21st-century literacy. The IESLF illustrates that these five dimensions are mutually reinforcing: for instance, computational patterning enhances the precision of modeling, while dialogic talk refines the inquiry process. By mapping these interconnections, the framework provides a unified theoretical roadmap for educators to design holistic learning environments where curiosity is systematically transformed into foundational scientific understanding through high-quality teacher scaffolding.

Discussion

The findings of this systematic review reinforce a growing international consensus that effective early childhood science learning in the 21st century requires a developmentally appropriate pedagogical alignment, rather than early academic acceleration. The dominance of play-based guided inquiry, early STEM activities, scientific talk, model-based exploration, and foundational computational thinking reflects a shift toward viewing science learning in early childhood as a process of meaning-making, exploration, and disposition building, rather than formal concept mastery.

First, the prominence of play-based guided inquiry as the foundational instructional strategy aligns strongly with constructivist and socio-cultural theories of learning. Young children learn science most effectively when they are actively engaged in exploration and supported through adult scaffolding that guides attention, questioning, and reflection. This finding is consistent with prior research emphasizing that inquiry in early childhood must be structured and mediated to prevent unfocused exploration and cognitive overload. The results extend earlier inquiry research by demonstrating that inquiry remains central in early childhood contexts when embedded within play rather than treated as a simplified version of inquiry at higher educational levels.

Second, the increasing emphasis on early STEM activities highlights the importance of interdisciplinary and authentic learning experiences in early childhood science education. The reviewed studies suggest that STEM in ECE supports creativity, collaboration, and problem-solving when activities are designed around processes rather than products. This finding addresses concerns in the literature that project-based approaches may dilute scientific content. In early childhood contexts, the value of STEM lies not in producing sophisticated artifacts but in engaging children in exploration, experimentation, and collaborative thinking within meaningful contexts.

Third, the consistent appearance of scientific talk and explanation underscores the epistemic dimension of early science learning. Although formal scientific argumentation is developmentally inappropriate, young children are capable of explaining observations, comparing ideas, and justifying simple claims when supported through dialogic interaction. These practices foster early epistemic awareness and language development, positioning science learning as a social and communicative activity. This finding supports contemporary perspectives that view early scientific literacy as rooted in discourse and shared meaning-making rather than individual cognitive performance alone.

Fourth, the effectiveness of concrete model-based exploration reinforces the role of representation in early childhood learning. Models such as drawings, physical constructions, and gestures function as cognitive tools that help children externalize and revise their thinking. The reviewed studies emphasize that modeling should be iterative and closely connected to direct experience. This finding aligns with research

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positioning modeling as a core scientific practice that supports conceptual coherence and systems thinking, even at early developmental stages.

Finally, the emergence of foundational computational thinking (CT) as an instructional strategy reflects evolving understandings of 21st-century competencies in early childhood education. Importantly, the reviewed literature conceptualizes CT not as coding or programming, but as pattern recognition, sequencing, and logical reasoning embedded within play and inquiry. This finding challenges assumptions that computational thinking is inappropriate for young children and suggests that CT can enhance structured problem-solving when integrated in developmentally appropriate ways.

Taken together, the discussion indicates that no single instructional strategy is sufficient to address the multifaceted goals of early childhood science education. Instead, the findings support an integrated pedagogical ecosystem, where play-based guided inquiry serves as the foundation, and STEM activities, scientific talk, modeling, and computational thinking function as complementary practices. Instructional effectiveness is consistently mediated by teacher facilitation, quality of scaffolding, and alignment with children's developmental needs.

Overall, the findings contribute to ongoing debates in early childhood science education by demonstrating that 21st-century instructional strategies can be meaningfully adapted for PAUD/ECE contexts without compromising developmental appropriateness. Rather than accelerating formal science instruction, effective early childhood science learning nurtures curiosity, engagement, and early scientific literacy through thoughtfully designed, integrated pedagogical approaches.

Conclusion

This conceptual systematic review examined international research on instructional strategies for early childhood science learning in the context of 21st-century educational demands. The findings demonstrate that effective science learning in early childhood education (ECE) should not be oriented toward early academic formalization, but rather toward the development of curiosity, exploration, and foundational scientific literacy. Across the reviewed studies, science learning was consistently framed as a process of meaning-making that emerges through play, social interaction, and guided engagement with the natural and material world.

The synthesis of findings identified five dominant instructional strategies that are developmentally appropriate and widely supported by international research: play- based guided inquiry, early STEM activities, scientific talk and explanation, concrete model-based exploration, and foundational computational thinking. These strategies reflect a shift from content-centered instruction toward practices that emphasize inquiry, representation, communication, and problem-solving in early childhood contexts. Importantly, the review confirms that young children are capable of engaging in early scientific practices when instructional experiences are aligned with their developmental needs and learning characteristics.

One of the key conclusions of this study is that no single instructional strategy independently addresses the complex goals of early childhood science education. Instead, the reviewed literature consistently highlights the importance of integrating multiple strategies into a coherent pedagogical ecosystem. Play-based guided inquiry functions as the foundational approach, providing opportunities for exploration and questioning, while early STEM activities, scientific talk, modeling, and computational thinking serve as complementary practices that enrich inquiry experiences. This integrated approach supports not only early scientific literacy but also broader 21st-century competencies such as creativity, collaboration, and problem-solving.

The findings further emphasize the central role of educators in mediating early science learning. Instructional effectiveness is strongly influenced by teacher facilitation, quality of scaffolding, and the intentional design of learning environments. Developmentally appropriate guidance, dialogic interaction, and meaningful contexts are critical in ensuring that instructional strategies promote deep engagement rather than superficial activity. These insights underscore the need for professional development programs that strengthen early childhood educators' pedagogical content knowledge in science and inquiry-based learning.

In conclusion, this study contributes to the discourse on early childhood science education by synthesizing international evidence on instructional strategies aligned with 21st-century learning demands. By highlighting the importance of developmental appropriateness, integration of instructional approaches, and purposeful teacher mediation, the review provides a conceptual foundation for strengthening science learning in PAUD/ECE contexts. Future research is encouraged to explore integrated instructional models through longitudinal and design-based studies, particularly in diverse educational settings. Such efforts will further support the development of early scientific literacy and prepare young children for lifelong engagement with science and learning.

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Declaration on the Use of Artificial Intelligence (AI)

The authors declare that they utilized Artificial Intelligence (AI) tools during the preparation of this manuscript. Specifically, Large Language Models (LLMs) such as ChatGPT were utilized solely for the purpose of language editing, improving sentence structure, and ensuring grammar correction to meet international publication standards. All core ideas, conceptual frameworks, interpretations of the literature, data analysis, and final conclusions were developed independently by the authors. The authors assume full responsibility for the accuracy, integrity, and originality of the entire content of this work, ensuring it adheres to established academic integrity and artificial intelligence.

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