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Assessing Students' Engagement in Scientific Practices: Implications for Science Education Reform

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ABSTRACT: Over the past decade, scientific practices have emerged as a central paradigm in science education, reflecting a broader shift from content transmission toward epistemic engagement and authentic inquiry. This study employs bibliometric mapping to systematically analyze 594 peer-reviewed documents published between 2011 and 2025, aiming to explore how scientific practices have been defined, conceptualized, and assessed in the field. Results reveal a significant conceptual evolution: from the traditional notion of a linear scientific method to a multidimensional framework encompassing epistemic cognition, collaborative inquiry, and socio-scientific reasoning. Five key thematic clusters epistemic cognition, pedagogical models, nature of science, technology integration, and equity dominate the discourse. These clusters underscore the growing focus on student-centered, project-based, and digitally mediated learning environments. Despite growing interest and innovation in pedagogical strategies, assessment remains a persistent challenge. Traditional assessments fail to capture authentic engagement, prompting a call for performance-based and technologically supported tools that align with the complexity of scientific practices. Furthermore, the analysis highlights the increasing emphasis on equity and inclusivity, with citizen science initiatives serving as powerful models for democratizing science education. The findings offer strategic insights into the alignment of curriculum, teacher training, and assessment frameworks, ultimately contributing to global science education reform. By centering scientific practices, education systems can promote deeper learning, critical thinking, and civic engagement among learners worldwide.

KEYWORDS: Scientific Practices, Science Education Reform, Bibliometric Mapping, Assessment in Science Education.

INTRODUCTION

Over the past decade, science education has undergone a significant shift from rote memorization of decontextualized facts to fostering students' participation in authentic scientific practices. This transformation reflects a broader recognition that science is not simply a static body of knowledge, but a dynamic, inquiry-driven process of constructing and validating understanding. Practices such as asking questions, constructing explanations, and engaging in argumentation connect classroom experiences with how science is conducted in the real world, making learning more meaningful and relevant (Admawati & Jumadi, 2021; Demir, 2016; Nurfadilah et al., 2023; Saribas, 2023). This approach not only strengthens content knowledge but also cultivates critical skills such as reasoning, collaboration, and problem-solving (García-Carmona, 2020; Sparks et al., 2022; Tang, 2020b).

Globally, various educational initiatives have successfully embedded scientific practices into teaching, including inquiry-based curricula, project-based learning (PjBL), and citizen science projects. These approaches have been shown to enhance student motivation, creativity, and scientific literacy (Admawati & Jumadi, 2021; Kimura, 2021). For instance, when students engage in real-world investigations—like monitoring energy use or air pollution—they gain insight into the societal role of science while also developing essential cognitive and social skills (Cabrini et al., 2021; Carmel et al., 2019; Romero-Maltrana et al., 2019). These movements signal the potential of scientific practices to shape informed citizens who can participate in evidence-based decision-making.

Scientific practices are inherently multi-dimensional, involving cognitive, epistemic, and social processes (Kimura, 2021; Nurfadilah et al., 2023). Early education models often equated science with the rigid "scientific method" a step-by-step process of hypothesis testing and experimentation. However, scholars now argue that such models oversimplify scientific reasoning. Contemporary frameworks emphasize model-based inquiry and interrelated practices such as designing investigations, analyzing data, and critically evaluating claims (Sira et al., 2025; Wierzchowski & Wink, 2024).

Recent advances further conceptualize scientific practices as *epistemic tools* that support the development and justification of knowledge. For example, Tang (2020) describes how scaffolding strategies like the *Premise Reasoning Outcome* (PRO) structure help students formulate explanations while building metacognitive awareness. This dual emphasis on cognition and metacognition places scientific practices at the heart of students' epistemic development. From the perspective of Nature of Science (NOS) scholars, embedding these practices also promotes deeper understanding of how scientific knowledge evolves through evidence, critique, and revision (Hodson & Wong, 2017).

However, evaluating students' engagement in scientific practices remains a persistent challenge. Traditional assessments, such as multiple-choice tests, are inadequate for capturing complex skills like modeling, argumentation, or inquiry-based collaboration. To address this, researchers have proposed performance-based assessments portfolios, project outcomes, and discourse analysis as more authentic measures of student engagement (Abd Khalik & Hadi Bunyamin, 2024; Demir, 2016; Leowardy et al., 2025)

Digital technologies are also opening new frontiers in assessment. Tools such as simulation platforms and data analysis software now enable educators to evaluate students' inquiry processes in real time (Admawati & Jumadi, 2021). Additionally, historical studies reveal how the portrayal of scientific practices in textbooks can influence how they are taught and assessed (Saribas, 2023; Thomann, 2023). Despite these innovations, reviews continue to note gaps in developing assessments that are both valid and scalable across diverse educational contexts (Larasatie et al., 2024).

Multiple contextual factors shape student engagement with scientific practices. Curriculum policies that prioritize inquiry create opportunities for deeper learning, but implementation varies widely. Teachers play a pivotal role; their understanding of and confidence in practice-based instruction significantly influence student outcomes (Cooper et al., 2022; Demir, 2016; Gao et al., 2021). The effective integration of digital and project-based tools can also enhance authenticity and relevance (Admawati & Jumadi, 2021; Flemming et al., 2020; Paek & Fulton, 2021).

Participation in scientific practices correlates with numerous educational benefits. Students who engage in investigations and modeling tend to demonstrate improved conceptual understanding and stronger critical thinking skills (Fisher & Greer, 2024; Jardim et al., 2021; Tang, 2020a). Furthermore, citizen science projects offer students a platform to address real-world issues creatively, fostering both scientific literacy and civic engagement (Aridor-Berger et al., 2023; Cabrini et al., 2021; Kali et al., 2023). Historical accounts further show that educational systems emphasizing authentic scientific practices have contributed to scientific innovation and social progress (Mayo-Santana et al., 2016).

Despite a growing body of research, a notable gap remains in understanding how scientific practices are assessed and integrated into science education across diverse contexts. Much of the literature focuses on conceptual frameworks or isolated pedagogical innovations, with limited synthesis on how assessment practices evolve in tandem with curricular reforms. Furthermore, there is limited clarity on how these shifts align with broader educational goals such as equity and inclusivity. This study addresses that gap by systematically analyzing global literature to trace how scientific practices have been defined, categorized, and assessed, and what implications these developments hold for science education reform.

Evidence surrounding the assessment of scientific practices carries major implications for reform. First, curriculum design must treat scientific practices as core learning objectives—placing inquiry, modeling, and argumentation at the center of instruction (Hodson, 2014). Second, teacher preparation programs must train educators to both facilitate and assess practice-based learning. Third, more investment is needed in developing innovative, technology-enhanced assessment tools that provide actionable insights (Tang, 2020). Lastly, equity must be a guiding principle: assessment strategies and learning environments should ensure that all students—regardless of background—can meaningfully engage with science. In this regard, citizen science exemplifies an inclusive model that connects students, teachers, and communities in collaborative inquiry (Cabrini et al., 2021).

Research Questions

How have scientific practices been defined, categorized, and conceptualized in science education research over the past decade?

What are the implications of research findings on the assessment of scientific practices for science education reform, particularly in relation to curriculum policies and classroom pedagogical practices?

METHODS

1. Research Design and Approach

This study adopts a bibliometric mapping method to systematically analyze the development and trends of *scientific practices* within the field of science education. Bibliometric mapping has been widely applied to explore the structure, patterns, and evolution of scholarly domains by quantifying publications, citations, and keyword relationships (Tang, 2020; Demir, 2016). The strength of this approach lies in its ability to provide both descriptive and network-based insights, thereby uncovering not only the growth trajectory of publications but also the intellectual and thematic linkages within the field (Hodson, 2014).

The bibliometric approach was selected for three primary reasons. First, it allows for the systematic examination of a large body of literature, ensuring comprehensive coverage of global research output. Second, bibliometric visualization tools such as VOSviewer and Biblioshiny provide sophisticated mechanisms to represent co-authorship networks, keyword co-occurrences, and thematic clusters. Third, the approach aligns with previous educational studies that used bibliometric analysis to evaluate the integration of epistemic tools, inquiry-based practices, and the nature of science into classroom instruction (Cabrini et al., 2021; Admawati & Jumadi, 2021).

2. Data Source and Retrieval Procedure

The data for this study were collected from the Scopus database (https://www.scopus.com), which is recognized as one of the largest repositories of peer-reviewed scientific literature. Scopus was chosen due to its comprehensive coverage of international journals, conference proceedings, and book chapters, as well as its robust indexing of educational and interdisciplinary publications (Thomann, 2023).

An electronic search and retrieval process was conducted on June 22, 2025. The search query applied the TITLE-ABS-KEY field, which restricts the keyword search to the title, abstract, and keywords of indexed documents, thus ensuring relevance and specificity. The exact search string used was:

TITLE-ABS-KEY (“scientific practices” AND “science education”)
This query initially yielded 759 documents. The preliminary dataset included various document types and languages. To refine the dataset, a set of exclusion criteria was applied systematically.

3. Inclusion and Exclusion Criteria

The dataset was filtered according to three primary criteria:
Publication year coverage (2011–2024): To focus on recent trends and provide a temporal scope of analysis, documents published before 2011 and after 2024 were excluded. This reduced the dataset to 660 documents.
Document type: Only peer-reviewed scholarly works, including journal articles, conference papers, book chapters, books, and review papers, were retained. Editorials, notes, and non-research documents were excluded, resulting in 647 documents.
Language: Since the purpose of the study was to provide an internationally accessible analysis, only documents published in English were included. This step yielded a final dataset of 594 documents for analysis.
This multi-stage refinement process is consistent with established bibliometric studies in science education, which emphasize the importance of narrowing datasets to maintain methodological rigor and ensure comparability across studies (Hodson, 2014; Mayo-Santana et al., 2016).

4. Data Processing and Analytical Tools

The data analysis process began with acquiring the raw bibliographic data from Scopus in both CSV (comma-separated values) and RIS (research information system) formats. These formats are compatible with standard bibliometric software and allow for both quantitative and network-based analysis.
The analysis proceeded in three stages, for the first descriptive analysis with Microsoft Excel. Basic bibliometric indicators such as publication trends by year, distribution by source type, and geographical authorship patterns were tabulated and visualized using Microsoft Excel. This provided a foundational understanding of research output dynamics (Admawati & Jumadi, 2021).
Second stages is network visualization with VOSviewer. VOSviewer was employed to generate bibliometric maps that depict co-authorship networks, citation patterns, and keyword co-occurrences. This software is particularly effective for clustering related research themes and identifying intellectual structures within the field (Tang, 2020).
And the last thematic analysis with Biblioshiny. Biblioshiny, an R-based bibliometric tool, was used to complement VOSviewer analyses by providing thematic evolution maps, collaboration indices, and conceptual structure models. Its interactive interface enabled a deeper examination of research clusters and thematic developments over time (Cabrini et al., 2021). Together, these tools allowed for both macro-level trend identification and micro-level thematic exploration. This mixed-tool strategy enhances methodological robustness by triangulating findings across multiple software platforms (Thomann, 2023).

5. Validity, Reliability, and Limitations

Several measures were taken to ensure the validity and reliability of the study. The use of Scopus as the sole database ensured consistency in indexing standards and metadata quality, reducing the likelihood of duplication or misclassification of documents. The exclusion criteria were transparently defined and applied, ensuring replicability of the dataset selection. Additionally, the integration of three analytical platforms (Excel, VOSviewer, Biblioshiny) minimized tool-specific biases and increased the robustness of the analysis.
Nevertheless, limitations must be acknowledged. First, the exclusive reliance on Scopus may omit relevant studies indexed in other databases such as Web of Science or ERIC, potentially underrepresenting regional or non-English scholarship. Second, bibliometric mapping captures structural patterns but does not evaluate the substantive quality of research outputs. For instance, while co-occurrence analyses reveal frequently used keywords, they do not necessarily indicate the depth of theoretical or empirical contributions. Third, the temporal cut-off (2011–2024) excludes earlier foundational studies that may provide important historical context (Hodson, 2014).
Despite these limitations, bibliometric mapping remains a robust method for capturing large-scale trends, intellectual structures, and thematic developments in science education research. By focusing on scientific practices, this study offers valuable insights into how the field has evolved and where future research and educational reforms might be directed.

RESULTS

Conceptual and Theoretical Dimensions of Scientific Practices

Among the 594 documents, journal articles represented the largest share, accounting for more than two-thirds of the corpus. This indicates that scientific practices are primarily disseminated through peer-reviewed scholarly journals. Conference papers formed the second largest category, reflecting the role of academic conferences in sharing preliminary findings, methodological innovations, and practical implementations of scientific practices. Book chapters and books provided in-depth theoretical and conceptual explorations, while review papers synthesized research trends and helped shape future research directions.
The diversity of publication types highlights the multidimensional nature of the field: empirical studies tested classroom interventions, conceptual papers debated the definition and scope of scientific practices, and reviews provided systematic syntheses of prior work.

Most relevant sources

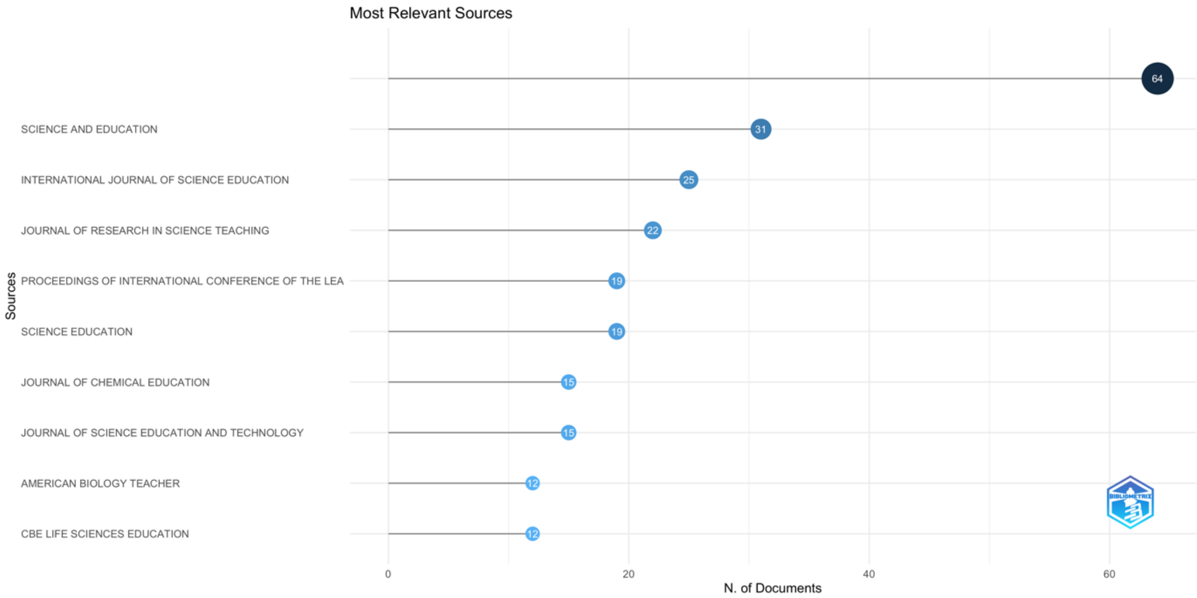

Figure 1. Most relevant sources for documents on scientific practices in science education (2011–2025).

Research outputs were concentrated in high-impact science education journals. Figure 1 highlights the *most relevant sources*, including *Science Education*, *International Journal of Science Education*, and the *Journal of Research in Science Teaching*. These venues dominate the discourse, complemented by specialized journals such as *Journal of Chemical Education*, *Journal of Science Education and Technology*, and *American Biology Teacher*.

In addition, Figure 2 shows longitudinal growth in cumulative publications by source. Both *Science Education* and the *International Journal of Science Education* have consistently contributed the largest number of studies, while other journals show steady increases, underscoring the diffusion of interest across multiple outlets.

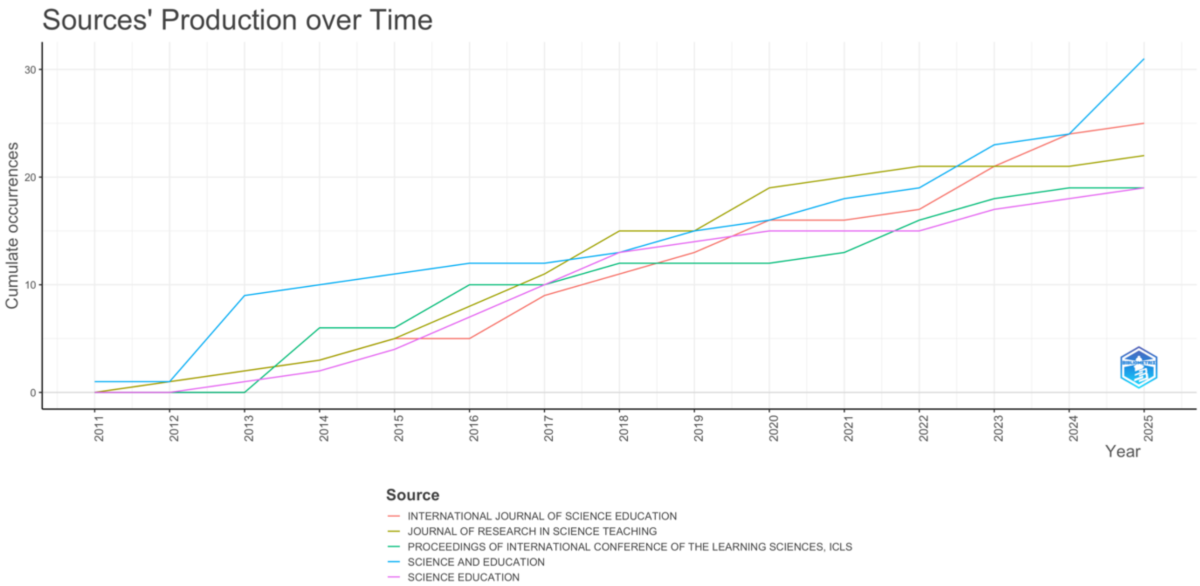

Figure 2. Sources' cumulative production over time (2011–2025).

Trend of publications and citation

The distribution of publications per year indicates a consistent growth in research on scientific practices over time. As shown in Figure 3, the number of publications rose steadily from 2011 onward, reflecting the increasing scholarly attention to scientific practices in science education. Early contributions were limited, but from 2015 onwards the field demonstrated rapid expansion. Peaks occurred around 2020–2023, coinciding with global discussions on science education reform, digital learning adoption, and the integration of STEM/STEAM approaches. This upward trajectory suggests that scientific practices have become a central theme in international science education research.

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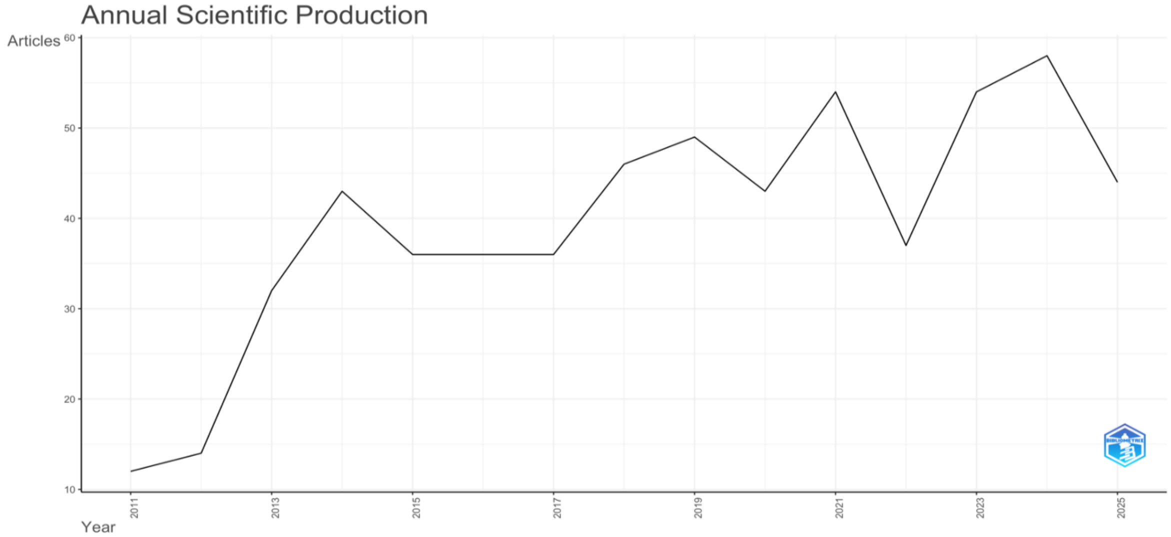

Figure 3. Annual scientific production of documents on scientific practices in science education (2011–2025).

The citation analysis provides insights into the impact of publications over time. Figure 4 illustrates the average number of citations per year. Higher citation averages were observed between 2014 and 2017, with a peak in 2016. This pattern indicates that foundational conceptual and methodological works published during this period exerted strong influence on subsequent scholarship. Although citation averages declined slightly in more recent years, this is likely due to the recency of publications, which have had less time to accumulate citations. These findings suggest that while the volume of publications has grown steadily, the field remains anchored in a set of highly influential contributions that continue to guide current research.

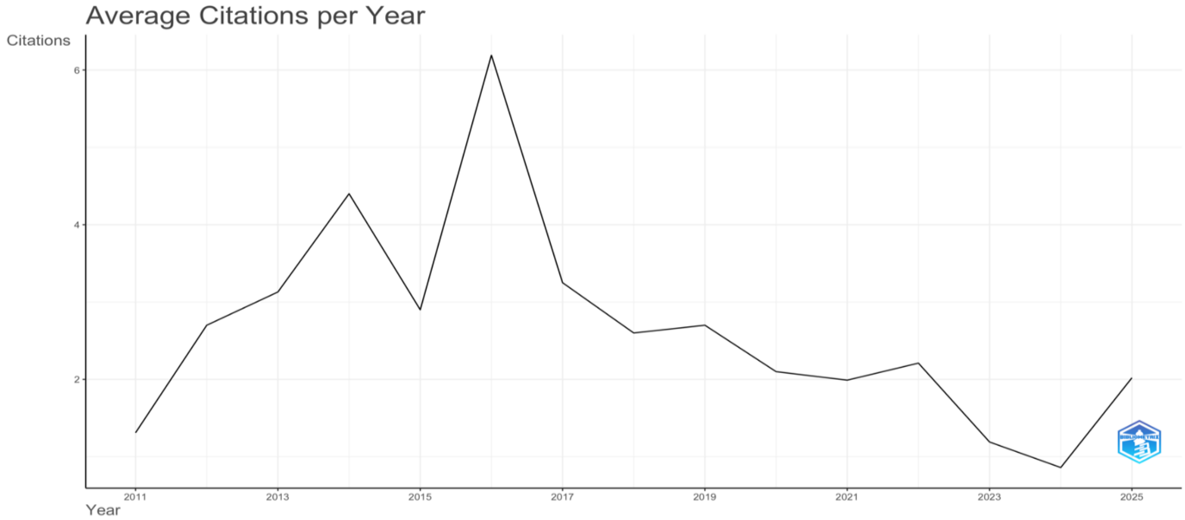

Figure 4. Average citations per year for publications on scientific practices in science education (2011–2025)

Most relevant keywords

Figure 5. Keyword co-occurrence cloud for research on scientific practices in science education (2011–2025).

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Keyword analysis revealed the dominant conceptual emphases within the field. Figure 5 (keyword cloud) shows that terms such as *science education*, *students*, *scientific practices*, *teaching*, and *curriculum* occur most frequently. This confirms the centrality of scientific practices in the broader discourse of education, student engagement, and curriculum design.

Thematic mapping further illustrates how research clusters are distributed. As shown in Figure 6, themes such as *epistemic cognition*, *STEM/STEAM education*, *inquiry-based learning*, *citizen science*, and *nature of science* occupy significant proportions of the literature. This mapping highlights the interdisciplinary scope of scientific practices, linking theoretical, pedagogical, technological, and socio-cultural dimensions.

Thematic Cluster Synthesis

The identified themes can be grouped into five broad clusters (see Table 1):

Table 1. Thematic clusters in research on scientific practices in science education (2011–2025).

Cluster	Key Themes
Epistemic Cognition	Epistemic tools, explanation structures, metacognition
Pedagogical Models	Inquiry-based learning, STEM/STEAM, project-based approaches
Nature of Science	NOS perspectives, curriculum reform, argumentation
Technology Integration	Digital platforms, modeling software, simulations
Equity & Participation	Citizen science, inclusivity, socio-scientific issues

Figure 6. Thematic tree map of clusters in research on scientific practices in science *education (2011–2025).*

The current research landscape in *scientific practices*

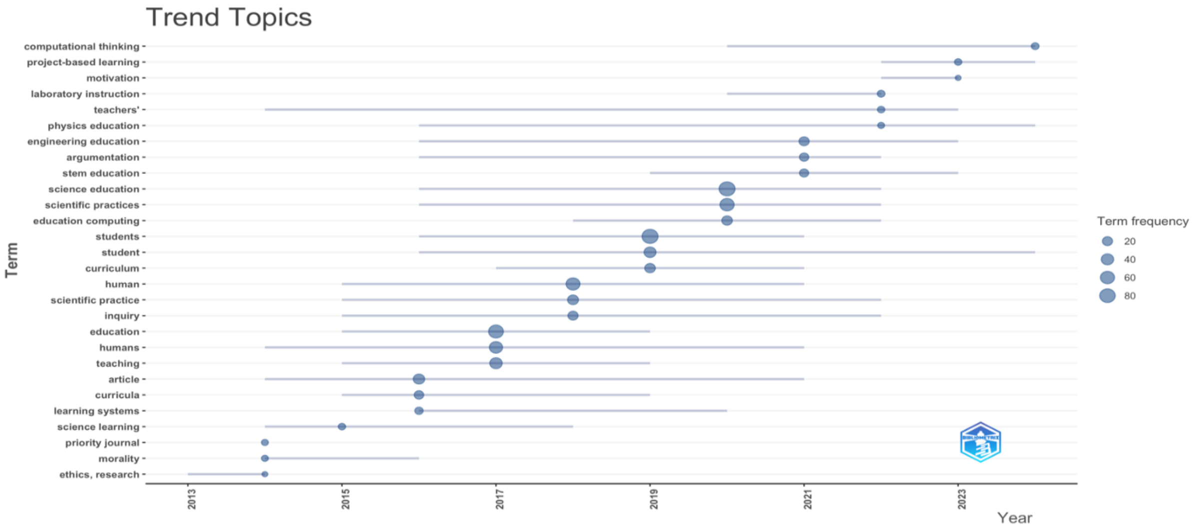

Figure 7. Trend topic of scientific practices

The analysis of trend topics on figure 7 reveals the chronological evolution of research on scientific practices in science education from 2011 to 2025. In the early years (2011–2014), the focus was primarily on conceptual foundations, with keywords such as *scientific inquiry*, *learning progression*, and *epistemology* dominating the discourse. This indicates that much of the early scholarship aimed to clarify definitions, categories, and theoretical perspectives on scientific practices. In the middle phase (2015–2018), the emphasis shifted toward pedagogical applications, reflected in the growing prominence of themes such as *argumentation*, *scientific modeling*, and *STEM/STEAM education*. This trend suggests increasing interest in integrating scientific practices into instructional strategies and classroom interventions. In the most recent period (2019–2025), new directions emerged, including *epistemic cognition*, *computational thinking*, *project-based learning*, and *citizen science*. These topics highlight the field's expansion into digital literacies, interdisciplinary learning, and socially relevant engagement, demonstrating a diversification of how scientific practices are conceptualized and implemented in contemporary education.

The thematic map on figure 8 provides further insight into the intellectual structure of the field by categorizing research themes according to their centrality and development. *Science education*, *students*, *scientific practices*, and *humans* are located in the motor themes quadrant, indicating that they are both highly developed and central to the discourse. These represent the conceptual and practical core of the field, anchoring most research outputs. Basic themes such as *higher education*, *curriculum*, and *biology* occupy a central but less mature position, suggesting their importance but also indicating that they require further theoretical and methodological refinement. In contrast, niche themes like *chemical education research* and *knowledge instruction* are well developed but peripheral, reflecting specialized areas with limited influence across the broader field. Finally, emerging or declining themes, such as *informal science education* and *learning identity*, appear in the lower-left quadrant, signaling either areas of diminishing focus or new lines of inquiry that have yet to gain prominence.

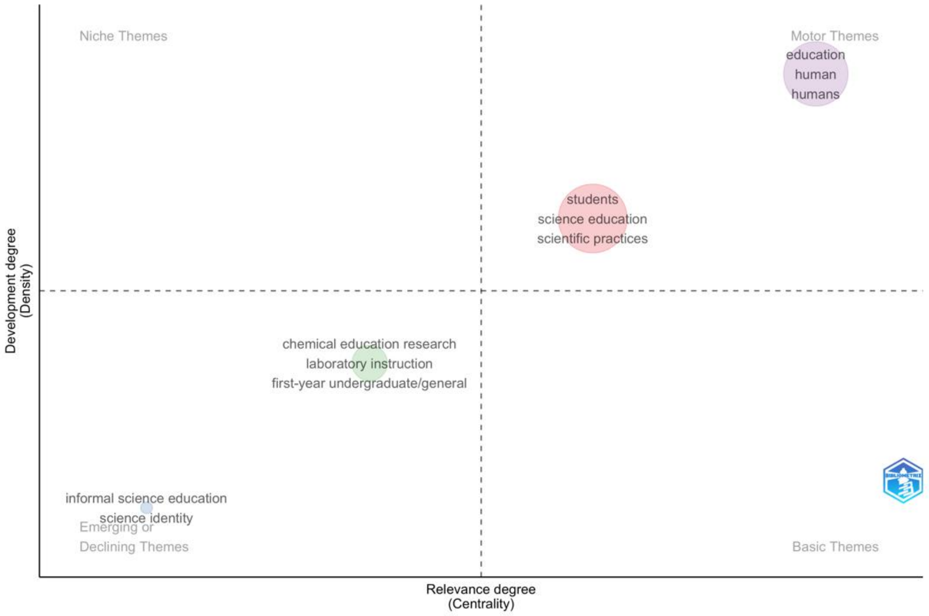

Figure 8. Thematic map of *scientific practices*

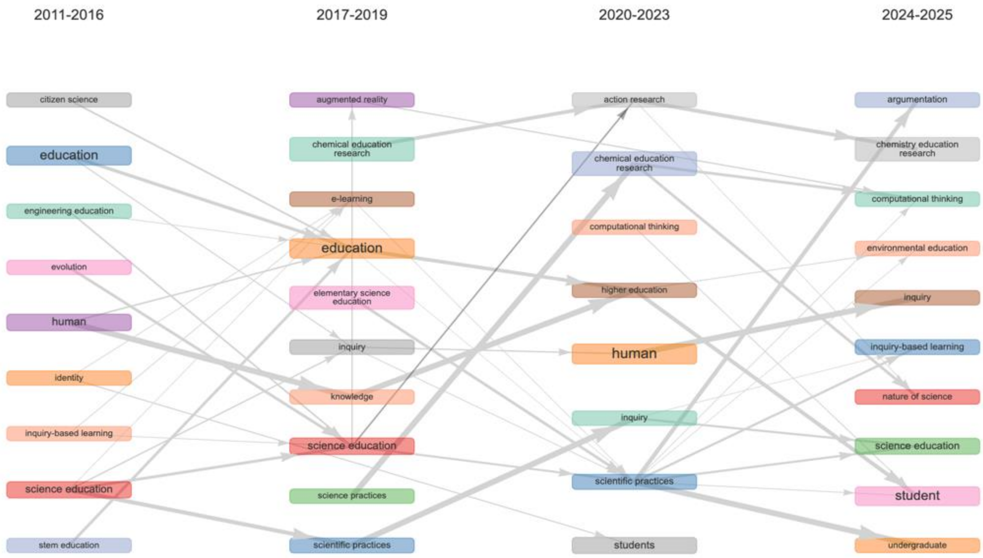

Figure 9. Thematic Evolution of *scientific practices*

The thematic evolution analysis (Figure 9) highlights how the discourse on scientific practices in science education has developed over time. In the period 2011–2016, early themes such as *education*, *science learning*, and *student engagement* dominated the landscape. These foundational concepts established the groundwork for integrating scientific practices into broader science education discussions. Moving into 2017–2019, the focus began to diversify, with the emergence of more specialized themes including *chemical education research*, *scientific modeling*, and *knowledge instruction*. This indicates a shift from general discussions of education toward more disciplinary and methodological explorations.

During the period 2020–2023, the thematic structure expanded further, reflecting the increasing complexity of the field. Central themes included *human*, *curriculum*, and *computational thinking*, alongside continued interest in *chemical education*. This stage suggests that the literature began to embrace both socio-cultural dimensions (human-centered education, inclusivity) and digital literacies (computational approaches) as essential components of scientific practices. Finally, in 2024–2025, the analysis shows that themes such as *comprehensive school*, *project-based learning*, *citizen science*, and *students* have gained prominence. These topics underscore the current orientation of research toward authentic learning contexts, interdisciplinary approaches, and equity-driven participation in science education.

Overall, the thematic evolution map demonstrates a clear trajectory: from broad educational foundations (2011–2016), through disciplinary and methodological specialization (2017–2019), toward technological integration and socio-cultural considerations (2020–2023), and finally to the present focus on applied, equity-centered, and student-driven practices (2024–2025). This evolution illustrates the maturation of the field, showing how scientific practices have become embedded within global reform agendas that emphasize innovation, inclusivity, and authentic engagement.

IMPLICATIONS FOR SCIENCE EDUCATION REFORM

The bibliometric review underscores significant implications for science education reform. First, the integration of scientific practices necessitates curriculum realignment, prioritizing inquiry, modeling, and argumentation as core goals rather than peripheral activities. Second, teacher professional development must be restructured to ensure educators are prepared to facilitate and assess scientific practices effectively. Third, investment in innovative assessment tools including epistemic scaffolds and technology-based measures—will be critical for capturing authentic student engagement.

Finally, the literature points toward equity and inclusivity as central concerns. Citizen science initiatives and contextually embedded studies demonstrate that scientific practices can serve as a vehicle for democratizing science education, connecting it with societal needs, and fostering wider participation. These findings highlight that reforms inspired by scientific practices must balance conceptual rigor with accessibility, ensuring that all students can benefit from engaging with science as a dynamic and socially relevant enterprise.

DISCUSSION

This study provides a comprehensive analysis of how scientific practices have been conceptualized, implemented, and assessed within science education research over the past decade. Through a bibliometric mapping of 594 peer-reviewed documents, the study uncovers thematic trajectories that reflect a broader transformation in science education—from content transmission to active engagement in epistemic practices. This paradigm shift aligns with arguments presented by Hodson (2014), who criticized the overreliance on a rigid “scientific method” and instead promoted a vision of science as a dynamic and socially embedded process. The reconceptualization of scientific practices framed through dimensions of epistemic cognition, modeling, argumentation, and socio-scientific reasoning has significantly influenced educational discourse and practice.

The evolution of these conceptual frameworks is evident in the identified thematic clusters, which demonstrate a growing emphasis on epistemic tools, such as the Premise–Reasoning–Outcome (PRO) structure (Tang, 2020), and their capacity to scaffold students’ metacognitive development. These tools reflect an important epistemological turn in science education, wherein learning is not only about acquiring knowledge but about understanding how knowledge is constructed, justified, and revised. This is further reinforced by the growing integration of Nature of Science (NOS) perspectives, which help students critically engage with the processes through which scientific knowledge emerges (Hodson, 2014). The clustering of themes such as “epistemic cognition” and “inquiry-based learning” confirms that scientific practices have become a central axis around which much of contemporary science education revolves.

The implementation of these practices in classrooms has been largely driven by pedagogical innovations such as project-based learning (PjBL) and STEM/STEAM frameworks. Studies such as those by Admawati and Jumadi (2021) have demonstrated the potential of PjBL to cultivate students’ engagement in engineering and scientific practices, emphasizing their relevance to real-world challenges. The effectiveness of such models stems from their capacity to position students as active constructors of knowledge, engaging in tasks that mirror the work of scientists. When coupled with digital platforms and modeling tools, these pedagogies provide immersive environments where students plan investigations, analyze data, and communicate findings in ways that are both meaningful and authentic (Demir, 2016). However, challenges remain in scaling these models due to discrepancies in teacher preparedness and institutional infrastructure. Despite the success of pilot programs, broader systemic reform is needed to ensure the widespread adoption of practice-oriented instruction.

A critical dimension of this shift is the assessment of scientific practices. The study highlights that while scientific practices have been conceptually embraced, assessment practices have lagged. Traditional assessments—relying heavily on multiple-choice formats—fail to capture the depth and complexity of student engagement in modeling, explanation, and argumentation (Larasatie et al., 2024). This misalignment threatens the integrity of reform efforts, as it reduces the visibility of students’ epistemic growth. In response, recent studies advocate for alternative assessment models, including performance-based tasks, portfolios, and digital simulations (Tang, 2020). These tools allow educators to evaluate both process and product, capturing students’ reasoning and metacognitive strategies. Although promising, these tools require further validation and contextual adaptation to ensure they are equitable, scalable, and pedagogically sound.

Beyond pedagogy and assessment, the thematic and temporal evolution of research signals broader changes in the field. From 2011 to 2014, the discourse was dominated by foundational concepts such as “scientific inquiry” and “epistemology.” These early discussions focused on clarifying definitions and conceptual boundaries. Between 2015 and 2018, attention shifted toward classroom practices, as themes like “argumentation,” "modeling," and "STEM education" gained prominence. This period marked a move toward practical integration of scientific practices into instructional frameworks. More recently, between 2019 and 2025, the literature has expanded to include "computational thinking," "project-based learning," and "citizen science," reflecting a growing interest in digital literacies and socio-scientific engagement. This progression suggests that the field is maturing, embracing both technological innovation and inclusive pedagogies that emphasize relevance, equity, and student agency.

The emergence of equity and inclusivity as central themes represents a significant development in the discourse on scientific practices. Citizen science, in particular, exemplifies how scientific engagement can transcend the classroom, connecting students with community-based inquiries and real-world problem solving (Cabrini et al., 2021). These initiatives allow learners from diverse backgrounds to participate meaningfully in science, challenging historical patterns of exclusion. Furthermore, when situated in students' lived experiences—such as investigating local air pollution or energy usage—scientific practices become more than academic exercises; they become tools for civic engagement and social change. As Larasatie et al. (2024) argue, any reform rooted in scientific practices must explicitly address issues of access and equity to avoid reproducing existing educational disparities.

The findings of this study make several contributions to the field of science education. First, it affirms that scientific practices have transitioned from peripheral innovations to central reform priorities. Second, it documents the proliferation of diverse pedagogical and assessment strategies aimed at operationalizing these practices. Third, it provides a meta-level view of how the field has evolved, offering educators, researchers, and policymakers a roadmap for future action. Importantly, it underscores that reform must be systemic. Without alignment among curriculum standards, teacher preparation, instructional resources, and assessment tools, the integration of scientific practices will remain uneven and fragmented.

The implications of this study for future research are both clear and urgent. There is a need for longitudinal studies that examine how sustained engagement in scientific practices shapes students' conceptual understanding, identity formation, and aspirations in STEM fields. Further empirical investigations are also needed to evaluate the reliability and equity of emerging assessment tools across varied cultural and educational contexts. Additionally, interdisciplinary collaboration—with experts in cognition, technology, and sociology—could enhance both the theoretical depth and practical relevance of future studies. In particular, future research must explore how scientific practices can be leveraged to promote social justice, address global challenges, and reimagine science education as a participatory, democratic, and inclusive endeavor.

CONCLUSION

This study offers a comprehensive bibliometric analysis of how scientific practices have been defined, conceptualized, and assessed within science education research over the past decade (2011–2025). Addressing the first research question, the findings reveal that scientific practices have evolved from being narrowly associated with the traditional scientific method to being understood as complex, multi-dimensional processes involving epistemic cognition, socio-scientific reasoning, and collaborative inquiry. Five major thematic clusters epistemic cognition, pedagogical models, nature of science, technological integration, and equity emerged as central to this reconceptualization. These themes collectively reflect a shift in science education toward more authentic, student-centered, and socially relevant learning experiences.

In response to the second research question, the implications of this evolution for curriculum and pedagogy are profound. Research underscores the need to redesign science curricula to position scientific practices as core learning goals, emphasizing inquiry, modeling, and argumentation. Pedagogical innovations, particularly project-based learning and the integration of digital platforms, have shown promise in making scientific practices accessible and meaningful for students. However, assessment practices remain a critical challenge. Traditional assessments are misaligned with the goals of scientific practice; hence, the field calls for scalable and valid performance-based tools that capture students' reasoning and metacognition. Furthermore, equity concerns are increasingly emphasized, with citizen science and community-based inquiry emerging as effective vehicles for inclusive engagement.

Overall, this study contributes to the field by mapping the intellectual structure and thematic trends of research on scientific practices. It highlights the need for systemic alignment across curriculum, teacher preparation, and assessment. Future research should explore longitudinal effects of practice-based learning and expand the development of equitable assessment strategies. By centering scientific practices, science education can evolve into a more democratic, engaging, and transformative endeavor, equipping all learners for active participation in knowledge-building and decision-making.

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