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Assessing Science Process Skills through Conceptual Frameworks: A Scoping Review

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Abstract

The assessment of science process skills (SPS) is a fundamental component in cultivating scientific literacy and promoting inquiry-oriented learning across educational settings. However, the conceptual and theoretical foundations guiding SPS assessment remain inconsistently defined and unevenly applied. This scoping review systematically maps existing conceptual and theoretical frameworks that inform the assessment of SPS, focusing on their definitions, components, and implementation practices across educational levels. Guided by the Arksey and O'Malley (2005) methodological framework and the PRISMA-ScR reporting guidelines, a systematic search was conducted in the Scopus and Web of Science databases. From an initial pool of 135 records, sixteen empirical studies met the inclusion criteria and were analysed thematically. The review pursued three objectives: to identify and categorise existing conceptual and theoretical frameworks, to examine how they define and operationalise SPS components, and to explore their application, adaptation, and validation in empirical contexts. The synthesis revealed four interrelated dimensions that underpin SPS assessment: conceptual and structural design, pedagogical alignment, psychometric validation, and contextual and participatory relevance. These dimensions interact dynamically within an integrated conceptual perspective that connects theoretical grounding, instructional practice, empirical validation, and contextual adaptability. While recent studies increasingly incorporate inquiry-based, metacognitive, and data-driven approaches, theoretical integration and construct coherence remain limited. The findings underscore the need for coherent, evidence-based frameworks that unite cognitive, metacognitive, and sociocultural perspectives, ensuring validity, reliability, and contextual responsiveness in assessing science process skills. This review contributes a comprehensive synthesis that advances theoretical clarity and supports the development of robust and inclusive SPS assessment practices in contemporary science education.

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Introduction

Science process skills (SPS) are fundamental competencies that empower learners to engage in scientific inquiry, critical thinking, and problem solving (Arantika et al., 2019; Deta et al., 2020; Hikmah et al., 2018; Inayah et al., 2020). These skills include observing, hypothesising, experimenting, analysing data, interpreting evidence, and communicating findings (Asy'ari et al., 2019; Safaah et al., 2017). They are integral to the development of scientific literacy, enabling students to construct understanding through evidence-based reasoning rather than memorisation of facts (Jurečková et al., 2024; Sholahuddin et al., 2020). In contemporary science education, mastery of SPS is recognised as a key indicator of students' ability to think scientifically (Arantika et al., 2019; Yulianti et al., 2024) and apply scientific knowledge to real-world contexts (Atush Sholihah & Aminah, 2020). International assessments such as PISA and TIMSS have shown that students who perform well in process-oriented tasks demonstrate higher scientific literacy, while many still struggle to apply inquiry-based reasoning to unfamiliar situations indicating persistent gaps in both instruction and assessment practices.

Conceptual and theoretical frameworks play a pivotal role in the assessment of SPS by providing structured perspectives on how these skills are defined, categorised, and measured (Bhakti et al., 2020; Indri & Nurosyid, 2020; Kalyana et al., 2023; Sholihah & Aminah, 2020). These frameworks offer educators and researchers coherent models for designing valid and reliable assessment tools that capture the multidimensional nature of scientific reasoning (Indri & Nurosyid, 2020; S. Jalil et al., 2018). For example, the Tool for Analyzing Science Standards and Curricula (TASSC) has been used to examine how national curricula align with inquiry-based competencies (Dani et al., 2014), while other frameworks focus on students' ability to integrate scientific models, link mechanisms and processes, and transfer conceptual understanding across contexts (Jansen et al., 2019). Yet, despite their contributions, research on SPS assessment remains fragmented. Many studies emphasise instrument development rather than theoretical synthesis, and inconsistencies persist regarding definitions, dimensions, and indicators of SPS (George, 1976; Sirajuddin Jalil et al., 2018; Shahali & Halim, 2010). This fragmentation has led to challenges in ensuring assessment validity, comparability across educational levels, and alignment between assessment frameworks and learning outcomes.

Given these issues, there is a pressing need to systematically map and synthesise existing conceptual and theoretical frameworks underpinning SPS assessment. Current scholarship lacks a consolidated overview that clarifies how these frameworks conceptualise process skills, how they are implemented in practice, and how they have evolved across contexts and educational levels. Furthermore, limited empirical validation of existing frameworks has resulted in uncertainty about their effectiveness in capturing students' inquiry competence. Understanding these relationships is vital because theoretically grounded assessment frameworks not only strengthen the reliability of evaluation practices but also inform curriculum design, teacher training, and the development of higher-order scientific reasoning skills.

A scoping review is the most appropriate approach for addressing these gaps, as it allows for the systematic mapping of diverse evidence, clarification of conceptual boundaries, and identification of emerging research trends. Therefore, this review aims to provide a comprehensive synthesis of the conceptual and theoretical foundations that guide the assessment of science process skills. The objectives of this review are threefold: (1) to identify and map the existing conceptual and theoretical frameworks that guide the assessment of science process skills across educational levels; (2) to examine how existing frameworks conceptualise and define the components, dimensions, and indicators of science process skills within science education; and (3) to explore how these frameworks have been implemented, adapted, or validated in empirical research on science process skills assessment. By achieving these objectives, this study will advance understanding of the theoretical landscape of SPS assessment, establish a foundation for the development of valid and reliable assessment models, and contribute to the global effort to enhance inquiry-based science education.

Methodology

A scoping review is an approach to evidence synthesis that systematically maps the breadth and depth of existing research within a particular topic, field, or concept. It is designed to provide an overview of the nature, range, and extent of research evidence rather than to answer a narrowly defined question. Scoping reviews are particularly valuable when the literature is complex, emerging, or heterogeneous, as they help clarify key concepts, identify research gaps, and determine the feasibility or focus of subsequent systematic reviews. By offering a structured yet flexible means of exploring the landscape of available evidence, scoping reviews contribute to conceptual understanding and inform policy, practice, and future research directions (Hadie, 2024; Munn et al., 2022; Peters et al., 2015; Rubinstein & Parrott, 2021).

Although both scoping reviews and systematic literature reviews adopt a systematic, transparent, and replicable approach to evidence synthesis, they differ in purpose, scope, and methodological rigor. Scoping reviews aim to map existing evidence and identify gaps in knowledge, while systematic reviews focus on answering a specific, well-defined research question using a rigorous and often quantitative approach. Scoping reviews generally use the PCC (Population, Concept, Context) framework to guide the review process, whereas systematic reviews typically apply the PICO (Population, Intervention, Comparison, Outcome) model. Moreover, scoping reviews usually do not include a formal assessment of study quality, while systematic reviews involve critical appraisal and, in many cases, meta-analysis to synthesize findings and produce high levels of evidence for decision-making (Gill, 2021; Munn et al., 2018; Peters et al., 2015; Pollock et al., 2024; Smith & Duncan, 2022).

In terms of applications, scoping reviews are most suitable for broad or exploratory research areas where literature is dispersed or not yet well established. They help clarify conceptual boundaries, map theoretical developments, and inform the design of future empirical or systematic reviews. Conversely, systematic reviews are best suited for addressing narrowly focused research or clinical questions, particularly when the goal is to provide conclusive, evidence-based answers to guide policy or practice. Due to their methodological precision, systematic reviews are widely used in developing guidelines and best practices, while scoping reviews play a more exploratory and foundational role in shaping future research agendas and theoretical advancements in a field(Gill, 2021; Khalil & Tricco, 2022; Peters et al., 2015; Smith & Duncan, 2022; Vanmeenen et al., 2024).This research article employs the six-step methodology developed by Arksey and O'Malley (2005) as explained in the below section:

In the first stage of Arksey and O’Malley’s (2005) framework, this study establishes clear and focused research questions aligned with the aim of the review, titled "A Scoping Review of Conceptual Frameworks for Assessing Science Process Skills." The review seeks to map and synthesise existing research on the theoretical and conceptual foundations underpinning the assessment of science process skills across educational levels. Three guiding questions were formulated: (1) What conceptual and theoretical frameworks have been developed or applied to guide the assessment of science process skills across different educational levels? (2) How do existing frameworks conceptualise the components, dimensions, and indicators of science process skills within science education? (3) In what ways have these frameworks been implemented, adapted, or validated in empirical research to assess science process skills in classroom settings? These questions provide the foundation for exploring the scope, diversity, and theoretical grounding of existing frameworks in science education assessment.

The second step focuses on systematically identifying relevant literature that aligns with the objectives of the review. The search was conducted using Scopus and Web of Science, two major databases known for their comprehensive and high-quality academic coverage. A search strategy combining keywords and Boolean operators (e.g., "science process skills," "assessment," "conceptual framework," "theoretical model," and "science education") was employed to ensure inclusivity and precision. Only peer-reviewed journal articles published in English were included, while non-peer-reviewed materials, book chapters, and conference papers were excluded. This approach ensured the inclusion of credible studies discussing conceptual and theoretical foundations related to the assessment of science process skills. The process provided a robust evidence base for subsequent analysis and synthesis, supporting the aim of mapping existing frameworks and identifying research gaps in this area.

The third step involved the systematic selection of studies that met the inclusion criteria established earlier, ensuring relevance and quality. All retrieved articles from Scopus and Web of Science were imported into reference management software to remove duplicates. A two-stage screening process was conducted, beginning with a review of titles and abstracts to determine initial eligibility, followed by a full-text screening to confirm alignment with the review's objectives. Studies were included if they discussed conceptual or theoretical frameworks related to science process skills assessment and were published in English peer-reviewed journals. Articles focusing solely on content knowledge or lacking a conceptual basis were excluded. The entire selection process was documented using a PRISMA flow diagram to enhance transparency. This rigorous selection ensured that the final body of literature provided a strong foundation for understanding and synthesizing conceptual frameworks in science process skills assessment.

The fourth step, charting the data, involved systematically extracting and organizing key information from the selected studies to enable comparative analysis. A structured data charting form was developed, which included bibliographic details, study context, educational level, type of conceptual or theoretical framework, assessment approaches, main findings, and identified gaps. This process allowed for consistent and comprehensive data collection across studies. Data were compiled into a matrix to facilitate thematic comparison and identify emerging trends. The charting process was iterative, with categories refined as familiarity with the literature deepened. This systematic approach ensured that both theoretical and methodological elements of each study were captured, providing a coherent foundation for the next stage of synthesizing and interpreting the findings.

The fifth step focused on synthesizing the charted data to provide a comprehensive overview of existing conceptual and theoretical frameworks related to science process skills assessment. A descriptive numerical summary was first used to present the distribution of studies by year, country, educational level, and framework type. This was followed by a thematic synthesis to identify recurring concepts, theoretical orientations, and patterns across studies. Themes such as the conceptualisation of science process skills, framework alignment with pedagogy, and assessment dimensions were examined. Tables and figures were used to present key patterns and conceptual relationships. The synthesis revealed gaps such as the limited empirical validation of frameworks and the underrepresentation of primary-level studies. Overall, this step transformed raw data into meaningful insights, laying the groundwork for interpretation and discussion in relation to the review's research questions and objectives.

The final step discusses and interprets the synthesized findings in relation to the review's aim and research questions. The analysis revealed significant variation in how conceptual frameworks for assessing science process skills are developed and applied, reflecting different theoretical perspectives such as constructivism, inquiry-based learning, and cognitive skill models. While many frameworks emphasize authentic scientific inquiry and reasoning, few studies have validated these models empirically or explored their classroom application, particularly in primary education. The discussion also highlights the need for closer alignment between theoretical frameworks and assessment practices, as well as the integration of innovative assessment tools such as digital and performance-based methods. Overall, the findings underscore the importance of developing coherent, theory-driven frameworks that effectively bridge pedagogy, assessment, and scientific literacy, while identifying key gaps to guide future research and practice in science education assessment.

Figure 1 illustrates the systematic process undertaken for identifying, screening, and selecting studies in the scoping review titled "A Scoping Review of Conceptual Frameworks for Assessing Science Process Skills." The figure follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) structure, which ensures transparency and reproducibility in the literature selection process. In the identification stage, a total of 162 records were retrieved which consists of 84 from the Web of Science (WoS) and 78 from Scopus, using a combination of keywords related to conceptual frameworks, science process skills, assessment, and education. The Boolean search string incorporated terms such as "conceptual framework," "theoretical framework," "model," "structure," "science process skills," "assessment," "evaluation," "measurement," and "competency evaluation." From the initial 7,910 search results, 7,776 records were excluded because they were systematic or meta-analytic reviews, book series, non-English papers, or published before 2022, and were not within the domain of Science Education or Social Sciences.

During the screening stage, 134 records remained after applying the exclusion criteria. Duplicate records were then identified and removed to prevent redundancy. In the eligibility stage, the remaining full-text articles were carefully examined for their relevance and methodological quality. A total of 117 articles were excluded at this stage because they lacked empirical data, were conference proceedings, belonged to the hard sciences rather than science education, or did not address both Science Process Skills (SPS) and Conceptual Frameworks. In the final inclusion stage, 16 studies met all eligibility criteria and were included in both the qualitative and quantitative synthesis. These studies underwent a further quality assessment to ensure methodological rigor and conceptual alignment with the review objectives. Overall, Figure 1 illustrates a rigorous and transparent selection process that reduced an initial pool of nearly eight thousand records to a final set of seventeen empirical studies. This systematic approach ensures that the review's findings are firmly grounded in recent, relevant, and high-quality research focusing specifically on conceptual frameworks for assessing science process skills within educational contexts.

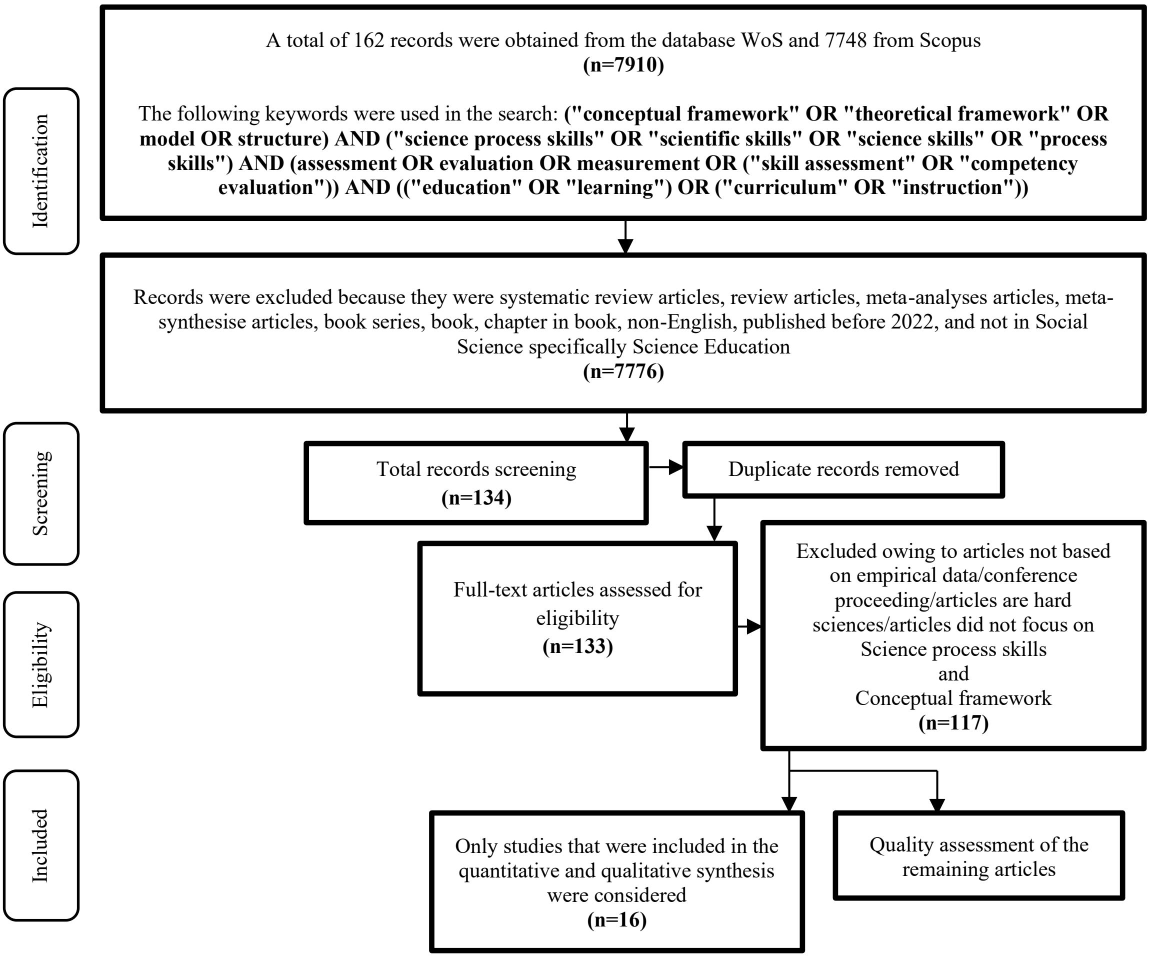

Figure 1. PRISMA Flow Diagram of the Study Selection Process

Findings

This scoping review identified a total of 16 empirical studies that conceptualised, developed, implemented, or validated frameworks related to the assessment of science process skills (SPS) across different educational levels and disciplinary contexts. Collectively, these studies illustrate an evolving and increasingly sophisticated landscape of research in SPS assessment, highlighting how conceptual frameworks are being empirically grounded, psychometrically validated, and contextually integrated into science education. The synthesis of findings reveals four dominant thematic areas: (1) Framework Design and Conceptualisation, (2) Framework Implementation and Validation, (3) Pedagogical and Learning Frameworks, and (4) Applied and Participatory Models.

The first theme, Framework Design and Conceptualisation, includes studies that sought to establish or refine theoretical and methodological bases for assessing SPS. For instance, Çoruhlu et al. (2023) demonstrated that the Prediction–Observation–Explanation (POE*)* model can function as both an instructional and assessment framework by enhancing students' prediction, observation, and evaluation skills. Similarly, Higde et al. (2024) applied the Many-Facet Rasch Measurement Model to laboratory-based SPS activities, providing empirical evidence for its validity and reliability in evaluating scientific performance. Both studies highlight the growing methodological precision and theoretical grounding in the construction of SPS assessment frameworks, which move beyond descriptive taxonomies toward empirically tested models that capture the multidimensional nature of scientific inquiry.

The second theme, Framework Implementation and Validation, encompasses studies that focused on the operationalisation and empirical verification of SPS-related frameworks. Berlian et al. (2023) developed and validated research-oriented learning tools, including assessment rubrics and lesson materials, that support SPS within science education courses. Campilongo et al. (2025) similarly validated a rubric for measuring inquiry-based learning and SPS using smartphone-assisted experimentation, demonstrating high inter-rater reliability and construct validity. Powell et al. (2024) advanced this direction by proposing a data-driven educational assessment model that links learning outcomes to SPS skill progression, while maintaining empirical rigour. Collectively, these studies indicate that the validation of conceptual frameworks is increasingly supported by quantitative measures and psychometric evidence, ensuring their credibility and applicability across different learning environments.

The third and most dominant theme, Pedagogical and Learning Frameworks, captures the integration of SPS into broader instructional models aimed at cultivating inquiry-oriented and metacognitive learning. Studies such as Pozuelo-Muñoz et al. (2025) and Nicol et al. (2023) showed that inquiry-based and problem-based learning (PBL) contexts effectively develop students' SPS, particularly in hypothesis formulation, experimental design, and data interpretation. Handee et al. (2025) extended this work through the Focus–Action–Reflection (FAR) analogy-based learning model, establishing empirical links between reflective thinking, conceptual modelling, and SPS mastery. Uludağ and Erkan (2023) demonstrated that integrating in-class and out-of-school science experiences promotes holistic SPS development through experiential engagement. Likewise, Gutierrez-Berraondo et al. (2025) revealed that interdisciplinary STEM projects support the application and assessment of SPS through collaborative, project-based inquiry. Together, these findings suggest that student-centred pedagogical models, particularly those grounded in inquiry, metacognition, and reflection, serve as robust frameworks for both developing and assessing science process skills.

The fourth theme, Applied and Participatory Models, includes frameworks that extend SPS assessment into professional, community, and interdisciplinary domains. Tøttrup et al. (2025) presented a co-creational participatory science framework, positioning SPS as both a scientific and civic competency developed through collaborative engagement with real-world problems. Ambrosino et al. (2024) proposed a place-based Course-Based Undergraduate Research Experience (CURE) framework that empirically connects SPS development to learners' science identity and motivation, particularly among underrepresented groups. Similarly, Sitawa et al.

(2023) and Schaller et al. (2023) developed and evaluated competency-based training models in epidemiology and doctoral science education, respectively, illustrating how SPS frameworks contribute to capacity building and professional readiness. These frameworks collectively underscore a growing movement toward inclusive, interdisciplinary, and context-driven approaches to SPS assessment that bridge classroom learning with authentic scientific practice.

In summary, the synthesis of these 16 empirical studies reveals a research field that is advancing from isolated instructional interventions toward integrated, validated, and theoretically informed frameworks for assessing science process skills. While early work focused primarily on establishing conceptual clarity and measurement reliability, recent studies emphasize contextualised, learner-centred, and participatory approaches that align SPS assessment with authentic scientific inquiry and real-world problem-solving. This shift reflects a broader transformation in science education research from static, content-driven assessment models to dynamic, process-oriented frameworks that integrate cognitive, metacognitive, and applied dimensions of scientific literacy.

Table 1. Charting the Data

No.	Publication (Author, Year)	Variables / Construct	Key Findings / Conceptual Focus	Sub-theme	Theme
1	Çoruhlu et al. (2023)	Framework: Prediction–Observation–Explanation (POE) Model; SPS dimensions (prediction, observation, evaluation)	Demonstrated that POE-based worksheets improved students' SPS; proposed integrating active learning stages as part of a conceptual assessment model.	Experimental Learning Structures	Framework for SPS Assessment
2	Campilongo et al. (2025)	Construct: Inquiry-Based Learning through Smartphone-Assisted Experimentation	Developed and validated a rubric to assess SPS components (hypothesis formulation, data analysis, interpretation); showed high inter-rater reliability and skill improvement.	Technology-Supported Inquiry	Framework Implementation
3	Higde et al. (2024)	Construct: Many-Facet Rasch Measurement Model for Assessing SPS	Applied Rasch model to laboratory assessment; provided empirical evidence of validity, reliability, and objectivity in measuring SPS performance.	Psychometric Validation	Assessment Models
4	Berlian et al.	Variables: Research-	Developed and validated	Tool	Framework

No.	Publication (Author, Year)	Variables / Construct	Key Findings / Conceptual Focus	Sub-theme	Theme
	(2023)	Oriented Learning Tools – Validity for SPS Support	teaching tools (lesson plans, assessments, textbooks) aligned with SPS; demonstrated strong empirical validity and reliability.	Development and Validation	Implementation
5	Uludağ and Erkan (2023)	Framework: Out-of-School Science Education Program; SPS dimensions	Implemented quasi-experimental design integrating in-class and out-of-school learning contexts to promote SPS development.	Integrated Learning Contexts	Experiential Frameworks
6	Pozuelo-Muñoz et al. (2025)	Framework: Problem-Based Learning (PBL) for Inquiry and SPS	Proposed and validated PBL-based framework to assess hypothesis formulation, variable identification, and data interpretation; improved inquiry competencies.	Inquiry-Based Pedagogy	Learning Frameworks
7	Handee et al. (2025)	Framework: Focus–Action–Reflection (FAR) Analogy-Based Learning	Developed and empirically tested a FAR model linking metacognition to SPS; confirmed relationship between reflective thinking and conceptual modeling.	Cognitive–Metacognitive Integration	Conceptual Process Models
8	Nicol et al. (2023)	Construct: Inquiry Process Skills via Guided Inquiry Chemistry	Designed and implemented guided inquiry model to enhance SPS development; validated using 4-H Inquiry-in-Action framework.	Guided Inquiry Design	Pedagogical Frameworks
9	Nixon et al. (2024)	Framework: Context-Based Enrichment for SPS Development	Introduced asynchronous enrichment program that enhanced SPS dimensions in investigation, data analysis, and	Lifelong Learning Integration	Skill-Based Frameworks

No.	Publication (Author, Year)	Variables / Construct	Key Findings / Conceptual Focus	Sub-theme	Theme
			communication.		
10	Gutierrez-Berraondo et al. (2025)	Framework: Problem- and Project-Based Learning (P2BL) in STEM	Developed interdisciplinary STEM project framework empirically shown to enhance SPS and conceptual understanding.	Interdisciplinary STEM Design	Learning Frameworks
11	Istyadji (2023)	Framework: Science Literacy and SPS Integration	Proposed and tested a conceptual model linking science literacy indicators to SPS; empirical data showed significant relationships between reasoning and communication skills.	Literacy–SPS Connection	Conceptual Framework Integration
12	Schaller et al. (2023)	Construct: Problem-Based Learning for Experimental Design	Developed competency-based empirical framework emphasizing design and reasoning SPS in doctoral science training.	Higher Education Frameworks	Inquiry Competence Models
13	Tøttrup et al. (2025)	Framework: Co-Creational Participatory Science Model	Implemented participatory science framework integrating collaboration, inquiry, and SPS practices in real-world projects.	Collaborative Inquiry	Participatory Frameworks
14	Ambrosino et al. (2024)	Framework: Place-Based Course-Based Undergraduate Research Experience (CURE)	Empirically identified SPS engagement indicators (skills, interest, identity) in CURE model; reinforced place-based learning relevance.	Place-Based Learning	Engagement Frameworks
15	Powell et al. (2024)	Construct: Data-Driven Educational Assessment Framework	Developed and empirically validated data-based model linking science learning outcomes to measurable SPS skill progression.	Data-Driven Evaluation	Measurement Models

No.	Publication (Author, Year)	Variables / Construct	Key Findings / Conceptual Focus	Sub-theme	Theme
16	Sitawa et al. (2023)	Framework: In-Service Applied Epidemiology Training (ISAVET)	Empirical evaluation of multi-sectoral framework integrating SPS into applied scientific training for workforce capacity building.	Applied Science Competence	Multi-Domain Frameworks

Background of the Research Included in the Review

The body of research analysed in this scoping review encompasses diverse educational levels, methodological orientations, and theoretical traditions, demonstrating a growing global focus on the assessment of science process skills (SPS) as a core component of scientific literacy and inquiry competence. Across the reviewed empirical studies, there is a clear shift from descriptive or content-based understandings of SPS toward the development of conceptually grounded, empirically validated, and contextually adaptable frameworks for assessing these skills in educational settings. The reviewed studies can be situated within four interrelated strands: (1) the conceptualisation of SPS frameworks; (2) the pedagogical and learning models that operationalise SPS; (3) psychometric and assessment model validation; and (4) contextual integrations of SPS within broader scientific and professional paradigms.

Early work in this domain focused on refining the conceptual boundaries and measurable indicators of SPS, often extending classical taxonomies such as the Basic and Integrated Science Process Skills (SAPA) framework. Recent empirical studies, however, reveal a movement toward dynamic, multidimensional, and empirically grounded frameworks. For instance, Çoruhlu et al. (2023) employed the Prediction–Observation–Explanation (POE) model as both a pedagogical and assessment framework, showing significant improvements in learners' prediction, observation, and evaluation skills. Similarly, Higde et al. (2024) used the Many-Facet Rasch Measurement Model to establish psychometric validity in evaluating laboratory-based SPS performance, ensuring reliability and rater fairness. In addition, Berlian et al. (2023) and Campilongo et al. (2025) validated instructional tools and rubrics that assess inquiry-based learning and SPS competencies, reinforcing the connection between conceptual frameworks and measurable learning outcomes.

Parallel to these developments, a substantial body of research applies pedagogical frameworks that embed SPS development within inquiry-based, problem-based, and metacognitive learning environments. Studies such as Pozuelo-Muñoz et al. (2025) and Nicol et al. (2023) empirically examined how problem-based learning (PBL) and guided inquiry models enhance learners' ability to formulate hypotheses, identify variables, and interpret data which are core components of SPS. Similarly, Handee et al. (2025) introduced the Focus–Action–Reflection (FAR) analogy-based learning model, which integrates metacognitive awareness with scientific reasoning, illustrating that reflective processes enhance conceptual understanding and SPS mastery. Uludağ and Erkan (2023) complemented this by combining in-class and out-of-school learning environments, revealing how experiential learning contexts strengthen the development of observation, analysis, and interpretation skills among young learners. In a related approach, Gutierrez-Berraondo et al. (2025) demonstrated that interdisciplinary STEM projects can serve as effective platforms for both teaching and assessing SPS through collaborative inquiry and applied problem-solving.

A third research strand focuses on assessment and validation models, particularly those that link SPS assessment to psychometric robustness and data-driven measurement. Powell et al. (2024) proposed a data-driven educational assessment framework that connects science learning outcomes with measurable skill progression, while Nixon et al. (2024) implemented a context-based enrichment program designed to assess investigative, analytical, and communication-related SPS. These studies demonstrate an increasing emphasis on empirical precision, statistical validation, and construct alignment in designing assessment instruments capable of reliably capturing complex dimensions of scientific reasoning.

In addition, several studies extend the application of SPS frameworks to professional and participatory science contexts, illustrating the versatility of SPS as a foundational competence beyond formal education. Schaller et al. (2023) developed a competency-based problem-based learning framework for doctoral training, showing that engagement with authentic experimental design enhances higher-order SPS such as planning, reasoning, and evidence-based evaluation. Similarly, Tøttrup et al. (2025) introduced a co-creational participatory science framework that integrates students and communities in collaborative research, thereby reinforcing inquiry skills as both cognitive and civic competencies. Ambrosino et al. (2024) proposed a place-based Course-Based Undergraduate Research Experience *(*CURE*)* model that fosters SPS development through engagement, identity, and contextual learning among underrepresented groups, while Sitawa et al. (2023) demonstrated that SPS can underpin cross-sectoral competence in scientific training through the In-Service Applied Epidemiology Training (ISAVET) framework.

Despite these advancements, several gaps persist in the literature. The most critical theoretical gap concerns the lack of comprehensive models that explicitly define the hierarchical structure, construct boundaries, and interrelationships among SPS dimensions. Many studies focus on applied or pedagogical interventions but do not integrate these within a unified theoretical framework. Empirically, while there is substantial progress in validation through quantitative and mixed-method designs, inconsistencies remain in how SPS constructs are operationalised across contexts. From a contextual perspective, the majority of studies originate from Asian regions particularly Indonesia, Turkey, and Malaysia with fewer contributions from European, North American, or African contexts, indicating a geographical imbalance and limited cross-national comparative research.

Overall, the reviewed literature portrays a progressively convergent but still fragmented research field. The 16 empirical studies collectively advance the understanding of how SPS can be conceptualised, assessed, and validated through varied frameworks that integrate cognitive, metacognitive, and experiential dimensions of scientific practice. These contributions establish a foundation for designing comprehensive, reliable, and contextually responsive assessment models that reflect authentic scientific inquiry across primary, secondary, and higher education levels. Figure 2 illustrates the geographical distribution of studies included in this review, revealing that the majority of SPS framework research has been conducted in Asian countries, followed by a smaller number of studies from European and North American contexts. Only limited research originates from African regions or involves cross-national collaborations, reflecting the need for broader global engagement in conceptualising and assessing science process skills.

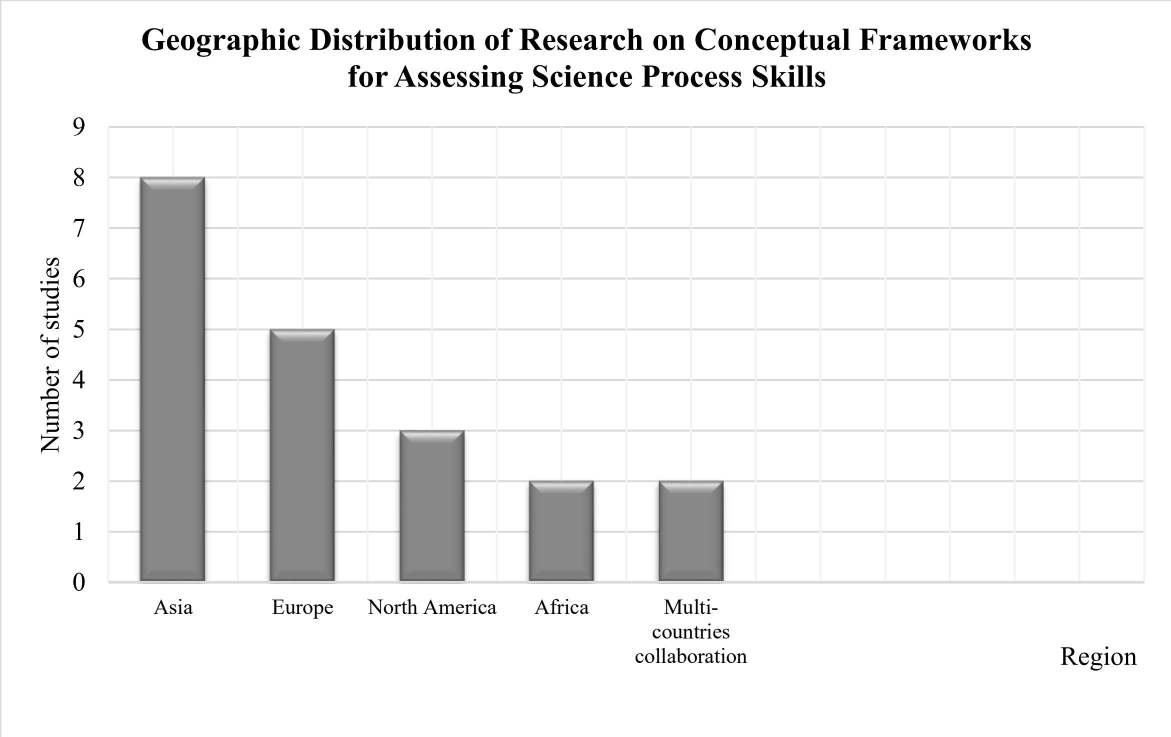

Figure 2. Geographical Distribution of the Studies by Continent

Discussion

This scoping review synthesised findings from sixteen empirical studies that conceptualised, implemented, or validated frameworks for assessing science process skills (SPS) across different educational and disciplinary contexts. Collectively, these studies reveal a maturing research field that has shifted from fragmented approaches to more integrated, theoretically informed, and empirically validated frameworks. The reviewed literature conceptualises SPS as multidimensional and context-sensitive competencies that are essential for the development of scientific literacy and inquiry-based learning. Studies were conducted across a range of educational levels, from primary to higher education, employing a variety of research designs such as quasi-experimental, psychometric, design-based, and mixed-method approaches. This diversity demonstrates that the assessment of SPS is evolving beyond static, content-driven testing towards dynamic frameworks that embed inquiry, metacognition, and authentic problem-solving processes within science education.

The reviewed studies reflect considerable diversity in the way SPS frameworks are conceptualised and applied. For instance, Çoruhlu et al. (2023) demonstrated that the Prediction, Observation, and Explanation (POE) model enhances learners' prediction, observation, and evaluation abilities while serving as both an instructional and assessment framework. Higde et al. (2024) advanced the psychometric robustness of SPS assessment through the use of the Many-Facet Rasch Measurement Model, providing empirical evidence for validity and objectivity in laboratory-based contexts. Similarly, Berlian et al. (2023) and Campilongo et al. (2025) contributed to the field by developing and validating instructional tools and rubrics aligned with inquiry-based learning. These studies represent a transition from descriptive taxonomies of SPS towards empirically verifiable frameworks grounded in educational measurement theory and cognitive psychology.

Another key development emerging from this review concerns the integration of SPS within pedagogical and learning models. Studies by Pozuelo-Muñoz et al. (2025) and Nicol et al. (2023) confirmed that inquiry-based and problem-based learning environments strengthen higher-order SPS such as hypothesis formulation, variable identification, and data interpretation. Handee et al. (2025) demonstrated that the Focus, Action, and Reflection (FAR) analogy-based learning model promotes metacognitive reflection, which enhances scientific reasoning and conceptual understanding. Uludağ and Erkan (2023) showed that combining classroom and out-of-school learning contexts fosters deeper observational and analytical skills, while Gutierrez-Berraondo et al. (2025) found that interdisciplinary STEM projects provide authentic opportunities to develop and assess SPS through collaborative inquiry. Taken together, these studies highlight a clear pedagogical shift toward student-centred and inquiry-oriented frameworks that view SPS as interrelated elements of scientific reasoning rather than as isolated procedural skills.

From a methodological perspective, the reviewed studies demonstrate increasing sophistication but also expose several limitations. Quantitative validation studies, such as those by Higde et al. (2024) and Powell et al. (2024), successfully established reliability and construct validity in SPS assessment tools, yet their scalability remains constrained due to small sample sizes and short implementation periods. Although several studies, including those by Pozuelo-Muñoz et al. (2025) and Ambrosino et al. (2024), adopted mixed-method or participatory approaches, most research still relies heavily on quantitative data. This trend has resulted in limited exploration of the qualitative dimensions of SPS, such as students' reasoning processes, reflective thinking, and collaborative inquiry. Therefore, future studies should employ longitudinal, mixed-method, and multi-site designs to better capture the development of SPS as a progressive and context-dependent construct.

The review also reveals contextual disparities in the literature. A majority of the empirical studies originated from Asian contexts, particularly Indonesia, Turkey, and Malaysia, reflecting strong engagement in inquiry-oriented science education reform. In contrast, fewer studies have been conducted in European or North American contexts, and research from Africa remains scarce. Only a few studies, such as those by Tøttrup et al. (2025) and Ambrosino et al. (2024), extend SPS assessment beyond the formal classroom to community-based and participatory learning environments. These efforts demonstrate the potential of SPS frameworks to bridge scientific inquiry with civic engagement, professional readiness, and interdisciplinary collaboration. However, such initiatives are still limited. The absence of culturally responsive and contextually adaptable frameworks restricts the global applicability of SPS assessment models. To ensure relevance and equity, future frameworks must integrate local epistemologies, indigenous knowledge systems, and principles of global citizenship education.

Theoretically, the current body of literature still lacks a unified model that integrates cognitive, metacognitive, and sociocultural dimensions of SPS within a single framework. While most studies acknowledge SPS as a foundation of scientific literacy, they rarely address how cognitive operations, reflective regulation, and contextual practices interact in shaping scientific reasoning. For example, although Handee et al. (2025) emphasised reflective thinking and Istyadji (2023) linked SPS to literacy and reasoning, neither accounted for affective or cultural dimensions. Consequently, there is a pressing need for integrative conceptual frameworks that capture the dynamic interplay between cognitive, reflective, and contextual aspects of scientific reasoning and inquiry.

Synthesising insights from the sixteen reviewed studies, this review proposes an integrated conceptual perspective comprising four interrelated dimensions: conceptual and structural design, pedagogical alignment, psychometric validation, and contextual and participatory relevance. These dimensions interact dynamically to form a coherent system. Conceptual clarity informs pedagogical design; pedagogical enactment generates empirical data for validation; psychometric testing ensures reliability and construct coherence; and contextual relevance ensures responsiveness to real-world scientific practices. Together, these dimensions provide a theoretical foundation for developing coherent, evidence-based, and contextually responsive frameworks that strengthen the assessment of SPS across educational settings.

Overall, the synthesis indicates that empirical research on SPS frameworks is progressing toward integrative, authentic, and theory-driven approaches to assessment. Nonetheless, theoretical disunity, methodological fragmentation, and contextual imbalance continue to limit the coherence and generalisability of findings. Future research should focus on developing unified and empirically validated frameworks that bridge cognitive, metacognitive, and sociocultural dimensions while ensuring inclusivity, sustainability, and cultural adaptability. Advancing in this direction will enable SPS assessment to more accurately represent how learners observe, hypothesise, experiment, and reason as authentic participants in scientific inquiry. Figure 3 shows the integrated conceptual perspective proposed in this review for assessing science process skills.

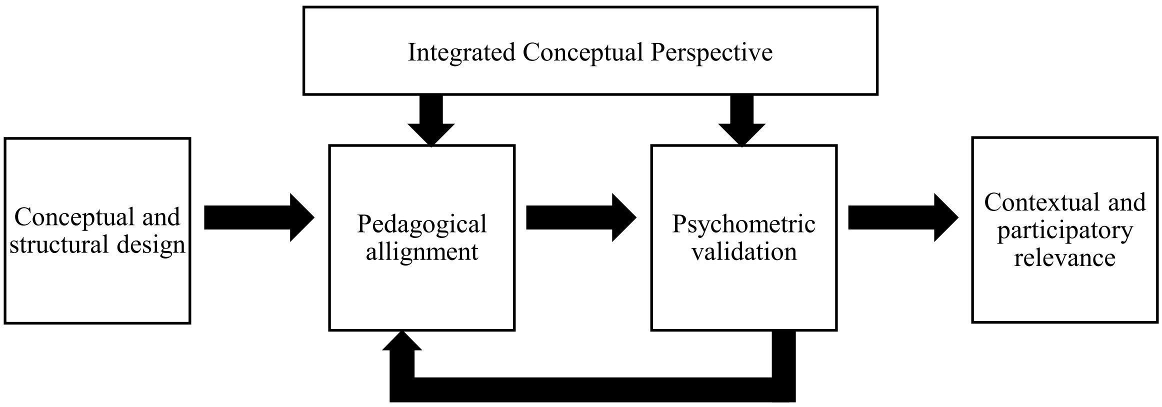

Figure 3. Integrated Conceptual Perspective for Assessing Science Process Skills

The model illustrates the dynamic relationship among four interrelated dimensions: conceptual and structural design, pedagogical alignment, psychometric validation, and contextual and participatory relevance. These dimensions operate as a coherent system rather than independent elements. Conceptual and structural design provides the theoretical foundation that defines the constructs and measurable indicators of science process skills. Pedagogical alignment ensures that the assessment of these skills is embedded within inquiry-based and metacognitive learning environments. Psychometric validation establishes the reliability, accuracy, and interpretive consistency of assessment instruments, while contextual and participatory relevance extends the application of frameworks to authentic, culturally diverse, and collaborative learning contexts. Together, these dimensions form an interconnected cycle that bridges theory, practice, and context, offering a comprehensive structure for developing valid, equitable, and evidence-based assessments of science process skills across educational settings.

Summary

This scoping review provides a systematic synthesis of sixteen empirical studies that developed, implemented, or validated conceptual frameworks for assessing science process skills in diverse educational contexts. The findings indicate a clear evolution in the field, moving from traditional test-based assessments toward comprehensive frameworks that integrate inquiry, reflection, and authentic scientific engagement. Contemporary approaches to SPS assessment increasingly emphasise the relationship between conceptual coherence, pedagogical alignment, and psychometric validation, illustrating a growing understanding of how learners develop and demonstrate scientific reasoning.

Across the reviewed literature, four interrelated trends are evident. The first concerns the development of theoretically grounded frameworks that establish conceptual clarity and definitional consistency. The second involves the empirical validation of assessment tools that align with authentic classroom practices. The third highlights the integration of inquiry-based and learner-centred pedagogies as the foundation for meaningful SPS assessment. The fourth demonstrates the expansion of SPS frameworks into participatory and interdisciplinary contexts that connect learning to real-world scientific practice. Collectively, these directions reflect a paradigm shift toward holistic, authentic, and contextually responsive assessment practices.

Despite substantial progress, the field continues to face several challenges. Theoretical fragmentation, uneven methodological rigor, and geographical concentration limit the formation of a unified and globally relevant model. To address these gaps, future studies should develop comprehensive and culturally responsive frameworks that integrate cognitive, metacognitive, and sociocultural perspectives. Longitudinal and mixed-method designs are particularly important for capturing the development of SPS across time and diverse learning environments.

This review contributes to the growing body of literature on SPS assessment by providing a consolidated understanding of its conceptual and empirical foundations. Strengthening theoretical integration and methodological rigor will enable educators and policymakers to embed SPS assessment within curricula and teacher training programs. In doing so, science education can more effectively cultivate learners who are scientifically literate, capable of critical reasoning, and equipped with the inquiry skills necessary to address complex global challenges in the twenty-first century.

Limitation and Recommendations

Although this scoping review offers a comprehensive synthesis of conceptual and theoretical frameworks for assessing science process skills (SPS), several limitations should be acknowledged. First, the review was limited to studies retrieved from the Scopus and Web of Science databases. While these databases are among the most reputable and extensive sources of scholarly publications, they may not include all relevant works published in regional journals, institutional repositories, or non-indexed platforms. Consequently, potentially significant frameworks developed in local or non-English contexts may have been excluded. Second, the inclusion criteria focused primarily on empirical and conceptual studies published between 2023 and 2025. This temporal restriction may have excluded earlier foundational works that contributed to the historical development of SPS assessment frameworks. Third, this review did not conduct a quality appraisal of the included studies, as per the methodological scope of scoping reviews, which limits the ability to assess the relative robustness or methodological rigor of individual research designs. Lastly, the synthesis relied on reported conceptualizations within the articles, which may vary in clarity and depth, potentially influencing the comparability of findings across studies.

Despite these limitations, the findings of this review provide valuable directions for future research, theory building, and educational practice. Theoretically, there is a need for the development of a unified conceptual model that integrates cognitive, metacognitive, and sociocultural aspects of science process skills. Future studies should move beyond fragmented or discipline-specific frameworks to establish a holistic theoretical foundation for SPS assessment. Empirically, researchers are encouraged to employ longitudinal, mixed-method, and large-scale studies to capture the progression and transferability of SPS across learning contexts. Experimental validation of assessment tools, such as those based on Rasch measurement models or inquiry-based frameworks, should be expanded to confirm reliability and construct validity in diverse settings. Contextually, future research should explore the implementation of SPS assessment frameworks in non-formal and cross-cultural environments, particularly in developing countries where inquiry-based science learning is still emerging. This will ensure greater inclusivity and cultural relevance in SPS conceptualization and measurement.

From a policy and practical standpoint, curriculum developers and educational authorities should consider embedding SPS assessment frameworks into national science standards and teacher training programs. Professional development initiatives should equip educators with the skills to design authentic assessments aligned with inquiry-based learning, critical thinking, and problem solving. Collaboration between researchers, policymakers, and educators is essential to ensure that assessment frameworks are empirically grounded, pedagogically meaningful, and contextually adaptable. Finally, integrating digital and data-driven assessment tools could enhance the accessibility and scalability of SPS measurement, supporting evidence-based decision making in science education.

In conclusion, while the limitations of this review highlight the complexity of synthesizing diverse conceptual frameworks, they also point to fertile ground for future inquiry. Advancing theoretical integration, methodological rigor, and contextual diversity in SPS assessment research will strengthen the global movement toward more authentic, equitable, and inquiry-driven science education.

Implications

The findings of this scoping review carry significant implications for theory development, educational practice, and policy formulation in science education. Theoretically, the review underscores the need for a more integrated and coherent conceptual model of science process skills (SPS). While the reviewed studies present diverse frameworks such as inquiry-based, prediction–observation–explanation (POE), and focus–action–reflection (FAR) models, they remain conceptually fragmented. Future theoretical work should consolidate these frameworks into a unified model that connects cognitive, metacognitive, and sociocultural dimensions of scientific reasoning. Such theoretical synthesis would provide a comprehensive foundation for understanding how students' progress from basic observational abilities to higher-order scientific inquiry and reasoning, supporting curriculum coherence across educational levels.

From a pedagogical perspective, the findings suggest that teachers should adopt assessment frameworks that are authentic, process-oriented, and aligned with inquiry-based learning. Educators can utilise validated tools, such as those developed in Berlian et al. (2023) or Higde et al. (2024), to evaluate students' SPS through meaningful performance tasks rather than through isolated tests of factual knowledge. Incorporating learning models such as problem-based learning (Pozuelo-Muñoz et al., 2025) and out-of-school experiential programs (Uludağ & Erkan, 2023) can also enhance students' engagement with scientific inquiry and improve the validity of SPS assessment. Teacher professional development programs should therefore focus on enhancing educators' capacity to design, implement, and interpret SPS-based assessments that reflect authentic scientific practices. Furthermore, the integration of metacognitive training, as emphasised by Handee et al. (2025), can empower students to regulate their inquiry processes, evaluate evidence critically, and transfer skills across disciplinary contexts.

At the policy level, the review highlights the importance of embedding SPS within national science curricula and assessment standards. Policymakers should encourage the inclusion of conceptual frameworks that align with global competency goals, such as those outlined by the Organisation for Economic Co-operation and Development (OECD) and UNESCO, which emphasise scientific literacy and inquiry competence. Curriculum developers and education ministries should invest in establishing assessment policies that prioritise the evaluation of scientific reasoning, problem-solving, and communication skills. Moreover, as several studies (e.g., Sitawa et al. (2023); Garden (2023) demonstrate, SPS frameworks can support the development of professional and vocational competencies, suggesting their potential for integration into workforce training and lifelong learning programs. Policies that foster collaboration between researchers, educators, and curriculum agencies can ensure the scalability, inclusivity, and sustainability of SPS assessment frameworks across diverse educational systems.

In summary, the implications of this scoping review extend beyond academic theory to practical and systemic transformation. By adopting integrated conceptual models, implementing authentic inquiry-based pedagogies, and institutionalising SPS assessment in educational policies, stakeholders can create more equitable, relevant, and future-oriented science education systems. Strengthening these dimensions will not only improve the quality of science learning and teaching but also equip learners with the critical inquiry skills necessary for addressing complex global challenges.

Conclusion

This scoping review systematically mapped and synthesised sixteen empirical studies that conceptualised, implemented, or validated frameworks for assessing science process skills (SPS) across a range of educational contexts. The analysis revealed that SPS assessment has evolved from discrete, test-based measurements toward the adoption of comprehensive frameworks that integrate inquiry, cognitive, and reflective dimensions of scientific thinking. The reviewed studies collectively demonstrate that assessment of SPS is no longer limited to procedural testing but now involves holistic models that connect conceptual understanding, scientific reasoning, and practical engagement in inquiry-based learning environments.

The findings indicate that most of the empirical studies have advanced the field by designing frameworks that embed SPS within inquiry-driven and problem-centred pedagogies such as prediction, observation, and explanation models, problem-based and project-based learning structures, and data-driven assessment frameworks. These studies show increasing methodological sophistication, particularly in the validation of assessment instruments, including the use of psychometric models such as the Rasch measurement and data-driven analytics. However, while progress has been made in connecting theory with empirical application, the findings reveal persistent issues of conceptual fragmentation, limited theoretical integration, and uneven contextual representation across global education systems.

The review identified four dominant thematic directions within the current research landscape. First, a growing trend toward the development of theoretically grounded frameworks emphasises conceptual coherence and validity in SPS assessment. Second, many studies have shifted attention to the practical implementation and empirical testing of these frameworks in authentic classroom and laboratory contexts. Third, inquiry-based and learner-centred pedagogies remain central to the assessment of SPS, reinforcing the value of authentic learning experiences. Lastly, an emerging line of research extends SPS frameworks into applied and participatory domains, connecting science learning to professional readiness, interdisciplinary collaboration, and community-based inquiry.

Despite these advancements, several challenges remain. The theoretical fragmentation of SPS research continues to limit the consolidation of a unified framework that integrates cognitive, metacognitive, and affective dimensions of scientific reasoning. Empirical studies often rely on short-term interventions or small samples, limiting scalability and generalisability across educational levels. Moreover, the majority of SPS research originates from Asian contexts such as Indonesia, Turkey, and Malaysia, with limited representation from African or cross-cultural studies, resulting in contextual imbalance and restricted global generalisation.

This review makes an important contribution to the growing body of literature on SPS by providing a comprehensive overview of how conceptual frameworks are being developed and implemented to assess inquiry, reasoning, and experimentation in science education. It offers an evidence-based foundation for advancing both research and practice in the field. Moving forward, future research should aim to design unified and empirically validated frameworks that interlink theory and practice, integrate cognitive and affective processes, and adapt effectively to diverse educational contexts. Longitudinal and mixed-method studies are particularly needed to explore how SPS develop over time and across different learning environments.

For educators and policymakers, the findings underscore the need to embed well-structured SPS frameworks within science curricula and assessment policies to foster inquiry, creativity, and critical thinking. Strengthening SPS assessment will contribute to producing scientifically literate learners who are capable of problem-solving, reasoning, and engaging meaningfully with the complex challenges of modern society. By promoting coherent and contextually relevant assessment practices, science education can move closer to its goal of nurturing active and reflective thinkers who understand and apply the processes of science in both academic and real-world contexts.

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