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Phenomenon-based learning and storylines in K-12 science education: a systematic review of current research, implementation, and future directions

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Phenomenon-based learning (PhBL) and storylines represent emerging pedagogical approaches in K-12 science education that emphasize student-centered inquiry and real-world connections, yet comprehensive synthesis of research in this field remains limited. This systematic review synthesizes current literature on PhBL and storyline approaches to identify key themes, implementation practices, and research gaps in K-12 science education. Using PRISMA guidelines, we systematically searched education journals, identifying 24 articles published between 2013 and 2024. Qualitative inductive analysis revealed six major themes through iterative coding and collaborative discussion. Six interconnected themes emerged: (1) Theoretical Foundations encompassing constructivist frameworks and pedagogical principles; (2) Curriculum Design and Implementation addressing NGSS alignment and materials development; (3) Teacher Development focusing on professional learning and classroom practices; (4) Student Learning and Understanding examining engagement and outcomes; (5) Contextual Factors highlighting cultural responsiveness and cross-national perspectives; and (6) Implementation Challenges including teacher preparation gaps and systemic barriers. While PhBL and storylines show promise for enhancing student engagement and scientific reasoning, successful implementation requires sustained professional development, culturally responsive curriculum design, and assessment approaches aligned with constructivist principles. Future research should address longitudinal impacts, scalability, and technology integration to strengthen the evidence base for these transformative approaches to science education.

KEYWORDS

systematic review, phenomenon-based learning, storyline, NGSS, curriculum design, student-centered

1 Introduction

The trajectory of science education is characterized by a persistent cycle of reform, each iteration seeking to enhance student understanding and engagement. The current paradigm has shifted from traditional didactic methods toward a model where students actively engage in scientific inquiry, mirroring the practices of professional scientists, through the application of the three-dimensional framework aligned with the Next Generation Science Standards (National Research Council, 2013; Cherbow, 2023; Lowell and McNeill, 2023).

Phenomenon-based learning (PhBL) represents a transformative educational approach that centers instruction around observable events occurring in the natural world, fundamentally shifting the focus from traditional subject-based teaching to integrated, authentic inquiry-driven learning experiences (Saberi and Nouri, 2025). Similarly, storylines emerged within the NGSS framework to organize science instruction into coherent sequences driven by student questions about phenomena, sharing PhBL's commitment to anchoring learning around real-world events while providing more structured pedagogical sequences (Reiser et al., 2021). Anchored in the principle that students can use their scientific knowledge to explain, interpret, or predict natural phenomena (Amplify Science, 2019), these approaches draw from multiple learning theories (i.e., constructivism, social constructivism), which together form a comprehensive educational structure (Naik, 2019). These pedagogical approaches requires students to think and act like scientists and engineers, engaging them in seeking natural phenomena and solving real-world problems, leading to deeper understanding of scientific content and enhanced critical thinking skills (Bendici, 2019) while providing a context to explicitly and reflectively communicate nature of science (Saberi and Noushin, 2024). PhBL takes place in a flexible learning environment where objectives are not imposed and definitive, and the learning process is planned with student participation (Kubat, 2020).

However, enthusiasm for phenomenon-based approaches must be tempered by important theoretical concerns about instructional design. Research in cognitive science raises fundamental questions about minimally guided instruction. Kirschner et al. (2006) demonstrate that discovery-based approaches can overwhelm novice learners' working memory, leaving insufficient cognitive resources for constructing stable knowledge structures. Their critique challenges the assumption that students can effectively discover scientific principles through unguided exploration of phenomena, regardless of engagement levels.

These concerns may apply differently to PhBL depending on implementation specifics—particularly the degree of instructional scaffolding and explicit guidance provided. Hmelo-Silver et al. (2007) argue that structured inquiry with appropriate support can mitigate cognitive overload concerns, yet the extent to which PhBL implementations actually incorporate such scaffolding remains an empirical question requiring systematic examination. If PhBL operates as truly minimal-guidance instruction, it may face the same limitations Kirschner et al. identify. Conversely, if effective PhBL implementations embed substantial teacher guidance and explicit instruction—using phenomena as organizing anchors rather than expecting independent discovery of all principles—they may avoid these pitfalls while maintaining engagement benefits. This distinction between "phenomenon as anchor 'versus' phenomenon as discovery prompt" is critical for understanding PhBL's effectiveness and represents a key dimension for analyzing implementation approaches.

Translating these theoretical foundations into effective classroom practice presents significant implementation challenges. Teacher preparation represents a critical challenge, as educators require deep interdisciplinary content knowledge, strong inquiry facilitation skills, and comfort with less structured learning environments while simultaneously providing sufficient guidance to prevent cognitive overload. A notable gap exists in teacher preparation programs regarding effective implementation strategies (Sangha et al., 2024). Without proper training, teachers may implement PhBL superficially or revert to traditional methods, potentially reducing phenomena to disconnected examples rather than integrated driving forces for investigation. While research has documented PhBL's effectiveness across multiple educational contexts, systematic analysis remains limited. The meta-analysis conducted by Adipat (2024) examined PhBL implementations across multiple countries (Finland, Norway, United States, UAE, Turkey, Vietnam, and Thailand), documenting positive impacts on student engagement, metacognitive awareness, and critical thinking skills. However, this work focused primarily on broad educational outcomes rather than providing comprehensive frameworks for understanding implementation processes, challenges, and contextual adaptations. Critical gaps persist in our understanding of how theoretical foundations translate into classroom practice, how teachers navigate the transition from traditional to phenomenon-based approaches, and how cultural and contextual factors influence implementation success across different educational settings.

This systematic review addresses these gaps by examining how PhBL and storyline approaches are conceptualized and implemented across multiple dimensions, including theoretical foundations, curriculum design challenges, teacher development needs, student learning outcomes, and contextual factors that influence successful adoption. To ensure inclusivity and generate comprehensive insights, we employed the following research questions.

1. How are phenomenon-based learning and storyline approaches conceptualized and implemented in current K-12 science education literature?
2. What theoretical frameworks underpin PhBL and storyline approaches in science education?
3. What curriculum design and teacher development challenges emerge in implementing these approaches?
4. How do cultural and contextual factors influence the implementation of phenomenon-based approaches?
5. How do students perceive project-based learning (PBL) and storyline?

2 Literature review

Science education research increasingly emphasizes student-centered approaches that engage learners with authentic scientific phenomena. Two notable approaches in this domain are

Phenomenon-Based Learning (PhBL) and storylines. This review examines current literature on both approaches to identify their characteristics, applications, educational impacts, and the contextual factors that mediate their effectiveness.

2.1 The next generation science standards framework: a contested foundation

Contemporary science education reveals a transformation from compartmentalized, content-focused instruction toward integrative methodologies engaging students with real-world phenomena. This shift represents a philosophical reconceptualization of how students develop scientific understanding, supported by international evidence showing that phenomenon-based approaches foster 21st-century competencies and scientific reasoning skills (Adipat, 2024).

The effectiveness of this transformation, however, depends heavily on context. The goal is to move beyond rote memorization and cultivate students' capacity to construct explanations for real-world events (Mualem and Eylon, 2010). The NGSS advances this by integrating three dimensions: Disciplinary Core Ideas (DCIs), Science and Engineering Practices (SEPs), and Crosscutting Concepts (CCCs) (National Research Council, 2013). However, successful integration requires extensive teacher expertise, collaborative planning, and adequate curricular resources, which are not equally distributed across schools. Teachers in under-resourced settings often lack professional development and materials, which can limit the impact of three-dimensional learning even when the framework is well designed. While phenomena-based learning amplifies this integration, its success hinges on sustained support systems and teacher capacity (Penuel et al., 2019).

2.2 Phenomenon-based learning and storylines: comparative definitions and scope

PhBL places real-world phenomena at the center of instruction, emphasizing interdisciplinary inquiry (Garner, 2015). Students observe natural events, generate questions, and develop explanations that integrate multiple scientific disciplines. Storylines, in contrast, were developed within the NGSS framework to sequence instruction around student-driven questions about phenomena (Reiser et al., 2021). Both approaches engage students in authentic inquiry, yet they differ in scale, structure, and implementation demands. Chen and Techawitthayachinda (2021) characterizes storylines as connected learning experiences that help students construct a coherent understanding of scientific ideas over time. Cherbow (2023) adds that storylines promote engagement and relevance by organizing science content around questions that arise naturally from phenomena. While both approaches engage students through authentic contexts, PhBL and storylines also differ in scope and implementation demands.

PhBL originated within Finland's educational reforms as a broad interdisciplinary philosophy that extends beyond science to integrate multiple subjects across the curriculum (Silander, 2015). Storylines, however, emerged to address coherence challenges within U.S. science education and to operationalize the three-dimensional learning framework of the NGSS (Reiser et al., 2021; Severance et al., 2016). These differences have practical implications. PhBL's interdisciplinary nature often requires significant curricular restructuring and collaboration across departments, whereas storylines can frequently be implemented within existing course frameworks. Both share constructivist foundations that position students as active participants in knowledge construction, yet their differing scopes shape the kinds of supports teachers need. In accountability-driven systems with limited flexibility, storylines may offer a more feasible pathway to phenomena-based instruction, while PhBL may be more successful in contexts that afford teachers greater autonomy, resources, and time for interdisciplinary planning.

2.3 Origins and theoretical foundations: distinguishing PhBL from related approaches

While phenomenon-based approaches share foundational elements with established educational frameworks, critical distinctions warrant clarification to avoid conflating PhBL with existing pedagogies. These distinctions have important implications for implementation and effectiveness.

To begin, inquiry-based learning, which emerged prominently in the 1960s through scholars such as Schwab (1962), emphasizes students asking questions and investigating to construct knowledge. However, PhBL differs in its specific anchoring around real-world phenomena that serve as consistent reference points throughout the learning sequence rather than discrete inquiry tasks (Silander, 2015). This distinction matters pedagogically because while inquiry-based learning may involve disconnected investigations, PhBL's sustained focus on a central phenomenon provides coherence that can better support knowledge integration. This advantage depends on careful curricular design and teacher facilitation.

Building on this foundation, constructivism, as developed by Piaget (1977) and later expanded by social constructivists like Vygotsky (1978), provides the theoretical basis for many student-centered approaches, including PhBL. Yet PhBL's distinctive feature lies in its systematic integration of the three NGSS dimensions around compelling phenomena (Penuel et al., 2019). This focus can promote deeper learning when implemented well, but also increases cognitive demands on teachers who must orchestrate interdisciplinary connections and inquiry simultaneously.

In addition to its relationship with constructivism, PhBL must also be distinguished from other design-oriented pedagogies such as problem-based learning and project-based learning. The distinction between PhBL and both PBL and project-based learning mirrors the difference between the nature of science and the nature of engineering. Problem-based learning, developed in medical education in the 1960s (Barrows and Tamblyn, 1980), and project-based learning both emphasize solving problems or creating solutions, reflecting an engineering mindset focused on addressing human needs and constraints. In contrast, PhBL embodies the nature of science by prioritizing understanding natural phenomena for knowledge itself, seeking to explain how and why phenomena occur rather than solving predetermined problems. While traditional PBL presents problems with set learning outcomes, PhBL's phenomenon-centered approach allows the phenomenon to serve as both the starting point and coherent thread throughout learning, with objectives emerging through student questioning about the phenomenon itself (Adipat, 2024).

Taken together, these philosophical distinctions create practical tensions. If learning objectives truly emerge through student questioning, this conflicts with standards-based systems that require predetermined outcomes. Teachers must therefore navigate a key contradiction: maintaining authentic inquiry while ensuring coverage of mandated content standards. The success of this balance depends on teacher expertise, curricular support, and systemic flexibility, which vary widely across educational contexts.

2.4 Implementation approaches and educational outcomes: the mediating role of context

Research demonstrates positive outcomes for both PhBL and storyline approaches, yet effectiveness varies considerably based on implementation quality and contextual factors. These variations, including differences in resources, teacher knowledge, and curricular support, remain insufficiently addressed in much of the current literature.

In PhBL, learning begins with observing real-world phenomena, followed by student-driven questioning, investigation, and explanation development (Silander, 2015). A distinguishing feature is that learning objectives often emerge during the process rather than being predetermined (Kubat, 2020). This design encourages interdisciplinary connections that cross traditional subject boundaries. Storylines similarly engage students with anchoring phenomena but typically follow more structured sequences of connected activities. Reiser et al. (2021) outline strategies within storylines such as eliciting questions from phenomena, identifying knowledge gaps, navigating investigations collaboratively, and supporting students in synthesizing findings.

While both PhBL and storylines promote student agency and conceptual coherence, they differ in the level of scaffolding provided. PhBL's open-ended structure supports deeper inquiry but can place greater cognitive demands on students and teachers. Storylines, by contrast, offer structured guidance that can mitigate cognitive load concerns (Kirschner et al., 2006) and may be more manageable in classrooms with limited instructional time or resources. However, excessive structure risks constraining authentic inquiry. The most effective implementations balance student autonomy with targeted scaffolding, an equilibrium that depends on teacher skill and preparation.

Teacher framing significantly influences how students engage with phenomenon-based approaches, shaping the degree of epistemic agency students assume. Kawasaki and Sandoval (2019) found that effective framing positions students as knowledge builders, while unclear framing often results in passive participation. This finding suggests that professional development focused on epistemic framing, inquiry facilitation, and cross-disciplinary integration is crucial for successful implementation. Teachers require both deep content knowledge and pedagogical understanding to sustain inquiry around complex phenomena, particularly in under-resourced or test-driven environments.

Empirical studies document gains in student motivation, content retention (Janna et al., 2019), engagement (Lefkowitz, 2020), and metacognitive awareness (Akkas and Eker, 2021). Demircioğlu et al. (2013) found that storylines embedded in context-based learning helped students connect theoretical concepts to real-life applications, leading to stronger conceptual understanding. Nation and Kang (2024) demonstrated how storylines support inclusivity by acknowledging students' diverse experiences and cultural backgrounds. Both approaches also enhance student development of scientific practices and critical thinking skills (Makarova et al., 2020; Penuel et al., 2022). Despite these benefits, outcomes often depend on strong curricular and institutional supports. Adipat (2024) and Andersen et al. (2024) note that educator resistance, insufficient training, and uncertainty about facilitating open-ended inquiry remain persistent barriers. These issues are especially acute in settings where teachers lack time for collaboration or access to interdisciplinary resources.

Most problematically, Lowell et al. (2021) identified additional concerns about commercial curricula that reduce phenomena to superficial examples rather than genuine drivers of investigation. When this occurs, both PhBL and storyline instruction risk reverting to traditional content delivery under a new label. This finding suggests that simply adopting phenomenon-based approaches without adequate curricular materials and teacher preparation may actually undermine intended benefits, transforming phenomena into superficial "hooks" rather than sustained inquiry anchors. The gap between theoretical promise and practical implementation appears particularly pronounced in under-resourced contexts or where teachers lack sufficient preparation time.

2.5 Synthesis: unresolved questions and contextual considerations

Despite the growing body of research on PhBL and storylines, several critical gaps remain. Most studies focus on isolated elements such as outcomes or instructional strategies rather than offering an integrated synthesis of theoretical foundations, implementation practices, and contextual influences. As a result, the field still lacks a comprehensive understanding of how these approaches function across varied educational settings. Although many studies report positive effects on student motivation, conceptual understanding, and engagement, few directly compare PhBL and storylines or examine how implementation fidelity, teacher expertise, and institutional resources shape results. Consequently, it is unclear whether reported benefits arise from the pedagogical models themselves or from the conditions under which they are implemented.

Contextual and cultural variables also require further examination. Limited attention has been paid to how sociocultural values, policy environments, and equity considerations influence adoption and outcomes. Educational systems that emphasize collaboration and curricular flexibility may better support interdisciplinary inquiry, while those governed by high-stakes testing or rigid pacing guides may restrict authentic implementation.

Another enduring challenge involves balancing open-ended inquiry with structured scaffolding. Research in cognitive science shows that students benefit from guided inquiry to manage cognitive load, yet few studies analyze how teachers achieve this balance in classroom practice. Identifying scaffolding strategies that maintain inquiry without reducing student agency remains an important direction for future research. Sustainability and scalability also remain underexplored. Many successful implementations occur in short-term or highly supported contexts, and little evidence addresses long-term impact, maintenance of instructional fidelity, or the role of professional learning communities and administrative structures in sustaining practice.

These gaps limit the ability of educators and researchers to make evidence-based decisions about when and how to implement phenomenon-based approaches most effectively. Future research should move beyond determining whether these approaches work and instead investigate the conditions that make them most successful. This systematic review addresses that need by synthesizing evidence across theoretical, practical, and contextual dimensions to clarify how PhBL and storylines can most effectively promote authentic, equitable, and conceptually coherent science learning.

3 Materials and methods

3.1 Study design

A systematic review is a review of individual studies meant to summarize the existing information into a single report (Smith et al., 2011). This was the goal of our study. Our review uses the Preferred Reporting Items for Systematic Review and Meta-Analyses-PRISMA instrument, an established instrument for systematic reviews and meta-analysis, to analyze our abstracts and articles (Moher et al., 2009). Using this method allowed us to increase the construct validity of our search procedures. PRISMA provides a clear step-by-step format for the phases of a systematic review. The first phase identifies publications based on certain search criteria. The screening process reviews all publications identified. Next, the criteria for literature inclusion and summaries report characteristics and potential bias of the article selections. Finally, the interpretation and results are discussed per the context (research question) (Page et al., 2021). The result of this process is a set of publications that have strategically resulted from a systematic review process that has been well-researched and repeated (Moher et al., 2009; Smith et al., 2011).

3.2 Positionality

Both authors are shared first authors and faculty members in science education with expertise in curriculum and instruction, teacher professional development, and science pedagogy. We collaborated on an NSF-funded grant focused on phenomenon-based learning and have published research on PhBL in K-12 contexts. We acknowledge our professional commitment to PhBL may influence our interpretation of the literature. To address this, we employed independent article screening, collaborative coding verification, and iterative consensus-building throughout the analysis.

3.3 Systematic review protocol

In choosing articles for this systematic review regarding phenomenon-based learning or storyline, we sought to find studies focusing on the current state of PhBL or storyline (as it is referred to in NGSS) in K-12 classrooms. Specifically, studies that reported student or teacher data on rationales for using these teaching approaches or explaining applications of the approaches were included. This allowed us to locate articles related to our research question on how PhBL and storyline are characterized or implemented. We conducted a wide search of qualitative articles, including review articles to minimize reporting bias for this study (Smith et al., 2011). Quality assessment was inherently addressed through our inclusion criteria, which required all articles to be peer-reviewed publications from established science education journals indexed in SCOPUS. This ensured that included studies had already undergone rigorous editorial and peer review processes that evaluate methodological quality, theoretical grounding, and Contribution To The Field. Given that our review focused on synthesizing theoretical frameworks and implementation approaches rather than quantitative outcomes, formal quality assessment tools designed for experimental studies were not applicable to our predominantly qualitative corpus.

3.4 Search strategy

One of the researchers, an expert in the field, generated a list of keywords and phrases to initiate the article search. A systematic search was conducted within the SCOPUS database using a two-step Boolean search strategy to ensure comprehensive coverage while maintaining focus on science education research. The first search parameter targeted journal titles using the "Source Title" field in SCOPUS, where keywords were combined using the Boolean operator "OR": "Science Education" OR "Science and Education" OR "science teacher" OR "science teaching" OR "Science and mathematics education" OR "Frontiers in Education" OR "STEM Education." This approach ensured that any journal containing these keywords in its title would be included in the search scope. For example, while "Journal of Science Teacher Education" was not explicitly listed, it was automatically captured due to the inclusion of the keyword "science teacher."

The second search parameter used the Boolean operator "AND" to combine the journal selection with content-specific criteria. Within the selected journals, the search targeted three fields: article title, abstract, and keywords for the terms "Phenomenon-based" OR "phenomena-based" OR "storyline." The complete search logic instructed SCOPUS to search for the specified phenomenon-based learning keywords within the title, abstract, and keyword fields of articles published in journals whose titles contained any of the science education-related terms. No limitations were placed on subject area, source type, document type, or access type. The search was limited to articles published from 2013 to 2014 to present and restricted to final publication stage. This refined search strategy prevented the retrieval of hundreds of unrelated articles that would have resulted from an unrestricted search, while ensuring comprehensive coverage of relevant science education journals and phenomenon-based learning research.

3.5 Study selection

In this step, a content expert on the team independently screened the titles and abstracts of the articles generated by the SCOPUS search to compile a list of potentially relevant full articles. Another member of the research team, independently compiled all articles into a reference management software, Mendeley, and read all abstracts. In this stage, we were broadly searching for any article regarding PhBL or storyline within science education. At this stage, articles were excluded due to definitions of storyline that were discussing a story and not related to the actual phenomenon of a teaching strategy or not discussing science. This selection strategy assessed the literature by two members independently analyzing abstracts to reduce bias in review selection and discussion (Smith et al., 2011).

The next step involved this same individual reading the remaining articles in which those not aligning with the research question (articles focused on gaming or simply listing teaching strategies) were excluded. In addition, citations were reviewed against the search strategy parameters and any not meeting the publication date were removed except for two due to their significant contributions. We included only articles that discussed implementing or analyzing PhBL or storyline. The PRISMA table (see Figure 1) explains specifically how articles were narrowed down to the final number that is included in the literature analysis.

3.6 Data synthesis

Our review of Phenomenon-Based Learning (PhBL) and storyline approaches employed a qualitative inductive methodology to synthesize current research trends and identify emerging patterns. Working with our corpus of 24 selected articles, one member of our research team, with expertise in science education, undertook the comprehensive task of reading each article in full and developing an initial coding scheme. This involved identifying key theoretical contributions, methodological approaches, findings, implementation contexts, challenges, and recommendations within each publication. Through this deep

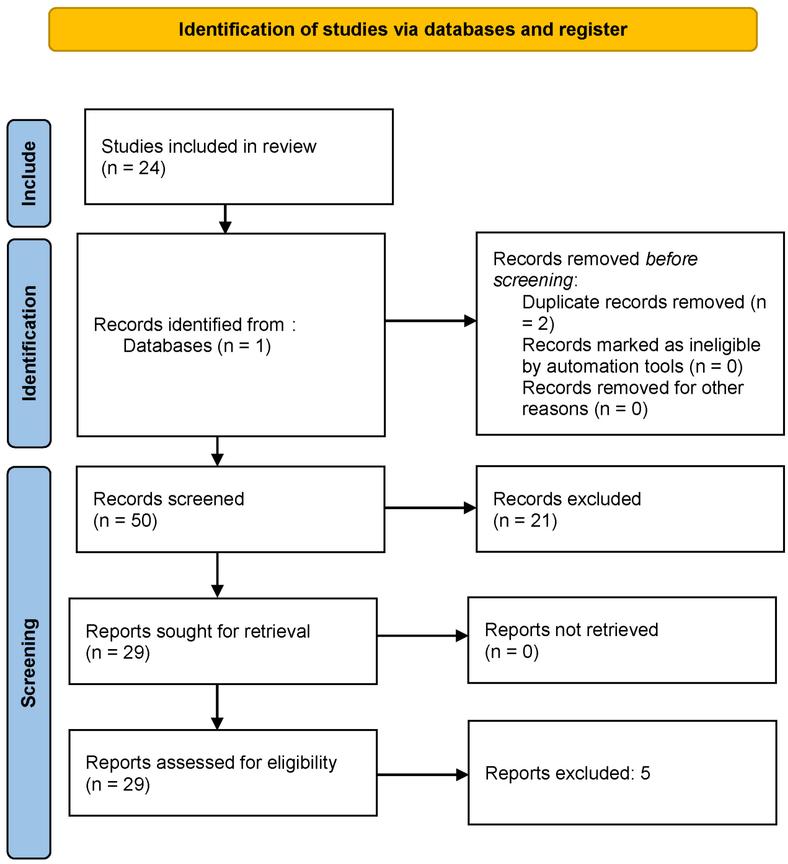

FIGURE 1
PRISMA protocol for article selection of the systemic review of PhBL (Page et al., 2021). PRISMA protocols derived from Page et al. (2021).

engagement with the literature, preliminary themes began to emerge organically, reflecting the multifaceted nature of PhBL and storyline research.

Following this initial analysis, our research team engaged in collaborative discussions to refine our understanding of the emerging patterns. These discussions led to the identification of preliminary categories, including theoretical foundations, classroom implementation, teacher perspectives, student outcomes, and assessment approaches. As we examined the relationships between articles and themes, we recognized that many publications contributed insights across multiple categories. To enhance our analysis of these complex interconnections, we incorporated Generative Artificial Intelligence (GenAI) as a supplementary analytical tool to help visualize potential relationships between our existing codes and to suggest possible category structures based on the summaries and codes we had already developed.

Our team critically evaluated the organizational framework that emerged from this process, comparing proposed categorizations against our deep understanding of the literature. This iterative analytical process led to significant refinement of our initial framework. We expanded theoretical foundations to distinguish between conceptual frameworks and pedagogical approaches, differentiated classroom implementation from curriculum design and teacher development categories, and added sections on contextual factors (circumstances surrounding classroom learning) and future research directions. Throughout this process, our research team maintained authority over the final categorization decisions, ensuring that the framework accurately represented the literature while providing a useful organizational structure for researchers.

4 Results

Our systematic review of phenomenon-based learning (PhBL) and storyline approaches revealed research spanning diverse educational contexts and methodological approaches. The 24 qualitative articles analyzed (see Table 1) represent scholarship from nine countries, demonstrating global interest in these pedagogical approaches. Two articles prior to the timeframe of 2013 were included due to their specific PhBL examples identified.

The final categorization scheme reflects both the breadth and depth of research on PhBL and storylines, organizing the literature into six main themes with corresponding categories: (1) Theoretical Foundations (conceptual frameworks and pedagogical approaches), (2) Curriculum Design and Implementation (curricular materials development and instructional approaches), (3) Teacher Development and Implementation (professional development, classroom practices, and assessment approaches), (4) Student Learning and Understanding (student agency and learning processes), (5) Contextual Factors (cultural contexts and cross-national perspectives), and (6) Implementation Challenges. This framework captures the integrated nature of research in this field (see Figure 2), acknowledging that individual studies often contribute to multiple themes while providing a comprehensive structure that accurately represents current knowledge and offers guidance for future scholarly exploration of PhBL and storyline approaches in science education.

While substantial literature addresses curriculum design and professional teacher development, studies focusing on student experiences provide particularly valuable insights given PhBL's student-centered nature. The geographic distribution shows U.S.-based studies dominate (n = 15), but international perspectives from Finland—where phenomenon-based learning originated—along with contributions from various countries offer important comparative insights. The chronological distribution indicates growing scholarly interest, with over half the articles published within the last 3 years (2021–2024), suggesting PhBL and storyline research is an emerging field coinciding with global educational reforms emphasizing student-centered learning. The following sections present our findings organized by the six themes, synthesizing key insights while highlighting patterns and gaps that emerged from our analysis.

4.1 Category 1: theoretical foundations of storylines and phenomenon-based learning

Two categories within the theme, theoretical foundations of storylines and phenomenon-based learning, are conceptual frameworks and pedagogical approaches. This theme addresses the research question: What theoretical frameworks underpin PhBL and storyline approaches in science education? The literature on conceptual frameworks provides fundamental definitions and principles that underpin both storylines and phenomenon-based learning approaches. Thirteen articles were identified as connected to this theme (Adipat, 2024; Andersen et al., 2024; Chen and Techawitthayachinda, 2021; Cherbow, 2023; Hanuscin et al., 2016; Kawasaki and Sandoval, 2019; Lehesvuori and Ametller, 2021; Lowell et al., 2022; Nation and Kang, 2024; Pelamonia and Corebima, 2015; Penuel et al., 2019, 2022; Reiser et al., 2021).

4.1.1 Conceptual frameworks: definition and principles of phenomenon-based learning

A common definition for PhBL is an approach to learning centered around real-world phenomena in which students engage in sensemaking to ask questions and work together to provide a comprehensive, often interdisciplinary approach, to understanding a phenomenon in science (Adipat, 2024; Lowell et al., 2022). Part of this requires students to rely on previous knowledge to make connections using their own experiences (Pelamonia and Corebima, 2015; Reiser et al., 2021). It also is a shift away from memorizing to understanding the construction of scientific knowledge so is a shift away from traditional curriculum. The framing of the activities in relation to the anchoring phenomenon is a crucial part of PhBL for teachers to understand (Kawasaki and Sandoval, 2019). Importantly in connection to NGSS, PhBL emphasizes the use of scientific practices or engineering practices to pose questions around the phenomenon that provides students with the opportunity to understand how scientists approach their work (Penuel et al., 2019).

TABLE 1 Summary of Article search listed alphabetically by first author.

First author and year	Classroom	Country	Article type (*denotes review article)	Data collection tools	Key findings
Adipat (2024)	K-12	Multiple	Meta-analysis review*	Article synthesis	The article examines PhBL across countries (Finland, Norway, USA, UAE, Turkey, Vietnam, Thailand), showing it effectively enhances student engagement, metacognitive awareness, creative thinking, and 21st-century skills.
Andersen et al. (2024)	7th	U.S.	Phenomenology case study	Videos, interviews, curriculum	The study examines how a middle school science teacher perceives and resolves uncertainties in his understanding that emerge during his interaction with the curriculum.
Chen and Techawitthayachinda (2021)	3–8 grade	U.S.	Design-based empirical study	Videos	This study discussed managing uncertainty through a process where teachers raise, maintain, and reducing epistemic uncertainty by involving students in the learning process.
Cherbow (2023)	Middle school-physical science	U.S.	Single instrumental case study	Curricular materials, videos, artifacts	The article provides an overview that storylines can be used to make science learning more relevant and engaging for students, and that it can also help students to develop important skills such as critical thinking and problem-solving
Demircioğlu et al. (2013)	6th grade physics/chemistry	Turkey	Empirical experimental design	Questionnaire, curriculum materials	This article investigated embedding storylines within context-based learning. They found it helped students connect theoretical knowledge with real-life applications, creating meaningful learning experiences that effectively remediated most of their alternative conceptions.
Hagenah and Thompson (2021)	Secondary	U.S.	Multiple empirical case study	Lesson plan analysis (part of larger study), observations, artifacts, interview	The study addressed an existing theory-to-practice gap by providing evidence for how teachers attend to students' lived experiences in planning and in the moments of teaching across units of instruction by examining three pedagogical phases: planning meetings, interactions in classroom lessons, and lesson debriefs with teachers.
Hanuscin et al. (2016)	Elementary	U.S.	Exploratory case study	Lesson plans, content representation Tool, interviews, artifacts	The goal of this article was to determine how professional development (PD) can improve the conceptual coherence of teachers' lessons as they modify materials for classroom usage.
Kawasaki and Sandoval (2019)	7–12 grade physical science	U.S.	Single empirical case study	Observations, videos	This article found when teachers appropriately framed a unit, lesson, and/or activity, students took on roles as epistemic agents and sensemakers. When the teacher's framing was unclear, students took on more traditional roles that resembled didactic science teaching. The authors conclude that teachers need support in framing instruction so that students can develop science concepts through science practices.
Lehesvuori and Ametller (2021)	9th-physics, math, chemistry	Finland, Germany, Switzerland	Theoretical case study	Videos, student responses	The authors examine the interplay between communicative approaches and pedagogical link-making, with a focus on coherence. Through three case studies, the research reveals how teachers make connections between past and new knowledge, and how the authorship of these links (teacher or student) affects student engagement.
Li et al. (2024)	High school chemistry	Korea, China	Comparative empirical study	Comparative study coding teaching guides	The study examines the categories, frequencies, and depth of supports within teacher guides, focusing on design rationales, storylines, and transparency. The study suggests that more effective teacher guides should explicitly state rationales behind pedagogy and activities, address learning difficulties, and promote interdisciplinary teaching.
Lowell and McNeill (2023)	6–8 grade	U.S.	Qualitative longitudinal survey	Professional development activities, surveys	They found that while teaching beliefs may change initially, self-efficacy often requires more time and practical experience to evolve. The study emphasizes the importance of designing professional development that not only builds trust but also provides a clear rationale for activities to enhance teachers' understanding and perceived value.

(Continued)

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TABLE 1 (Continued)

First author and year	Classroom	Country	Article type (*denotes review article)	Data collection tools	Key findings
Lowell et al. (2021)	6th grade	U.S.	Theoretical framework and empirical case study	Curriculum materials, interviews, videos	The authors in this study found that the commercial curriculum and its implementation oversimplified key NGSS features by using phenomena as examples, separating the three dimensions of science learning, placing cognitive load on teachers, and prioritizing teacher-directed learning coherence. The authors suggest that future curricula should focus on students explaining how and why phenomena occur to better support coherence, three-dimensionality, and student involvement.
Lowell et al. (2022)	Middle, human body	U.S.	Single case study	Curriculum implementation, videos, discussions	The authors focus on three types of discussions: initial ideas, building understandings, and consensus. They found that each discussion type requires a distinct set of teacher moves to achieve its goal, but that one skilled teacher relied too heavily on Propose, Probe, Clarify, Restate (PPCR) sequences even when they didn't quite fit.
Mualem and Eylon (2010)	Junior high school physics	Israel	Empirical qualitative study	Questionnaires, interviews, tests	The strategy involves visual representations and guides students from characterizing the system in terms of interactions to constructing free-body force diagrams. The authors conclude that this approach can be effective in promoting qualitative understanding of mechanics in junior high students.
Nation and Kang (2024)	10th chemistry	U.S.	Ethnographic case study	Videos, student artifacts, surveys, interview	The study focused on explore how three Latinx female students contributed to their high school chemistry class and influenced the science storyline. These findings emphasize the importance of acknowledging students' experiences and contributions to create a more inclusive and engaging science classroom.
Østergaard (2015)		Norway	Phenomenological review*	Teaching approach	This article explores an argumentation of uprooting/rooting pair of concepts, students' feeling of alienation and loss of fundamental sense of the earth as ground, and potential consequences for teaching science in a rooted manner. Conditions for rooting in science education are discussed against three challenges: Restoring the value of aesthetic experience, allowing time for open inquiry and coping with curriculum.
Park et al. (2016)	Primary	Korea	Case studies	Recordings, interviews, field notes	This article explores the different kinds of unintended learning in primary school practical science lessons. What emerged was that there were three types of knowledge that students learned unintentionally: factual knowledge gained by phenomenon-based reasoning, sconceptual knowledge gained by relation- or model-based reasoning, and procedural knowledge acquired by practice.
Pelamonia and Corebima (2015)	8th	Indonesia	Phenomenological case study	Student test	This study concluded that (1) the cognitive basis of phenomena based reasoning were orientation, inferential abstraction, and inferential affirmation; (2) students were able to analyze phenomena by using systematic cognitive framework only if they had complete information of the phenomena; (3) inference validity related to the cognitive basis is heavily determined by the phenomena analysis ability; (4) the general semantic structures in phenomena based reasoning were definitional and assertional; (5) the semantic structure complexity was determined too by the phenomena knowledge availability which was analyzed.
Penuel et al. (2019)	High school biology	U.S.	Empirical design pilot study	Curriculum, assessments	This article describes the development and validation of a set of proximal transfer tasks for high school biology classrooms where teachers were implementing a problem-based curriculum that was aligned with the Next Generation Science Standards (NGSS). The authors conclude that proximal transfer tasks have the potential to be a valuable tool for assessing phenomenon-based science learning.

(Continued)

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TABLE 1 (Continued)

First author and year	Classroom	Country	Article type (*denotes review article)	Data collection tools	Key findings
Penuel et al. (2022)	High school biology	U.S.	Conceptual review*	Article review	The "storylines" approach aims to address this issue by centering science learning around questions and problems that students themselves identify as relevant and interesting. They focus on knowledge building and address real-world problems, connecting science learning to real-world phenomena and issues that are relevant to students' lives.
Reiser et al. (2021)	Middle/high	U.S.	Empirical design-based	Framework analysis, curriculum design and teaching	The model of storylines reflect strategies asking teachers to elicit questions from anchoring phenomena, navigate to engage students as partners in managing the direction of investigations, problematizing to help students find gaps in their work so far, and putting pieces together to support students in assembling what they have figured out.
Roth et al. (2011)	Elementary	U.S.	Quasi experimental	Assessments, videos, student content knowledge test	The researchers examined a professional development program named, Science Teachers Learning from lesson analysis (STeLLA). Rarely have studies focused on the professional development impact toward teacher's knowledge, teaching practice, and student learning.
Sangha et al. (2024)	Elementary, physical science	U.S.	Mixed methods	Questionnaire, assessments, video observations	Integrating such phenomena-based approaches in existing science courses within teacher education programs present potential challenges for both preservice elementary teachers and for laboratory instructors this study concludes by discussing challenges facing laboratory instructors that need careful consideration for phenomena-based approaches.
Sardana and Muddgal (2024)	7th grade	India	Descriptive case study	Artifacts, lessons	The results of this study supported context-based STEM learning for the twenty-first century and strengthened cultural anchoring from an early stage. This implies the need for teacher professional development, curricular reform, and school infrastructure improvements to support policy implementation.

*Denotes review articles.

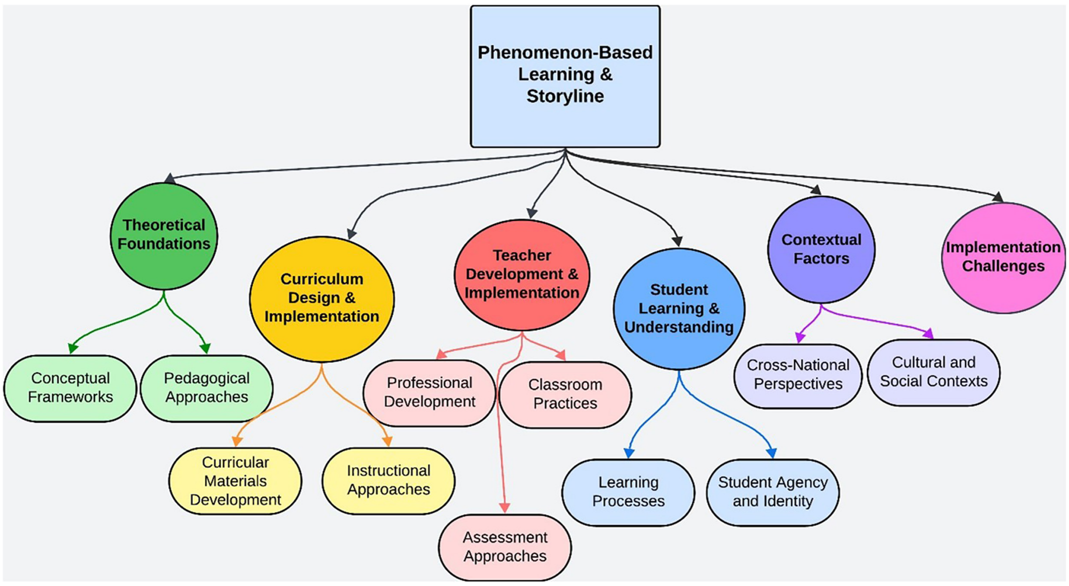

FIGURE 2
Systematic review themes and categories.

4.1.2 Conceptual frameworks: definition and principles of storylines

A consensus definition for storyline is in structuring a sequence of learning activities, presented coherently, around an anchoring phenomenon in which students work together, driving the questioning and learning as they interact (Andersen et al., 2024; Chen and Techawitthayachinda, 2021; Cherbow, 2023; Lowell et al., 2022, Nation and Kang, 2024). Chen and Techawitthayachinda (2021) expand on this by emphasizing learning as a connection that helps students develop a deep understanding of scientific concepts, emphasizing their role in making science learning more relevant and engaging. Penuel et al. (2022) frame storylines as a conceptual approach that addresses traditional curriculum shortcomings by centering science learning around student-identified questions, emphasizing student agency and connection to real-world problems. Student agency refers to students assuming responsibility for a portion of knowledge production (Kawasaki and Sandoval, 2019). In taking on this responsibility, "epistemic agency supports students' development of an understanding of the practices of knowledge construction of the scientific community" (Kawasaki and Sandoval, 2019, p. 906).

A key term used to describe some of what students do as they develop an understanding of science practices is sensemaking. Sensemaking is both cognitive and social and refers to student thinking and highlights communication between students about their thinking (Lowell et al., 2022). A purposeful storyline is composed of a sequence of science concepts that can relate to a goal, develop a sequence of activities, and allow students to engage in questioning that generates knowledge-building work from investigations (Cherbow, 2023; Hanuscin et al., 2016).

4.1.3 Pedagogical approaches

The pedagogical approach of PhBL follows reforms focused toward active learning approaches which, much like this new practice, shifted toward placing the student as the center of their learning in line with constructivism. Active learning has roots in a social constructivist theory framework, meaning experiences and interactions are the framework under which the learning takes place. Lehesvuori and Ametller (2021) state that learning science requires active involvement of students from a sociocultural perspective. Research on pedagogical approaches examines how coherence and constructivist principles are implemented in science education. The "core of learning science through inquiry or phenomenon-based approaches" (Lehesvuori and Ametller, 2021, p. 2792) works on language-building skills in science knowledge construction so natural phenomena are learned via scientific practices (Lehesvuori and Ametller, 2021). Reiser et al. (2021) emphasizes the importance of coherence from the student's perspective, presenting routines that support navigation and help students assemble what they've figured out. Students figuring out scientific phenomena are expected to engage in questioning and exploring, like an inquiry-based assignment, another framework and a topic of education reform that encourages students to ask questions and explore science with each other. Lehesvuori and Ametller (2021) investigate the construction of knowledge in science classrooms, focusing on how teachers help students develop coherent understanding by connecting fragmented information through communicative approaches and pedagogical link- making. Penuel et al.'s (2019, 2022) emphasizes student-centered learning approaches, which are a key feature of PhBL.

4.2 Category 2: curriculum design and implementation

Twelve articles included discussions on framing PhBL within the NGSS standards in Curriculum Design and Implementation, the second theme (Adipat, 2024; Hagenah and Thompson, 2021; Li et al., 2024; Lowell et al., 2021; Mualem and Eylon, 2010; Nation and Kang, 2024; Penuel et al., 2022; Reiser et al., 2021; Roth et al., 2011; Sangha et al., 2024; Sardana and Muddgal, 2024). Categories developed in this theme include curricular materials development and instructional approaches in K-12 classrooms. This theme addresses the research question: What curriculum design and teacher development challenges emerge in implementing these approaches? Studies on curricular materials development examine how teaching resources are designed to support phenomenon-based and storyline approaches. A key example of this is in Lowell et al. (2021) evaluates NGSS-aligned curricula and their implementation, finding that commercial materials often oversimplify key features by using phenomena as mere examples rather than driving forces for investigation.

4.2.1 Curricular materials development: teacher guides

Curriculum materials such as teacher guides are meant to help teachers guide students in making sense of phenomena and provide guidance on strategies to help students build, test and revise their models (Reiser et al., 2021). The need is in explicit strategies and content-specific support for students to feel empowered by teachers to take ownership of their learning. Li et al.'s (2024) comparative analysis of high-school chemistry teacher guides in China and Korea highlights a fundamental issue: the clarity of curricular intentions. While teacher guides are intended to facilitate effective instruction, Li et al.'s (2024) findings suggest a significant gap in supporting interdisciplinary connections and differentiated instruction. This lack of explicit guidance leaves teachers struggling to bridge disciplinary boundaries and cater to the diverse learning needs of their students, ultimately hindering the realization of a holistic science education. The implication is clear: curriculum designers must prioritize making their intentions transparent, providing detailed strategies and resources that empower teachers to navigate complex pedagogical demands.

4.2.2 Curricular materials development: alignment with standards (NGSS)

In this category, we address the teacher's perspective in NGSS and the design of PhBL to support 21st-century skills like critical or creative thinking and problem-solving (Adipat, 2024). PhBL also weaves together aspects of the standards that relate to project-based learning and engaging in science like a scientist in order to make content meaningful (Penuel et al., 2022). Each PhBL lesson is intended to integrate the three dimensions for students to use scientific ideas to understand phenomena (Reiser et al., 2021).

However, as PhBL embodies the framework of the NGSS, the implementation has not always been consistent. Lowell et al. (2021) noted a common problem for teachers with poor curriculum materials or design, utilize PhBL as a discrepant event or "hook" for the lesson rather than allowing students to ask questions and drive investigation. Designing lessons to align with the standards requires centering the student as the one who does most of the scientific thinking in the classroom. Not all phenomena may be appropriate for three-dimensional instruction as its explanation may not require crosscutting concepts (Lowell et al., 2021; Penuel et al., 2022). Typically curriculum highlights connections to the CCC or scientific practices but not in a way that supports teachers' understanding of how NGSS envisions science learning, making phenomena selection unclear. Teachers and students alike are likely to struggle with sensemaking of the scientific phenomenon without a clear anchoring phenomenon (Reiser et al., 2021). Lowell et al. (2021) state that teachers need time to make curriculum changes required in NGSS and perhaps more research could provide instruction on how PhBL embodies the goals of NGSS. Teachers must prepare and shift their mindset on how they approach this new curriculum design within NGSS, including how it is to be assessed.

4.2.3 Instructional approaches: curriculum integration

Research on instructional approaches examines integrated teaching methods within phenomenon-based learning and storylines. The approach to storyline builds knowledge across time in a coherent approach (Penuel et al., 2022). Four principles helped guide this in Penuel et al.'s (2022) article. Addressing the idea of what makes a project meaningful, leveraging that project through conversations involving students, an iterative review and refinement process can generate a list of questions students are likely to pose and can be anticipated in further lessons, and working together as a classroom community all contribute to a coherent storyline approach to scientific practices. This article found the storyline approach supported students in seeing science as more than checking off a task for the day and supported learning goals. It works toward effectively integrating science and classroom communities, making that real-world connection. Students provided with a phenomenon situated in real-world situations have the opportunity to utilize prior knowledge in making connections between scientific principles and everyday life (Lowell et al., 2021; Penuel et al., 2022).

Real-life contexts encourage student learning and by connecting to science-based practices, this may lead to an opportunity for the use of non-conventional methods like PhBL (Sardana and Muddgal, 2024). Each teacher is likely to make sense of instructional changes in a slightly different way applicable to their own discipline and specific students. In the article by Mualem and Eylon (2010), the author found the application of PhBL and the use of diagrams in predicting phenomena helped students in this junior high (9th grade) physics class in Israel improve their understanding of solving qualitative problems The teacher presented everyday occurrences that students realized cannot be analyzed without more knowledge and understanding of physics terms, within the context of learning mechanics, thus providing students with the ability to make sense of physics phenomena. The results revealed that students using this strategy improved their results on the force concept inventory from pre-test to post-test. Interviews supported their ability to explain phenomena using physics and retain the information. The author hopes for additional studies in physics using this approach (Mualem and Eylon, 2010).

4.2.4 Instructional approaches: context-based learning

Hagenah and Thompson (2021) explore how teachers contextualize science phenomena to capitalize on students' everyday experiences, addressing the challenge of responsive teaching that connects science to students' lives. Nation and Kang

(2024) focus on how Latinx female students contribute to their high school chemistry class and influence the science storyline about reaction rates contextualized by local wildfire experiences. Sardana and Muddgal (2024) examine Indian cultural context to create interdisciplinary storylines connecting natural and social science concepts. The phenomenon requires multiple disciplinary lenses to fully understand the concept. Mualem and Eylon (2010), Roth et al. (2011), and Sangha et al. (2024) all investigate an instructional approach for teaching mechanics that explicitly teaches qualitative problem-solving strategies, showing that junior high students can develop a sophisticated understanding of physics concepts through structured visual representations and system analysis. The interdisciplinary nature of phenomenon-based learning is highlighted and demonstrates how cross-disciplinary approaches enhance student engagement and understanding of complex concepts.

4.2.5 Instructional approaches: adaptation

In its design, a PhBL lesson is a process with clear connections to disciplinary core ideas and cross-cutting concepts (Cherbow, 2023). In a phenomenon-based lesson, there is potential for students to diverge from the plan due to their questioning and knowledge building. Commonly across studies, students work with the teacher along the trajectory of their science work and it is the interactions that move the sensemaking forward (Cherbow, 2023). In the overview provided by Cherbow (2023), divergent science work, something that cannot possibly be planned, includes student questions and ideas, interpretations, and behaviors. Teachers must constantly adapt. A teacher's response and decisions in these moments of instruction is a necessary aspect of PhBL (Cherbow, 2023; Hagenah and Thompson, 2021). The teacher needs to listen carefully and guide students back to the central scientific concepts.

Teacher adaptation is something difficult to train in preservice teachers and is a skill required for PhBL. There are both benefits and challenges to the use of PhBL and with the development of curriculum tools and practice in implementing PhBL, teacher adaptability has the potential to improve. However, making decisions to address student thinking and support instructional goals should be further studied for professional development (Cherbow, 2023). Furthermore, teacher reflections on how they improvise their decision-making will help shape future curricular design (Cherbow, 2023).

4.3 Category 3: teacher development and implementation

Eleven articles investigated the theme of teachers developing and implementing PhBL in the classroom (Andersen et al., 2024; Chen and Techawitthayachinda, 2021; Demircioğlu et al., 2013; Hanuscin et al., 2016; Kawasaki and Sandoval, 2019; Lehesvuori and Ametller, 2021; Lowell et al., 2021, 2022; Lowell and McNeill, 2023; Penuel et al., 2019; Roth et al., 2011). This theme addresses the research question: How are phenomenon-based learning and storyline approaches conceptualized and implemented in current K-12 science education literature? It is important to develop students' science content knowledge (Roth et al., 2011), and the standards that schools in the US have adopted require teaching that supports increasing students' responsibility for their own learning. In this section, we discuss training for teachers and how practices are implemented as we explore how teachers work with their students to participate in their own learning. Major categories in the theme, teacher professional development and implementation, included professional development with sub-categories: teachers' beliefs, curricular sensemaking, and subject knowledge development (see Figure 3). A second category under this theme was classroom practices, which included facilitating discussions, framing student agency, and pedagogical link-making. The third category includes assessment approaches with subcategories of proximal transfer tasks and developing conceptual understanding.

4.3.1 Teacher professional development: teacher beliefs and self-efficacy

Lowell and McNeill (2023) investigated how teachers' beliefs about science instruction and their self-efficacy in implementing reform-based curricula change over time, finding that while teaching beliefs may change initially, self-efficacy requires more

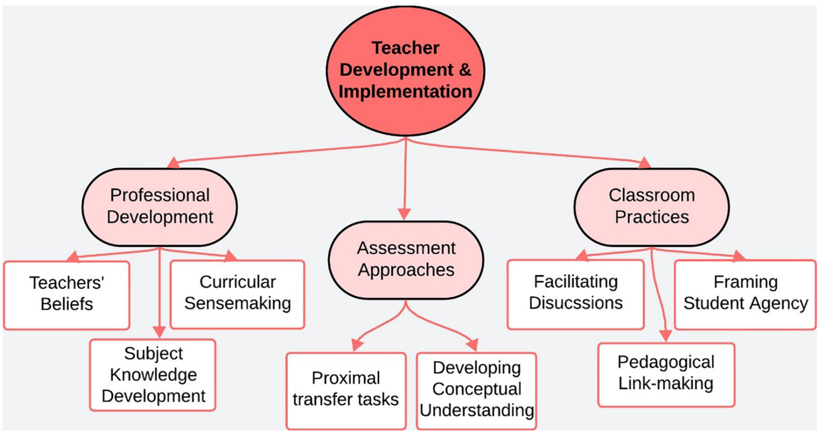

FIGURE 3
A breakdown of teacher development and implementation.

practical experience to evolve. "[T]o support students' epistemic agency, teachers must respond to the ideas students bring with them to the classroom and the ways they make sense of classroom learning experiences rather than asking students to memorize." (Lowell and McNeill, 2023, p. 1458). This type of work requires teachers to be knowledgeable in their content, anticipate ways students may respond, and how they will help students develop their understanding (Lowell and McNeill, 2023; Roth et al., 2011). In future studies, we need to study teachers participating in workshops, specifically examining their learning patterns and the differences among them.

Teachers may lack personal experience in conducting scientific practices and struggle to believe how a student can investigate problems without knowing the science concepts first (Kawasaki and Sandoval, 2019). This type of training for PhBL could be highly beneficial in that by allowing them to act as their students would in generating questions about natural phenomena the teachers would increase their ability to grow their own knowledge and beliefs (Kawasaki and Sandoval, 2019).

4.3.2 Teacher professional development: curricular sensemaking

Part of the focus on professional development is finding ways to support teaching in designing ways to teach that are rooted in conceptual coherence for the students (Hanuscin et al., 2016; Lowell and McNeill, 2023). Hanuscin et al. (2016) examines how professional development can improve conceptual coherence in 3rd grade teachers' lessons across school districts in the Midwest of the USA. "Sequencing and connecting scientific concepts in a storyline is important because this conceptual structure can help provide meaning to students" (Hanuscin et al., 2016, p. 395). Programs should be developed for teachers' specific situations and problems to tie together personal and curricular resources that are a part of lesson planning. The author found that professional development focused on the construction and analysis of conceptual storylines may help teachers plan and implement lessons with conceptual coherence and that this, in turn, can improve student learning. However, two gaps in the literature remain. The teacher's priority in lesson planning approaches (using conceptual coherence instead of the specific professional development practices) and how conceptual storylines could assist teachers in adapting the new curriculum. Andersen et al. (2024) case study provided a deep analysis of the complexity involved in supporting teacher learning and curricular sensemaking as well as the need for supporting future research on how different teachers approach their curriculum use.

Andersen et al. (2024) explored a middle school science teacher's sensemaking of the new curriculum demands by looking at the uncertainty experienced and how the teacher's interactions and interpretations of planning and implementing a storyline curriculum impacted students' sensemaking. This case study revealed uncertainties in navigating students' sensemaking of particular scientific practices and navigating the storyline curriculum driven by student ideas.

Hanuscin et al. (2016) research emphasizes the crucial role of professional development in bridging the gap between curricular materials and classroom practice. By investigating how professional development improves the conceptual coherence of teachers' lessons when they modify materials, effective training can empower teachers to adapt resources to their specific contexts. However, the study also underscores the importance of making conceptual storylines explicit. Teachers need a clear understanding of the underlying narrative of the curriculum to effectively guide students through complex scientific concepts. This necessitates a shift toward professional development that not only focuses on content knowledge but also on pedagogical content knowledge and the ability to navigate complex curricula. Future research is needed so we can understand the support teachers need and the professional development opportunities offered to teachers for making sense of the instructional changes (Andersen et al., 2024).

4.3.3 Teacher professional development: subject matter knowledge development

The literature on teacher professional development examines how teachers develop the knowledge necessary to implement phenomenon-based and storyline approaches. Given the evidence of success for this new trend, PhBL, in-service teachers need opportunities for training to stay current in approaches to science education. Demircioğlu et al. (2013) analyzed 6th grade students from Turkey to understand physical and chemical change concepts. After implementing a storyline approach, they found students improved their connections between real life and scientific knowledge. The teaching approach and questionnaire were given by experts with PhBL. Pre-service teachers keep up with the trends because it is embedded in their training. There is a need for more opportunities for this same training for in-service teachers (Demircioğlu et al., 2013).

Hanuscin et al. (2016) focuses on how professional development can improve conceptual coherence in teachers' lessons, while Kawasaki and Sandoval (2019) highlight the need to help teachers frame instruction to promote student agency. Chen and Techawitthayachinda (2021) discussed the depth of learning that is required to identify a problem related to a phenomenon, recognize gaps in knowledge, and seek solutions. In this study, tactics were developed for teachers to help students with uncertainty in the development of deep scientific knowledge. These tactics included raising uncertainty, maintaining uncertainty, and reducing uncertainty (Chen and Techawitthayachinda, 2021). These tactics played a role in the sensemaking process by allowing students to make meaning of science and construct their knowledge meaningfully by comparing ideas, critiquing one another, collectively finding a solution and purposefully connecting the phenomena to target concepts (Chen and Techawitthayachinda, 2021).

4.3.4 Classroom practices: framing student communication

Facilitating classroom communication is particularly important because the teacher can support students in deepening their thinking or making it visible to others. For example, teachers could help students in hypothesis generation of the presented phenomena or the revision of their model. Depending on the age of the students or the familiarity with PhBL, students may require more prompting. The focus is on students engaging in initial ideas, building understandings, and consensus in different types of discussions. Lowell et al. (2022) investigated the implementation of class-wide discussions in a storyline curriculum and how teachers supported students' sensemaking. "For example, when students are first exposed to a phenomenon, the necessary sensemaking work involves considering the phenomenon, identifying any gaps in their understanding, and motivating the need for future investigations" (Lowell et al., 2022, p. 196). The authors found that the way teachers spoke and clarified ideas became important for building understanding between students and forming a consensus in discussion (Lowell et al., 2022).

4.3.5 Classroom practices: framing for student agency

"Early PD effort around the NGSS suggests teachers struggle to design lessons around conceptually coherent storylines" (Kawasaki and Sandoval, 2019, p. 907). Kawasaki and Sandoval (2019) studied a teacher's ability to redesign their teaching based on the NGSS standards and storyline design. The study was part of a larger PD project in which opportunities were given for teachers to organize lessons for science practices to be the means for conceptual development. Key to this was selecting appropriate phenomena for instruction (Kawasaki and Sandoval, 2019). The teacher in this study exhibited many appropriate lesson designs but occasionally struggled with a lack of clarity in framing the lesson. If a teacher does not frame the lesson well (meaning understand the purpose of an activity and make sense of it as a PhBL that meets the NGSS standards), professional development should focus on areas of framing and epistemic agency.

4.3.6 Classroom practices: student questioning and communication

Each unique classroom of students and teachers may form questions and pedagogical links differently. These different choices in communication and approaches to the scientific concepts and their link to the storyline impact student learning (Lehesvuori and Ametller, 2021). Lehesvuori and Ametller (2021) explored communication and pedagogical link-making in science classroom discourse in 9th grade classrooms in Finland, Germany, and Switzerland. In each classroom, they found the teacher approached the questions and conceptual pedagogical link differently. Overall, student sensemaking requires questioning and communication to be effective between students, especially in the use of consistent language and in how students contribute to the activities (Lehesvuori and Ametller, 2021). " Cherbow (2023) provides a concrete example of this sensemaking in action, noting that "the students analyze and interpret data from their graphs to identify a nonlinear relationship between the independent and dependent variables" (p. 833), demonstrating how storylines position students to actively engage in scientific practices. Communicating coherent approaches should be something incorporated into teacher training specifically in how language use connects to effective learning.

In the study by Roth et al. (2011), the researchers examined a professional development program named, Science Teachers Learning from lesson analysis (STeLLA). Rarely have studies focused on the professional development impact toward teacher's knowledge, teaching practice, and student learning for elementary teachers as it relates to science (Roth et al., 2011). Teachers were given the opportunity to participate in a summer institute and engage in video analysis to improve teaching using storyline methods for science content. "The STeLLA study demonstrates that a carefully designed and implemented 1-year science PD program can build elementary teachers' science content knowledge and their pedagogical content knowledge about the Science Content Storyline and Student Thinking Lenses, and can improve their ability to use that content and pedagogical content knowledge in teaching science, and as a result, enhance their students' science learning" (Roth et al., 2011, p. 136).

4.3.7 Assessment approaches

Collectively, these articles (Lowell et al., 2021; Penuel et al., 2019) underscore the urgent need for assessment approaches that align with the constructivist, phenomenon-based nature of instruction. These approaches must move beyond traditional fact-based assessments and evaluate a deeper conceptual understanding of student's ability to apply knowledge to explain phenomena. Furthermore, these assessments must be designed to be equitable, ensuring that all students have the opportunity to demonstrate their understanding regardless of their background.

4.3.8 Assessment approaches: proximal transfer tasks

This pedagogical shift to PhBL necessitates the development of assessment tools that prioritize scientific reasoning, explanation, and application, rather than rote memorization. Penuel et al. (2019) focused on the need for developing assessments for phenomenon-based learning and provided an approach to assessment design of student three-dimensional learning that integrated the cross-cutting concepts. "[I]f we expect students to gain mastery of core ideas and Cross Cutting Concepts (CCCs) through phenomenon-based teaching, then we need to assess whether they can apply those core ideas and CCCs in problem contexts" (Penuel et al., 2019, p. 1373). This study, conducted in high school biology classrooms, tested students on two tasks that were meant to be multicomponent to the instruction students received around a scientific phenomenon. These are called proximal assessments, where the tasks are the same as the instruction, but the context is unfamiliar (Penuel et al., 2019). The study concluded that proximal transfer tasks could be used to assess PhBL, but the authors caution that even selecting phenomena that well suits the three-dimensional assessment design of NGSS could yield variance in quality of assessment (Penuel et al., 2019).

4.3.9 Assessment approaches: developing conceptual understanding

Lowell et al. (2021) work, which utilizes a framework for evaluating NGSS- aligned curricula and instruction, emphasizes the importance of assessing students' ability to explain "how and why" phenomena occur. This focus on explanation aligns perfectly with the core principles of NGSS, which prioritize scientific reasoning and the construction of explanations over mere factual recall. By shifting the emphasis from "what" to "why" and "how," assessments can delve into the depth of students' conceptual understanding and their ability to apply scientific principles to real-world contexts. This approach ensures that students are not just memorizing facts but are developing the critical thinking skills necessary for scientific inquiry. The curriculum is designed for "students" integrated understanding of the three dimensions" and student assessment must align in this way (Penuel et al., 2019, p. 1368)

4.4. Category 4: student learning and understanding

Six articles investigated the theme, Student Learning and Understanding (Andersen et al., 2024; Cherbow, 2023; Lowell et al., 2021; Park et al., 2016; Penuel et al., 2022; Reiser et al., 2021). Major categories in this theme include learning processes and Student Agency and Identity. This theme addresses the research question: How do students perceive project-based learning (PBL) and storyline?

4.4.1 Learning processes: unintended learning

Research on learning processes investigates how students develop understanding through phenomenon-based and storyline approaches. Even a well-designed lesson may be received by students in an unexpected way. An article by Park et al. (2016) specifically studied what students learn in primary science lessons, which was classified as unintended learning, defined as learning not planned by the teacher for that specific lesson. This study took place in Korea and studied five teachers who were observed delivering a science lesson from the national curriculum so was nearly identical. The authors identified unintentional learning occurrences from transcriptions from video recordings and identified three types of unintended learning. These were: factual knowledge gained by phenomenon-based reasoning, conceptual knowledge gained by relation- or model-based reasoning, and procedural knowledge acquired by practice. Though this study will undoubtedly have implications for improving teacher professional development, students engaging with science are learning nature of science as these unexpected occurrences arise. In Park et al.'s (2016), students learned that in scientific experimentation, there is no single step-by-step method. The inherent human element in scientific inquiry renders it susceptible to occasional unforeseen complications.

4.4.2 Student agency and identity: student contributions to science storylines

Reiser et al. (2021), analyzed how students are supported and teachers guided in their sensemaking by researching student engagement in PhBL in a high school biology classroom. PhBL is such a vastly different teaching and learning approach that the dificulties teachers face in quickly learning and implementing this change were particularly highlighted in this article. Enacting these changes requires "deep understanding of the instructional principles since enacting these routines needs to be situated within the specifics of the trajectory of discussions" (Reiser et al., 2021, p. 825). The teacher must establish students as collaborators and the importance of each person in the knowledge-building process. If the teacher is successful in positioning the original anchoring phenomena, based on instructional materials, the students should have a strong voice throughout the lesson (Reiser et al., 2021).

The viewpoint of the students in driving learning, acting as co-constructors of scientific knowledge, and making sense of the content from their perspective, established the need for PhBL (Andersen et al., 2024; Lowell et al., 2021). This student viewpoint of science allows teachers to support coherence and collaboration, key connections to NGSS, if the phenomenon chosen is well selected (Lowell et al., 2021).

4.4.3 Student agency and identity: epistemic agency development

Curriculum materials and classroom routines seen from the student perspective must promote equitable coherence in design. For student questioning, anchoring the phenomenon in a way that promotes student brainstorming allows students to investigate their questions once they are posed (Reiser et al., 2021). A good example of a phenomenon provided in Reiser et al. (2021) as, "A high school unit on natural selection begins with an anchoring phenomenon of an adolescent girl who is suffering from an infection that is resistant to antibiotics (p. 816)." The study finds that PhBL adds contextualization to general science questions, which refines the phenomena to connect with students' lives. Much research still needs to be done on any potential learning consequences of increasing student epistemic agency (Reiser et al., 2021).

Current studies focusing on student agency and identity examine how students actively contribute to knowledge construction and develop scientific identities. This includes how teachers provide for a student's epistemic agency. Epistemic agency is defined by Cherbow (2023) as "students being positioned with, perceiving, and acting on, opportunities to shape the knowledge-building work in their classroom community," (Cherbow, 2023, p. 809). Reiser et al. (2021) emphasize student agency through routines that elicit student questions from phenomena and position students as partners in directing investigations. Penuel et al. (2022) center the storyline approach on questions and problems that students themselves identify as relevant, prioritizing student engagement and agency in science learning.

4.5 Category 5: contextual factors

Six papers (Adipat, 2024; Hagenah and Thompson, 2021; Nation and Kang, 2024; Penuel et al., 2022; Reiser et al., 2021; Sardana and Muddgal, 2024) were identified as emphasizing culture in phenomenon-based learning, though it is worth noting that some articles in this analysis were international studies. These articles state that as teachers practice and utilize PhBL it is crucial to understand their students' background, including the cultural environment from whence they grew up. This theme addresses the research question: How do cultural and contextual factors influence the implementation of phenomenon-based approaches? Research on cultural and social contexts (the circumstances to which events take place) examines how local environments and student backgrounds influence the implementation of phenomenon-based learning and storylines. The categories developing out of this theme included cultural and social contexts and cross-national perspectives. Penuel et al. (2022) and Reiser et al. (2021) emphasize the importance of connecting science to real-world phenomena and social issues relevant to students' lives by demonstrating how anchoring in familiar contexts supports student engagement.

4.5.1 Cultural and social contexts: cultural anchoring

By connecting natural and social science concepts within a familiar cultural framework, Sardana and Muddgal (2024) demonstrate how cultural context can enhance student engagement and understanding. This approach not only makes science more accessible but also highlights the interconnectedness of scientific disciplines with other areas of knowledge, empowering students to think critically and apply their knowledge to new situations.

An example of this type of cultural context anchoring in a phenomenon-based science lesson explores Indian cultural implications in a 7th grade science education class in India. The goal was to measure students' adaptation to an interdisciplinary storyline, check with challenges preservice teachers faced in implementing the lessons, and how cultural context was included. The results supported context-based STEM learning and how learning was strengthened by the inclusion of students' cultural backgrounds. In essence, the cultural context was found to have a positive effect on learning while using phenomenon-based learning to help integrate STEM disciplines (Sardana and Muddgal, 2024).

It is noted that teachers must have the ability to acknowledge and integrate many different cultural scenarios in some countries, such as the US, into the phenomena in the science classroom to address the varying cultures their students bring (Nation and Kang, 2024; Sardana and Muddgal, 2024).

4.5.2 Cultural and social contexts: connecting to students' lived experiences

Teachers spend a great deal of time connecting natural phenomena to students' lives and frame sensemaking to support students' connection to prior knowledge, but it is time-consuming and difficult to make connections to scientific processes (Hagenah and Thompson, 2021). Teachers must use students' lived experiences as a way to contextualize the scientific phenomena and in doing so can refer students back to the phenomena when student talk begins to misalign with intended goals. Teachers often resort to trial and error in how to effectively weave student experiences into PhBL lessons and further tools are needed to support teachers (Hagenah and Thompson, 2021).

Hagenah and Thompson (2021) studied and reported different approaches teachers took to responding to students as they made connections to scientific phenomena. One teacher intentionally used students' lived experiences as the basis for planning and "created opportunities for sensemaking that provided a context for students to make sense of the science phenomena" (Hagenah and Thompson, 2021, p. 542). Another teacher framed units on what was assumed students care for locally. A third teacher used lived experiences but without direct relevance or solid connection to the scientific phenomenon. These cases only provide a snapshot of the variance in teacher approaches in the implementation of PhBL. There is further research needed regarding the nuances of how teachers make connections to students' lived experiences and how students are stepping through the sensemaking process (Hagenah and Thompson, 2021).

4.5.3 Cross-national perspectives: implementations across different countries

Studies from a cross-national perspective examine how phenomenon-based learning or storylines are implemented across different countries. Cross-national studies reveal both universal principles that transcend cultural boundaries and the importance of cultural adaptation in implementing phenomenon-based learning effectively in different educational systems. Adipat (2024) conducted a meta-analysis that found the use of PhBL in several countries including Finland, Norway, USA, UAE, Turkey, Vietnam, Thailand resulted in student sensemaking improvements. Adipat (2024) found evidence in the literature that the use of PhBL successfully prepared students for real-world problems with its holistic approach. In addition, five dimensions were reported as helping support understanding of real-world phenomena: "holisticity, authenticity, contextuality, problem-based inquiry, and instructional process" (Adipat, 2024, p. 2). "Contextuality is a key aspect of PhenoBL" (Adipat, 2024, p. 2), because it helps personalize learning and provides a scaffold for situating lessons into past knowledge. The meta-analysis called for additional research in areas of interdisciplinary knowledge, technology integration, inclusion of multiple disciplines to improve student knowledge, and the use of different research methodologies.

4.5.4 Cross-national perspectives: cultural adaptations

In some countries, government-controlled curricula and standards must be used. In countries such as Korea or India, teachers and students alike find themselves having little exposure to science practices or integrated STEM education (Sardana and Muddgal, 2024). Indian culture may provide opportunities to have context for learning science. To find ways to reach students and connect their learning to the community they live in, "it is essential to attend to the ways in which minoritized students' (counter-) stories dismantle and reconfigure traditional science learning" (Nation and Kang, 2024, p. 876). Nation and Kang (2024) describe using creativity to provide an opportunity to leverage students' cultural assets to "expand the discipline of science" (p. 874) in a high school chemistry class. For example, a new perspective on a scientific phenomenon could "account for a view of science content that expands beyond traditional disciplinary content knowledge and understand how funds of knowledge rooted in Latinx female students' personal social history are leveraged to the discipline and practices of science" (Nation and Kang, 2024, p. 878). Nation and Kang (2024) collected data through interviews, recordings, and student documents to find making personal connections as a teacher improved the storyline along with recognizing students' epistemological contributions.

4.6 Category 6: implementation challenges

Research highlights significant challenges in implementing phenomenon-based learning and storyline approaches. Some of the articles we identified included challenges faced by educator resistance and training needs across multiple countries, despite evidence of its effectiveness (Adipat, 2024). Kawasaki and Sandoval (2019) finds that unclear framing by teachers leads students to adopt traditional passive roles rather than becoming epistemic agents, suggesting a primary challenge for professional development is helping teachers frame instruction appropriately. Andersen et al. (2024) identified two types of teacher uncertainty: facilitating students' scientific sensemaking through specific practices and navigating storyline curriculum using student ideas. Training implemented in the pre-service programs and for in-service teachers could address these issues and add to the research base. Sardana and Muddgal (2024) documented specific challenges faced by pre-service teachers implementing interdisciplinary storylines, including connecting content across disciplines and managing student engagement. These challenges collectively point to the need for sustained professional development, improved curricular materials, and institutional support for teachers implementing these approaches.

5 Discussion

Our analysis identified six interconnected themes that collectively shape how these approaches are conceptualized, implemented, and evaluated across diverse educational contexts. This organization provides researchers and practitioners with a structured framework for understanding the complex landscape of phenomenon-based learning and storyline approaches, including the identification of research gaps and underrepresented dimensions.

Our comprehensive systematic review provided an overview of PhBL in K-12 and how teachers and students alike are using it in the classroom and adopting this approach to learning. Specifically, this research reveals a consistent thread across the theoretical foundations, curriculum design, teacher development, and student outcomes resulting in a structured framework of current practices (Kawasaki and Sandoval, 2019; Lowell et al., 2022). Notably, the theoretical frameworks underscore the importance of students actively constructing knowledge through real-world phenomena and collaborative inquiry, a principle that directly influences curriculum design (Adipat, 2024; Chen and Techawitthayachinda, 2021).

Framing this approach within NGSS is an important piece of using and promoting the use of PhBL, yet we identified research gaps still in the clarity and support provided by curriculum materials (Li et al., 2024; Lowell et al., 2021). Commercial curricula often reduce phenomena to disconnected examples rather than integrated driving forces for investigation, creating significant challenges for teachers attempting to implement authentic phenomenon-based approaches. This curriculum design tension highlights the need for materials that better align with the fundamental principles of student-driven inquiry while providing sufficient scaffolding for teachers. Teachers, as evidenced by the literature on professional development, require substantial support to navigate PhBL, needing to develop not only content knowledge but also the pedagogical skills to facilitate student- driven inquiry within the context of NGSS (Hanuscin et al., 2016; Lowell and McNeill, 2023).

The gap between teachers' changing beliefs and their developing self-efficacy suggests that traditional professional development approaches may be insufficient. More sustained, practice-embedded professional learning opportunities may be necessary to develop the complex facilitation skills required for effective implementation. This need for teacher support is directly linked to student outcomes, where assessments must evolve to evaluate students' ability to apply knowledge and engage in scientific reasoning, rather than simply recall facts (Lowell et al., 2021; Penuel et al., 2019). The development of proximal transfer tasks represents a promising direction, but widespread adoption of assessment approaches aligned with phenomenon-based learning principles remains limited.

Our review also highlights the importance of underrepresented dimensions, specifically cultural context in phenomenon-based learning. The work of Nation and Kang (2024) and Sardana and Muddgal (2024) demonstrates how culturally responsive implementations can enhance student engagement and learning outcomes by connecting scientific phenomena to students' lived experiences and cultural backgrounds. This cultural responsiveness represents a critical dimension of equity in science education that deserves greater attention in both research and practice. While the majority of the reviewed literature centered on curriculum design and teacher professional development, the articles focusing on the student perspective offered a particularly critical viewpoint. This emphasis on student experience is essential, given the student-centered nature of phenomenon-based learning (PhBL), which actively positions learners as central participants in the knowledge construction process.

Science needs to be accessible to all students and through PhBL students have an active role in their learning and understanding of science practices and content. The authors pointed out in that ultimately a holistic approach that prioritizes student agency and sensemaking is required as the defining feature of PhBL (Penuel et al., 2022; Reiser et al., 2021).

5.1 Limitations

The selection of keywords could have excluded related articles however we wished to remain true to our research question in seeking articles with a central focus on the use of PhBL.. Internationally, other countries mentioned such as Finland or Thailand have implemented PhBL for a longer period of time than the United States and though we did our best to include international articles, we did not conduct a robust review of quantitative international journals. Our methodological approach was qualitative so that we could provide theoretical foundation on PhBL and its implementation. Quantitative analysis could add to the data on article statistics involving publications in PhBL outcomes when applying the foundations we have discussed. As this curriculum reform increases in use, consistency in terminology, training, and implementation should be continually reported on. The varied terminology used across studies (phenomenon-based learning, storylines, anchoring phenomena) creates challenges in synthesizing findings and building a coherent knowledge base.

6 Conclusion and future implications

Analysis of the literature reveals several important research gaps that future studies should address. There is a notable lack of longitudinal research examining the long-term impact of phenomenon-based learning and storyline approaches on student learning trajectories, scientific identity development, and career choices. While Adipat (2024) provides evidence of PhBL's effectiveness in enhancing student engagement and 21st-century skills, more research is needed on sustaining these outcomes over time. Penuel et al. (2022) presents compelling theoretical arguments for the storyline approach, but more empirical evidence is needed about its comparative effectiveness against other instructional models. Comparative studies examining the relative effectiveness of different implementation models would provide valuable guidance for practitioners choosing among various approaches. Sardana and Muddgal (2024) suggest the need for research in varied sociocultural contexts and discipline combinations to offer broader perspectives on interdisciplinary storylines. This cross-cultural research is essential for understanding how phenomenon-based approaches can be adapted to diverse educational contexts while maintaining their core principles.

The analysis reveals that phenomenon-based learning (PhBL) and storylines represent a significant pedagogical shift toward student-centered, inquiry-driven science education, grounded in robust theoretical frameworks emphasizing sensemaking and epistemic agency. However, successful implementation is contingent upon addressing several key challenges. Curriculum design requires meticulous attention to NGSS alignment, moving beyond superficial connections and ensuring that phenomena serve as driving forces for investigation rather than mere examples. This necessitates curriculum materials that provide sufficient guidance for teachers while maintaining the flexibility required for authentic student inquiry. Effective professional development for teachers is paramount, focusing on developing teachers' content knowledge, pedagogical content knowledge, and self-efficacy. This includes training in facilitating classroom discussions, making pedagogical links, and adapting lessons in real time to address student thinking. The developmental nature of teacher learning in this area suggests the need for sustained, practice-embedded professional learning opportunities. Furthermore, assessment practices must evolve to prioritize scientific reasoning, explanation, and application, moving away from traditional fact-based assessments. Proximal transfer tasks show promise in evaluating students' ability to apply knowledge in novel contexts, but wider adoption of aligned assessment approaches remains a challenge. The importance of cultural responsiveness emerged as a critical dimension of effective implementation, with several studies highlighting how connecting to students' lived experiences and cultural backgrounds can enhance engagement and learning outcomes. This cultural dimension represents an essential consideration for equity in science education.

The literature also lacks sufficient studies on assessment approaches specifically designed for phenomenon-based and storyline teaching, with most existing research focusing on implementation rather than evaluation. Research on developing valid, reliable, and equitable assessment tools that align with the principles of phenomenon-based learning represents a critical need. Additionally, research on scalability is limited, with few studies examining how these approaches can be effectively implemented across entire school districts or educational systems. Studies exploring the systemic conditions, policies, and supports necessary for widespread adoption would provide valuable guidance for educational leaders seeking to scale these approaches.

Ultimately, the successful integration of PhBL and storylines necessitates a holistic approach that addresses curriculum design, teacher development, and assessment, ensuring that all students have equitable opportunities to engage in meaningful science learning. The six thematic categories identified in this review—theoretical foundations, curriculum design, teacher development, student engagement, contextual factors, and implementation challenges—provide a comprehensive framework for understanding and advancing these promising approaches to science education.

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