



GLOBAL TRENDS AND THEMATIC EVOLUTION OF PROBLEM-SOLVING RESEARCH IN SCIENCE EDUCATION: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Problem-solving is a central competence in science education, yet its research landscape remains fragmented across domains, problem types, pedagogical contexts, outcomes, and regions. This study systematically maps global trends and thematic evolution in problem-solving research in science education from 2005 to 2025. Using a systematic literature review supported by bibliographic and multidimensional thematic mapping, 457 analysis-ready articles were selected from 10,926 initial records through a PRISMA-oriented procedure. The articles were coded according to science domain, problem type, learning context, pedagogical pathway, main outcome, research purpose, problem-solving role, geographical region, and citation indicators. The findings show substantial growth in the field, with physical science and chemistry learning dominating publication volume and outcome structures, while integrated STEM, environmental and earth science, and life and health science remain under-represented. Structured, quantitative, diagnostic, and experimental tasks were the most established problem types, whereas open-ended, real-world, and SSI-based problems showed stronger mean citation impact despite lower frequency. Sankey and chord diagrams revealed a shift toward practical experimental contexts, authentic societal contexts, project/design pedagogy, and multidimensional outcomes. Despite these developments, authentic problems, sustainability-related contexts, interdisciplinary STEM, and project-oriented pedagogies are still frequently examined in isolation rather than as components of an integrated problem-solving framework. This review highlights the need for more integrative approaches that connect authentic problem-solving, contextual learning, sustainability, and interdisciplinary science education to support transferable competencies for addressing contemporary societal and environmental challenges.

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INTRODUCTIONS

Problem-solving has become a core construct in science education because it enables students to move beyond conceptual acquisition toward the application of scientific knowledge in interpreting phenomena, analyzing evidence, and resolving complex problems in meaningful con-

texts (Valladares, 2021; Price et al., 2021; Astuti et al., 2021; Nigussie et al., 2025; Arifin et al., 2025). This competence is not confined to routine numerical exercises, but extends to conceptual diagnosis, laboratory investigation, design-based projects, computational modeling, and authentic socio-scientific problems that require students to integrate concepts, procedures, evidence, and contextual reasoning (Sadler, 2011; Zeidler et al., 2019; Roehrig et al., 2021; Rexigel et al.,

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2024). STEM/STEAM-oriented and computational approaches further broaden the scope of problem-solving by positioning students as active designers, modelers, and evaluators of solutions to interdisciplinary problems (Ogegbo & Ramnarain, 2022; Liu et al., 2024). Socio-scientific issue-based learning also strengthens problem-solving as a bridge between scientific reasoning, argumentation, ethical judgment, and evidence-based decision-making in real-world situations (Wess et al., 2023; Viehmann et al., 2024). Contextual science learning can also be strengthened by integrating local wisdom through open inquiry, enabling prospective science teachers to investigate culturally embedded practices and reconstruct them through scientific explanations (Parmin et al., 2016). Thus, research on problem-solving in science education has expanded across various domains—including physics, chemistry, integrated STEM, life and health sciences, and environmental and earth sciences—demonstrating its multidimensional nature, linking conceptual understanding, scientific practices, higher-order thinking skills, and contextual application (PISA, 2018; Valladares, 2021; Kumar et al., 2024).

Problem-solving has been widely studied in science education, but the field remains fragmented across domains, learning contexts, pedagogical approaches, problem formats, and outcomes (Tripp et al., 2020; Ault, 2022). This fragmentation makes it difficult to understand the field as an integrated body of knowledge, especially because many studies focus on specific interventions, domains, or assessment formats rather than the relationships among task structures, contexts, pedagogical pathways, and outcomes (Amadi, 2021; McLure, 2022; Ortega, 2022). Research remains concentrated in physical science and chemistry learning, while environmental and earth science, life and health science, and integrated STEM contexts remain underrepresented despite their relevance to sustainability, public health, and socio-scientific decision-making (Roehrig et al., 2021; Kumar et al., 2024). A similar imbalance appears in problem types, with broad science tasks, structured quantitative tasks, conceptual diagnostic tasks, and experimental tasks dominating the field, while open-ended, real-world, and socio-scientific issue-based tasks remain less frequent (Badeo & Duque, 2022; Viehmann et al., 2024). This uneven landscape suggests that publication volume alone cannot represent academic impact or future relevance, because progress in problem-solving research also depends on task quality, contextual authenticity, and the potential of findings to inform transformative science learning (Tripp et al., 2020; Ault, 2022).

Problem-solving research in science education has shifted from evaluating isolated instructional strategies toward a multidimensional field that connects teaching design, scientific reasoning, technology, experimentation, and assessment (Tripp et al., 2020; Badeo & Duque, 2022). This shift shows that problem-solving is increasingly viewed not only as a cognitive achievement indicator, but also as a learning process involving inquiry, evidence evaluation, design thinking, socio-scientific reasoning, and interdisciplinary knowledge application (Badeo & Duque, 2022; Kumar et al., 2024). Recent studies also highlight diverse pedagogical pathways, including project/design pedagogy, problem-centered learning, inquiry pedagogy, technology-mediated support, social learning, conventional comparison, and no-direct-intervention approaches (Roehrig et al., 2021; Strat et al., 2024). Empirical evidence from physics education further indicates that different levels of inquiry may produce different cognitive outcomes, with guided inquiry laboratory activities providing stronger support for students' cognitive performance than inquiry lessons in the examined context (Sarwanto, 2020). Technology-mediated science learning has also expanded through augmented reality, which can visualize abstract chemical representations and support students' learning outcomes in chemistry education (Yamtinah et al., 2023). Research outcomes have expanded beyond cognitive achievement to include problem-solving and HOTS, affective outcomes, measurement outcomes, and process or difficulty-related outcomes (Vandegrift et al., 2020; Badeo & Duque, 2022).

Overall, the findings indicate that research on problem-solving in science education remains fragmented across dimensions such as science domains, problem types, learning contexts, pedagogical approaches, and learning outcomes. Previous literature reviews have also tended to examine these dimensions in isolation, failing to provide an integrated overview of their interrelationships as the field evolves (Tripp et al., 2020; Ault, 2022). Furthermore, geographical disparities persist, with knowledge production and citation visibility more pronounced in North America and Europe than in Asia and developing regions (Pinto et al., 2020; Oluwadele et al., 2023). Methodologically, there is a scarcity of studies that integrate domain mapping, problem types, learning contexts, pedagogical approaches, learning outcomes, geographical distribution, and citation impact through multidimensional visualizations—such as Sankey diagrams, chord diagrams, and geographic maps (Ariza et al., 2021; Viehmann et al., 2024). This gap highlights the

need for multidimensional mapping that provides a more comprehensive depiction of the structure, interconnections, and evolution of problem-solving research in science education.

The rapid growth in publications since 2018 underscores the need for a more comprehensive mapping of the developmental trajectory of problem-solving research in science education (Tripp et al., 2020; Ault, 2022). Consequently, this study aims to map global trends and the thematic evolution of problem-solving research in science education from 2005 to 2025 by analyzing science domains, problem types, learning contexts, pedagogical approaches, learning outcomes, geographical distribution, and citation impact. Unlike previous reviews that examined these dimensions in isolation, this study integrates them into a multidimensional mapping framework—encompassing 457 articles—by combining publication trends, citation analysis, and geographical patterns with visualizations of inter-dimensional relationships. Through this approach, the study seeks to identify dominant patterns, underrepresented areas, and emerging research directions, while providing an evidence-based foundation for establishing future research priorities regarding problem-solving in science education.

METHODS

Research Design

This study employed a systematic literature review supported by bibliographic and multidimensional thematic mapping. The identification, screening, eligibility assessment, and reporting of included studies were conducted in accordance with PRISMA 2020 (Page et al., 2021), while the literature search strategy was documented following PRISMA-S recommendations (Rethlefsen et al., 2021). Because PRISMA primarily guides transparent identification, selection, and reporting, the present study extended the review process by adding bibliographic, thematic, geographical, citation-based, and relational mapping after the study-selection stage. The modified review framework consisted of six stages: (1) defining the review scope and analytical dimensions; (2) identifying and retrieving potentially relevant records; (3) screening and assessing article eligibility; (4) extracting bibliographic and thematic data; (5) testing and refining the coding framework; and (6) conducting quantitative bibliographic analysis and multidimensional thematic visualization. This modification enabled the review to connect transparent article selection with systematic examination of relationships among science domains, problem types, learning con-

texts, pedagogical pathways, outcomes, research purposes, problem-solving roles, geographical regions, and citation indicators.

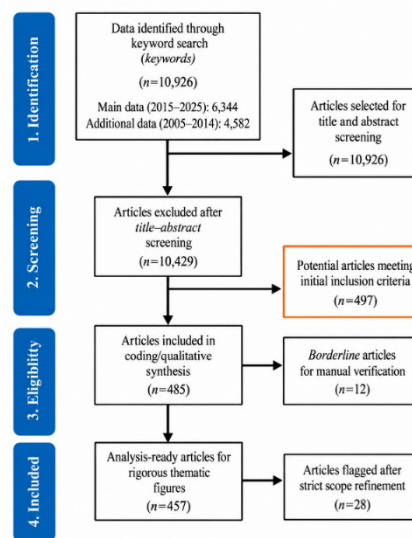


Figure 1. PRISMA Flow Chart of Study Selection

The overall selection process followed a PRISMA-oriented procedure, as illustrated in Figure 1. The identification stage began with keyword-based retrieval and produced 10,926 records: 6,344 from the main search period (2015-2025) and 4,582 from 2005-2014. All identified records were then subjected to title and abstract screening to determine their relevance to problem-solving in science education. After this screening stage, 10,429 records were excluded for not meeting the initial scope, while 497 articles were retained as potentially relevant studies that met the initial inclusion criteria. The eligibility stage then involved a more detailed examination of article relevance, coding potential, and thematic suitability. A total of 485 articles were included in the coding and qualitative synthesis stage, while 12 borderline articles were marked for manual verification because their relevance or classification required closer inspection. After further refinement of the analytical scope, 28 articles were marked or excluded, resulting in 457 analysis-ready articles that formed the final corpus for thematic mapping and bibliographic analysis.

The final review design connected the article selection process to the study's analytical objectives. The 457 analysis-ready articles were not only summarized but also systematically coded by science domain, problem type, learning context, pedagogical pathway, main outcome, research purpose, problem-solving role, country or region, and citation indicators. These categories enabled the study to examine problem-solving research

from multiple perspectives, including publication growth, citation impact, regional distribution, thematic flow, and cross-category relationships. Temporal analysis identified publication trends across years, citation analysis compared total citations and mean citation impact, and geographical mapping described global and regional patterns of contribution. Relational visualizations, including Sankey diagrams and chord diagrams, were used to interpret how learning contexts, pedagogical pathways, outcomes, domains, and problem types were interconnected. Through this design, the study aimed to provide a comprehensive and evidence-based map of problem-solving research in science education from 2005 to 2025, while also identifying frequency-impact gaps and future research directions.

Search Strategy and Data Sources

The literature search used a systematic, keyword-based strategy to identify publications on problem-solving research in science education. The search captured studies that explicitly addressed problem-solving in relation to science learning, science teaching, scientific reasoning, problem-based tasks, inquiry, assessment, or educational outcomes. The search covered publications from 2005 to 2025 to provide a broad longitudinal view of the field's development over two decades. The initial identification process produced 10,926 records based on the selected keyword combinations. This dataset included 6,344 records from the main search period of 2015-2025 and 4,582 additional records from 2005-2014, which were included to strengthen the review's historical coverage. The search results were then organized into a bibliographic database containing essential metadata, including publication year, article title, abstract, keywords, author information, citation data, country affiliation, and source information. This initial database became the foundation for the subsequent screening, eligibility assessment, coding, and thematic synthesis.

Article Selection Procedure

The article selection procedure followed a structured PRISMA-oriented flow to ensure transparency, consistency, and reproducibility in the screening process. The keyword-based search identified 10,926 records, which were first screened by title and abstract for relevance to problem-solving in science education. During this screening phase, 10,429 records were excluded because they did not meet the inclusion focus, were outside the scope of science education,

addressed problem-solving only incidentally, or lacked a clear educational connection. This screening process resulted in 497 potentially relevant articles that met the initial inclusion criteria. These articles were then examined more carefully to determine their eligibility for qualitative synthesis and thematic coding. A total of 485 articles were included in the coding and qualitative synthesis stage, while 12 borderline articles were marked for manual verification because their relevance, scope, or classification required closer inspection. After further refining the research scope, 28 articles were marked for exclusion because they did not fully align with the final analytical framework. The final dataset consisted of 457 analysis-ready articles, which formed the basis for all bibliographic, thematic, citation, geographical, Sankey, and chord diagram analyses.

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria ensured the final dataset aligned with the review's purpose. Articles were included when they explicitly addressed problem-solving in science education, involved a science-related learning context, and provided enough information to code according to the study's analytical dimensions. Eligible studies could focus on various areas of science education, including physical science, chemistry, integrated science or STEM, life and health science, environmental and earth science, or other closely related science learning domains. Studies were also included when they examined problem-solving through learning activities, pedagogical interventions, assessment instruments, conceptual diagnosis, experimental tasks, real-world problems, computational tasks, socio-scientific issues, or higher-order thinking outcomes. Articles were excluded when they were unrelated to education, focused only on general problem-solving outside science learning, discussed science content without a problem-solving component, lacked sufficient abstract or metadata information, or could not be reliably classified within the coding framework. Studies that mentioned problem-solving only as a general term without making it a central construct, task type, learning outcome, or analytical focus were also excluded from the final synthesis.

Data Extraction and Coding Scheme

Data extraction organized the final 457 articles into a structured analytical dataset. The extracted information included publication year, article title, source title, citation count, first-author country, geographical region, science do-

main, problem type, learning context, pedagogical pathway, main outcome, research purpose, and problem-solving role. Science domains were coded into categories such as physical science learning, chemical science learning, integrated science and STEM learning, life and health science learning, and environmental and earth science learning. Problem types were classified into broad science problem tasks, structured quantitative tasks, conceptual diagnostic tasks, experimental tasks, design or computational tasks, and authentic open problems, including real-world and socio-scientific issue-based problems. Learning contexts were coded according to the setting or orientation of the study, including practical experimental context, authentic societal context, general classroom setting, applied STEM context, technology-mediated context, health science context, and culture-based contextualization. Pedagogical pathways were coded into categories such as project/design pedagogy, no instructional intervention, problem-centered pedagogy, inquiry pedagogy, conventional comparison pedagogy, support strategy pedagogy, technology-mediated pedagogy, social learning pedagogy, and experience-based pedagogy. Main outcomes were coded into cognitive achievement, problem-solving and HOTS, affective outcomes, measurement outcomes, process or difficulty outcomes, general empirical outcomes, scientific competency, and conceptual change outcomes.

Coding Reliability and Refinement

The coding process involved iterative reading, classification, and refinement to improve consistency in category assignment across the dataset. Each article was examined based on its title, abstract, keywords, and available metadata to assign the most appropriate category for each coding dimension. Articles that were difficult to classify were marked as borderline and reviewed manually to avoid overgeneralization or misclassification. During refinement, broad, unclear, or overly fragmented categories were reorganized into more coherent clusters to improve interpretability and analytical consistency. This step was especially important because problem-solving research uses diverse terminology across domains, such as problem-based learning, problem-solving skills, scientific reasoning, HOTS, conceptual problem-solving, experimental problem-solving, design thinking, computational modeling, and socio-scientific decision-making. The final coding framework therefore balanced conceptual specificity with category parsimony, allowing systematic analysis without losing the field's thematic

complexity. The resulting coding structure enabled the study to identify both dominant patterns and emerging areas across the reviewed corpus.

Data Analysis and Visualization Techniques

The data analysis combined descriptive bibliographic analysis, citation analysis, geographical mapping, and relational thematic visualization. Annual publication trends were analyzed to identify the growth of problem-solving research from 2005 to 2025 by science domain and problem type. Citation analysis calculated total citations, mean citations per article, and median citations for each problem type to compare publication volume and scholarly influence. A frequency-impact quadrant map was then developed to position problem types by number of studies and mean citations per article. This analysis identified whether the most frequently studied problem types were also the most influential in terms of citation impact. Geographical analysis was conducted by mapping the country and regional distribution of included studies, using first-author affiliation or available country metadata as the basis for classification. Regional citation patterns were also calculated to compare publication productivity and mean citation impact across North America, Europe, Asia, Oceania, Africa, Latin America and the Caribbean, and other or unclear regions.

Relational thematic analysis used Sankey and chord diagrams to visualize multidimensional relationships among the coded categories. The Sankey diagram showed the flow from learning contexts to pedagogical pathways and main outcomes, allowing the study to examine how problem-solving research connects educational settings, instructional orientations, and expected learning results. Chord diagrams were used to analyze relationships between learning contexts and pedagogical approaches, research purposes and problem-solving roles, science domains and main outcomes, and problem types and science domains. These visualizations were selected because they can represent complex many-to-many relationships that tables or descriptive statistics alone cannot capture. The combined use of temporal trends, citation metrics, geographical mapping, Sankey diagrams, and chord diagrams allowed the study to construct a multidimensional picture of problem-solving research in science education. This analytical strategy provided a basis for identifying dominant structures, underexplored areas, frequency-impact gaps, and future research priorities in the field.

RESULTS AND DISCUSSION

Publication Trends by Science Domain and Problem Type

The cumulative trend presented in Figure 2a shows an increase in problem-solving research across science domains from 2005 to 2025, with physical science education emerging as the most dominant domain. The number of studies in this domain increased from 5 in 2005 to 78 in 2025, while chemistry education rose from 2 to 44 studies. This concentration aligns with prior literature showing that physics and chemistry have frequently become central domains for examining scientific reasoning, HOTS, literacy, experimentation, and problem-solving tasks (Kumar et al., 2024; Musengimana et al., 2025). Integrated science/STEM education also showed visible growth, reaching 28 studies by 2025, which reflects increasing attention to interdisciplinary and STEM-oriented problem-solving in science learning (Burrows et al., 2021; Roehrig et al., 2021). Life and health science education, biology education, and environmental/earth science education remained comparatively smaller, with 12, 11, and 4 studies, respectively. This pattern indicates that although problem-solving research has expanded substantially, its development remains uneven because broader environmental, health-related, and interdisciplinary domains are still less represented in the reviewed corpus (Vandegrift et al., 2020; Kumar et al., 2024).

The cumulative pattern in Figure 2b further shows that broad science problem tasks became the most frequently represented problem type. This category increased from 7 studies in 2005 to 95 studies in 2025, followed by structured quantitative/numerical

tasks (48 studies), conceptual diagnostic tasks (30 studies), and experimental/laboratory tasks (22 studies). The dominance of broad, quantitative, diagnostic, and experimental tasks reflects the strong presence of structured problem-solving formats in science education research, particularly those related to data interpretation, conceptual understanding, experimental reasoning, and evaluation of scientific arguments (Valladares, 2021; Badeo & Duque, 2022). Design/computational tasks and open-ended/real-world/SSI tasks appeared less frequently, reaching 18 and 9 studies, respectively, by 2025. This lower visibility is notable because SSI, open-ended tasks, and real-world problem contexts have been widely associated with scientific literacy, HOTS, ethical reasoning, and evidence-based decision-making (Badeo & Duque, 2022; Viehmann et al., 2024). Taken together, the two panels indicate that problem-solving research has expanded substantially but unevenly across both science domains and problem-type categories.

These findings indicate that problem-solving research in science education remains dominated by structured, quantitative, and discipline-specific tasks. While such approaches are important for developing analytical reasoning and conceptual understanding, contemporary issues—such as the environment, sustainability, and socio-scientific matters—are complex and multidimensional, requiring the integration of scientific knowledge with social, cultural, and ethical considerations. Therefore, there is still room to develop research that offers learners broader opportunities to engage in authentic problem-solving that reflects the complexities of real-world situations.

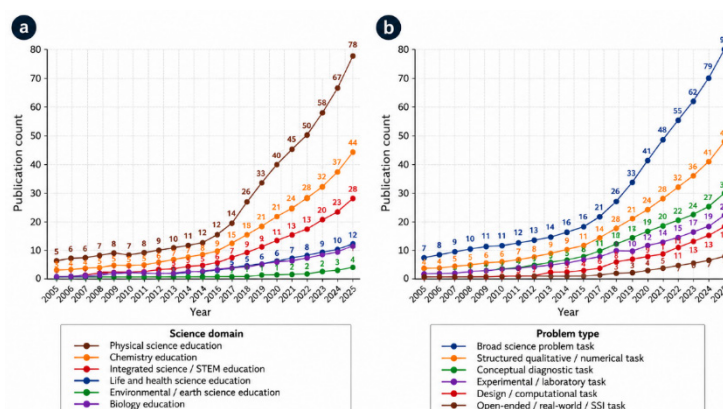


Figure 2. (a) Publication Trend by Science Domain (b) Publication Trend by Problem Type

Problem Type Distribution and Citation Impact

The total citation distribution in Figure 3a shows that general science/problem-solving tasks accumulated the highest citation count, with 2,770 cita-

tions from 159 articles, followed by conceptual/diagnostic problems with 2,505 citations from 76 articles. This dominance reflects the strong presence of broad, concept-oriented problem formats in science education research, particularly because such tasks often exa-

mine scientific reasoning, conceptual understanding, and higher-order thinking (Roehrig et al., 2021; Kumar et al., 2024). Quantitative/numerical problems received 1,863 citations from 94 articles, while laboratory/experimental problems obtained 1,382 citations from 74 articles. These categories remain central because science education problem-solving is often operationalized through calculation, data interpretation, experimental reasoning, and evidence-based evaluation (Valladares, 2021; Badeo & Duque, 2022). Open-ended/real-world/SSI problems accumulated 1,320 citations from only 20 articles, whereas computational/engineering design problems received 971 citations from 34 articles. This pattern indicates that problem types with larger publication volumes generally produced higher total citations, but citation accumulation was not fully proportional to the number of studies, particularly for authentic, computational, and SSI-oriented problem types (Ogebo & Ramnarain, 2022; Liu et al., 2024). The article-level citation pattern in Figure 3b shows a different hierarchy, with open-ended/real-world/SSI problems having the highest mean citation impact (66.00 citations per article) and a median of 19. This finding suggests that authentic and SSI-based problem types, although less frequent, may attract greater scholarly attention because they connect problem-solving with scientific literacy, ethical reasoning, argumentation, and real-world decision-making (Viehmann et al., 2024). Conceptual/diagnostic problems also performed strongly, with a mean of 32.96 and a median of 13, followed by computational/engineering design problems with

a mean of 28.56 and a median of 12. The relatively high impact of these categories is consistent with the growing emphasis on conceptual diagnosis, computational thinking, modeling, and design-based approaches in contemporary science education research (Psycharis et al., 2020; Viehmann et al., 2024). General science/problem-solving tasks, despite having the most studies and the highest total citations, recorded a lower mean citation impact of 17.42 and a median of 8. The quadrant map in Figure 3c further clarifies this frequency–impact gap by positioning general science/problem-solving tasks as frequent but lower in mean impact, whereas open-ended/real-world/SSI problems appear less frequent but highly influential. This result indicates that frequently studied problem types are not necessarily the most influential at the article level, and it highlights authentic, open-ended, and socio-scientific problems as a potentially high-impact direction for future research (Tripp et al., 2020; Ault, 2022).

Interestingly, the low publication frequency in open-ended problems, real-world scenarios, and socio-scientific issues was not accompanied by low academic impact. Conversely, the high average citation rates in these categories indicate growing scholarly interest in authentic, complex, and context-dependent problem-solving. These findings reveal a disparity between research frequency and academic impact, while also highlighting environmental, social, and sustainability contexts as promising areas for developing problem-solving research in science education.

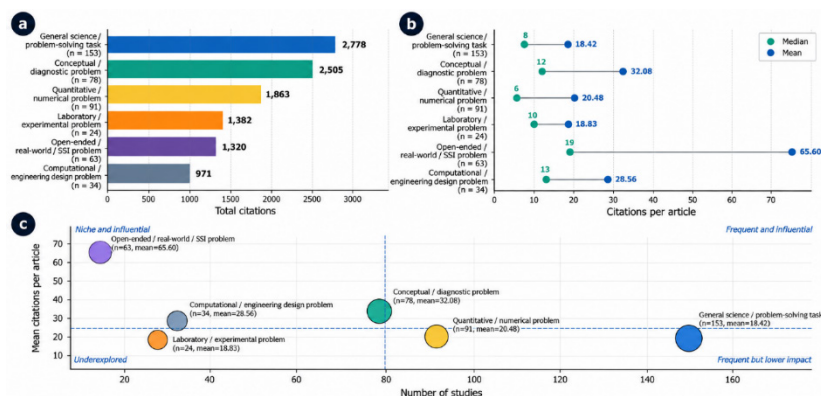


Figure 3. (a) Total Citations by Problem Type (b) Mean and Median of Citations per Article (c) Quadrant Map of Number of Studies and Mean of Citations

Geographic Distribution and Regional Citation Patterns

At the country level, Figure 4a indicates that problem-solving research in science education was globally distributed but unevenly concentrated across countries. The United States contributed the most studies, with 172 articles, followed by Indonesia (29), Turkey (26), China (18), the United Kingdom (16), and Germany (14). Other

contributors, including Greece, Spain, Australia, Taiwan, and Malaysia, appeared with smaller publication counts. Indonesia's visibility among Asian contributors suggests that research on problem-solving in science education has expanded beyond traditionally dominant Western contexts, although global production remains concentrated in a limited number of countries (Roehrig et al., 2021; Kumar et al., 2024).

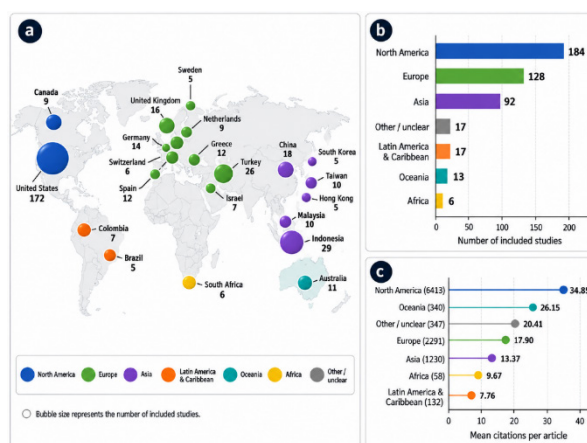


Figure 4. (a) World Map of Included Studies by Country (b) Number of Studies by Region (c) Mean of Citations per Article by Region

At the regional level, Figure 4b shows that North America dominated publication volume with 184 studies, followed by Europe with 128 studies and Asia with 92 studies. Other/unclear and Latin America & Caribbean each contributed 17 studies, while Oceania and Africa contributed 13 and 6 studies, respectively. The citation pattern in Figure 4c shows a similar regional imbalance, with North America having the highest mean citation impact (34.85 citations per article), followed by Oceania (26.15), Other/unclear (20.41), Europe (17.90), Asia (13.37), Africa (9.67), and Latin America & Caribbean (7.76). These findings suggest that productivity and citation impact are not evenly distributed across regions, with Asia showing substantial publication activity but lower average citation influence than North America and Oceania, a pattern that aligns with broader bibliometric concerns regarding international visibility, research networks, and citation concentration (Pinto et al., 2020; Oluwadele et al., 2023). The regional imbalance also indicates the need to strengthen cross-country collaboration and publication visibility in emerging research regions to support a more globally representative knowledge base in science education (Vandegrift et al., 2020; Viehmann et al., 2024). Thus, the geographical distribution indicates that the expansion in publication volume has not automatically been accompanied by an equitable distribution of academic visibility across regions—particularly for areas that are productive yet have relatively lower citation impact.

Thematic Evolution of Problem-Solving Research in Science Education

The Sankey-based thematic structure in Figure 5 shows that problem-solving research in science education is increasingly organized around interactions

among learning contexts, pedagogical pathways, and outcome orientations. Practical experimental contexts and authentic societal contexts appear as the most visible entry points, suggesting that problem-solving is often situated in settings where students are expected to connect scientific concepts with experimentation, evidence, real-world issues, and contextual decision-making. This pattern reflects the growing role of inquiry, socio-scientific issues, and integrated STEM/STEAM as learning environments that support scientific literacy, reasoning, and higher-order thinking (Badeo & Duque, 2022; Kumar et al., 2024). The presence of general classroom, applied STEM, technology-mediated, and specialized contexts further suggests that problem-solving is not limited to conventional classroom tasks, but is increasingly embedded in learning ecologies that combine conceptual understanding, practical investigation, technological mediation, and interdisciplinary application (Roehrig et al., 2021; Halawa et al., 2024).

These findings also align with empirical evidence showing that technology-assisted science learning—including QR code-based media—can support the development of students' problem-solving skills and scientific literacy (Savitri et al., 2021).

The dominant flow from learning contexts to project/design pedagogy in Figure 5 suggests that problem-solving research has shifted toward applied, design-oriented, and solution-focused science learning. This pattern supports the argument that project-based and design-based pedagogies provide a productive pathway for integrating concepts, modeling, experimentation, and real-world solution development in science education (Almulla, 2020; Yanto et al., 2026). The substantial absence of direct intervention also suggests that problem-solving is often treated as an assessment, mapping, diagnostic, or descriptive construct, rather than as a direct instructional treatment.

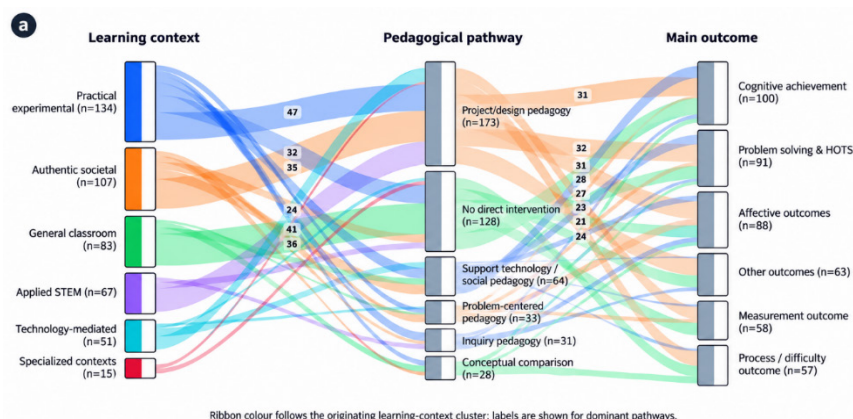


Figure 5. Thematic Flow of Learning Contexts, Pedagogical Pathways, and Main Outcomes

The outcome distribution in Figure 5 strengthens this interpretation because cognitive achievement appears alongside problem-solving and HOTS, affective outcomes, measurement outcomes, and process/difficulty outcomes. This multidimensional outcome profile implies that problem-solving has evolved from a narrow achievement-oriented construct into a broader framework for examining how learners reason, struggle, design, decide, and transfer scientific

knowledge across contexts (Badeo & Duque, 2022; Vandegrift et al., 2020). Overall, the relational analysis confirms that problem-solving research is increasingly connected to practical, authentic, and design-oriented learning, although these dimensions remain unevenly integrated across science domains.

Temporal Thematic Evolution of Problem-Solving Research

Table 1. Temporal Thematic Evolution of Problem-Solving Research in Science Education

Period	No. of Articles	Dominant Theme	Thematic Direction
2005-2010	68	Structured science tasks and laboratory-based problem-solving	Problem-solving was mainly positioned as a structured academic activity focused on conceptual understanding, quantitative reasoning, and experimental tasks.
2011-2016	71	Classroom-based assessment and diagnostic problem-solving	Research began to emphasize problem-solving as an assessment, diagnostic, and classroom-based construct.
2017-2021	155	Project/design pedagogy, STEM, and experimental learning	Problem-solving expanded toward applied, interdisciplinary, project-based, and process-oriented science learning.
2022-2025	163	Authentic, SSI-based, technology-mediated, and HOTS-oriented problem-solving	Recent research increasingly connected problem-solving with real-world issues, socio-scientific contexts, technology, and higher-order thinking.

As shown in Table 1, the temporal thematic evolution indicates that problem-solving research in science education has moved from structured academic tasks toward more contextual and multidimensional orientations. In 2005-2010, the dominant theme was structured science tasks and laboratory-based problem-solving, indicating that early studies mainly emphasized conceptual understanding, quantitative reasoning, and experimental work. In 2011-2016, the focus shifted toward classroom-based assessment and diagnostic problem-solving, showing that problem-solving was increasingly used to evaluate students' under-

standing, identify learning difficulties, and describe learning outcomes. This pattern indicates that the field's early development remained strongly rooted in well-defined academic problems, structured reasoning, and measurable cognitive achievement (Vandegrift et al., 2020; Agustian et al., 2022; Alarcón et al., 2023).

The data also show a stronger thematic expansion after 2017. In 2017-2021, the dominant theme moved toward project/design pedagogy, STEM-oriented learning, and experimental learning, indicating that problem-solving began to be positioned as a process of investigation, evidence

interpretation, and solution design. In 2022-2025, the theme shifted further toward authentic, SSI-based, technology-mediated, and HOTS-oriented problem-solving, suggesting that recent studies increasingly connect problem-solving with real-world issues, socio-scientific reasoning, digital learning environments, and contextual decision-making. This shift indicates that the field is gradually transforming from achievement-oriented problem-solving toward transferable competence for addressing complex scientific and societal problems. However, the continued presence of structured science tasks across periods suggests that authentic, interdisciplinary, and sustainability-oriented problem-solving still needs stronger integration in future science education research (Roehrig et al., 2021; Ariza et al., 2021; Badeo & Duque, 2022; Viehmann et al., 2024; Kumar et al., 2024).

Overall, this thematic evolution reflects a shift in problem-solving research from structured, discipline-oriented cognitive tasks toward learning that is more authentic, interdisciplinary, and contextual. However, elements such as inquiry, project-based learning, sustainability, and real-world contexts tend to develop as separate lines of research. This situation highlights the need for a more integrative approach to developing problem-solving as a transferable competence for addressing complex scientific and societal issues.

Pedagogical and Research Positioning of Problem-Solving

The cross-thematic relationship in Figure 6a shows that problem-solving research is strongly connected to practical, authentic, and design-oriented learning environments. Practical experimental contexts and authentic societal contexts formed the most visible connections with project/design pedagogy, indicating that many studies frame problem-solving as an applied process in which students investigate phenomena, interpret evidence, design solutions, and respond to real-world scientific problems. This pattern suggests that problem-solving pedagogy is increasingly shaped by learning designs that emphasize inquiry,

contextual reasoning, interdisciplinary application, and solution development (Roehrig et al., 2021; Kumar et al., 2024). Applied STEM and technology-mediated contexts also appear in the network, showing that technological and interdisciplinary environments have become part of the pedagogical landscape, although their connections remain less dominant than practical experimental and authentic societal contexts (Psycharis et al., 2020; Koç & Kanadlı, 2025). The absence of instructional intervention further indicates that Figure 6a includes not only intervention-based studies but also descriptive, diagnostic, assessment-oriented, and mapping studies that position problem-solving as an object of analysis rather than direct instructional treatment (Tripp et al., 2020; Vandegrift et al., 2020).

The research-positioning pattern in Figure 6b further shows that problem-solving is often treated as an evaluative, outcome-oriented construct. Product/design-oriented purpose was strongly connected to assessment role, broad focus role, and outcome role, indicating that many studies use problem-solving to assess student ability, evaluate learning products, and measure educational outcomes. This orientation reflects the field's strong concern with the quality of learning products and measurable performance, especially in studies related to project/design pedagogy, SSI, STEM, and scientific literacy (Roehrig et al., 2021; Badeo & Duque, 2022). The smaller proportions of process-oriented purpose, perception-oriented purpose, and task/social role indicate that fewer studies deeply examine how students construct, regulate, negotiate, or experience problem-solving processes. This gap matters because problem-solving cannot be understood solely as a final score or product; it also involves cognitive, metacognitive, social, and affective processes through which learners develop scientific reasoning and decision-making competence (Chen et al., 2020; Valladares, 2021). Together, Figure 6a and Figure 6b indicate that the field is shaped by a dual orientation: pedagogical innovation through practical, authentic, and design-based learning, and research positioning that still relies heavily on assessment and outcome measurement.

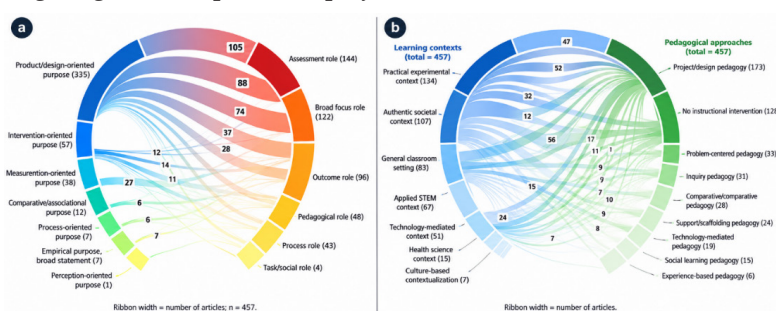


Figure 6. (a) Learning Contexts and Pedagogical Approaches (b) Research Purposes and Problem-Solving Roles

Disciplinary Structure and Outcome Orientation

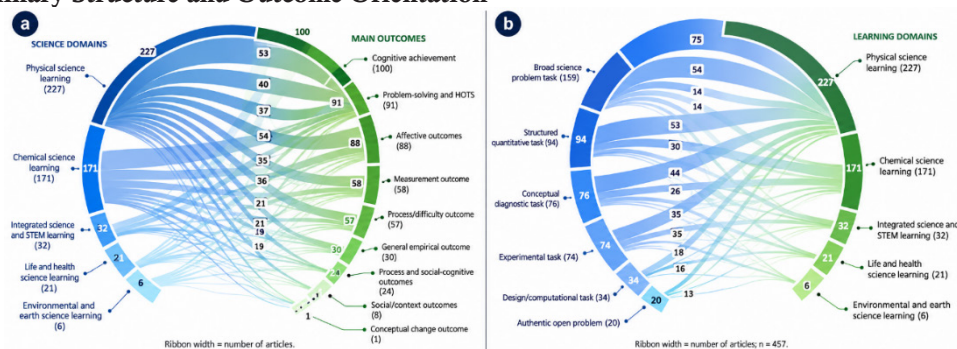


Figure 7. (a) Science Domains and Main Outcomes (b) Problem Types and Science Domains

The domain-outcome relationship in Figure 7a shows that problem-solving research is structurally concentrated in physical science learning and chemical science learning. These two domains form the strongest connections with cognitive achievement, problem-solving and HOTS, affective outcomes, measurement outcomes, and process/difficulty outcomes. This pattern indicates that the dominance of physical science and chemistry is not only reflected in the number of studies, but also in the outcome architecture that shapes the field. These domains' strong position is understandable because physics and chemistry commonly involve symbolic representation, quantitative reasoning, experimental interpretation, model-based explanation, and conceptual diagnosis, which align closely with established problem-solving tasks (Ariza et al., 2021; Hogan & O'Flaherty, 2021). The smaller connections involving integrated science/STEM, life and health science, and environmental and earth science learning suggest that problem-solving research has not yet fully captured the potential of interdisciplinary and socially relevant domains, particularly those related to sustainability, public health, environmental citizenship, and complex real-world decision-making (Vandegrift et al., 2020; Hogan & O'Flaherty, 2021).

The problem type-domain relationship in Figure 7b further shows that the disciplinary structure of problem-solving research is shaped by the types of problems most commonly used in each science domain. Broad science problem tasks, structured quantitative tasks, conceptual diagnostic tasks, and experimental tasks are most strongly connected to physical science learning and chemical science learning, suggesting that these domains are closely associated with structured, diagnostic, quantitative, and experimental forms of problem-solving. Authentic open problems show smaller connections across science domains, indicating that open-ended, real-world, and SSI-based problem-solving remains less embedded in environmental, health-related, and integrated STEM contexts. This limited connection is important because

authentic problem types can support uncertainty reasoning, ethical judgment, socio-scientific relevance, and interdisciplinary knowledge application (Tripp et al., 2020; Ault, 2022). Such expansion would help reposition problem-solving as a transferable scientific competence that supports contextual decision-making, rather than merely as a domain-bound measure of conceptual or procedural performance.

Thematic Diversification beyond Publication Growth

Cross-visualization findings indicate that the growth of research on problem-solving in science education has not necessarily been accompanied by balanced thematic diversification. The dominance of physics and chemistry, alongside the frequent use of structured, quantitative, diagnostic, and experimental tasks, suggests that the field's development remains strongly influenced by a problem-solving tradition oriented toward mastering concepts and procedures. At the same time, the increasing emergence of authentic contexts, integrated STEM, and project- and design-based pedagogies points to an expansion toward more applicative and contextual forms of problem-solving. Thus, the field's evolution is best understood as a transitional process rather than a fully realized paradigm shift.

Patterns of relationships among learning contexts, pedagogical approaches, and learning outcomes further reveal that the expansion of problem-solving extends beyond task types to encompass the learning objectives themselves. Problem-solving is increasingly linked to Higher-Order Thinking Skills (HOTS), affective aspects, learning processes, and design and decision-making capabilities. However, contexts involving the environment, health, sustainability, and authentic social issues remain disproportionately under-integrated. These findings highlight the need for research that not only broadens the range of instructional strategies but also connects

problem-solving more systematically to complex scientific and social contexts.

Pedagogical Positioning and Frequency-Impact Gap

Citation patterns in Figure 3a–c reveal that problem-solving research in science education is shaped by a frequency–impact gap between dominant problem types and academically influential problem types. General science/problem-solving tasks accumulated the highest total citations in Figure 3a, largely because this category includes the most articles and represents a well-established tradition of discipline-centered problem-solving research. This pattern reflects how citation accumulation is often shaped by the size of article clusters, especially in research areas dominated by broad, structured, quantitative, and experimental task formats (Agustian et al., 2022; Jiang, 2024). However, Figure 3b shows that open-ended, real-world, and SSI-based problems achieved the highest mean citation impact despite their lower publication frequency. Figure 3c therefore indicates that the most frequently studied problem types are not necessarily the most influential at the article level. This finding is important because authentic problem types tend to address complex, socially relevant, and interdisciplinary issues that attract broader scholarly attention across science education, environmental education, and citizenship-oriented research (Ariza et al., 2021; Schriebl et al., 2022).

Pedagogical mapping reinforces these findings by showing that problem-solving serves a dual role: both a pedagogical pathway and an evaluative construct. The strong link between authentic contexts and project- or design-based pedagogy indicates a shift toward learning that enables students to investigate phenomena, devise solutions, and evaluate evidence within contextual settings. However, research tends to treat problem-solving primarily as an indicator of learning outcomes or effectiveness, rather than examining the processes through which students construct, organize, negotiate, and experience problem-solving. This gap highlights the need for instruments and analytical frameworks that are more sensitive to processes, competence development, collaboration, and the complexities of problem-solving (Kim et al., 2021; Nakamoto et al., 2024).

Disciplinary, Geographic, and Future Research Directions

Geographically and disciplinarily, research findings reveal two interconnected forms of inequa-

lity. First, while knowledge production has expanded globally, citation visibility remains concentrated in specific regions, particularly North America. This suggests that a corresponding increase in global academic influence has not yet matched rising research productivity in regions such as Asia. Strengthening cross-national collaboration, cross-regional authorship, shared data use, and international dissemination strategies could help expand the circulation of knowledge from productive regions with relatively low citation visibility (DeCoito & Estaiteyeh, 2022; Susilayati et al., 2024).

Second, from a disciplinary perspective, problem-solving research remains deeply rooted in physics and chemistry, as well as in structured, quantitative, diagnostic, and experimental problem types. In contrast, authentic, open-ended, and socio-scientific issue-based problems remain less strongly linked to environmental science, health, and integrated STEM. Future research needs to extend problem-solving into the contexts of the environment, health, sustainability, and interdisciplinary STEM, while also developing assessments that are more sensitive to the process itself. Such expansion is crucial for positioning problem-solving not merely as a measure of conceptual or procedural mastery, but as a transferable scientific competence for addressing complex social and environmental challenges.

Overall, the findings indicate that several key elements in developing problem-solving skills—including authentic and open-ended problems, project- and design-based pedagogy, interdisciplinary STEM integration, environmental and sustainability contexts, and socio-scientific issues—remain on relatively separate research trajectories. This fragmentation may limit the development of transferable problem-solving competencies needed to address complex issues that require integrating scientific understanding, environmental responsibility, and contextual decision-making. Therefore, future research needs to move beyond isolated instructional innovations toward a more integrative approach by linking project-based learning, environmental and sustainability contexts, and authentic problem-solving experiences. This integration is crucial for preparing learners to address contemporary scientific and social issues through scientific reasoning, collaborative inquiry, contextual understanding, and sustainability-oriented decision-making.

CONCLUSION

This review shows that problem-solving research in science education has grown substantially from 2005 to 2025, yet its development remains uneven across science domains, problem types, pedagogical contexts, and geographical

regions. Beyond documenting publication trends, this review provides a multidimensional evidence map by integrating bibliographic, citation, geographical, temporal, and relational analyses to explain how problem-solving research has evolved over the past two decades. While physical science and chemistry continue to dominate the field, open-ended, real-world, and socio-scientific issue (SSI)-based problems demonstrate substantially greater citation impact despite their lower publication frequency, highlighting a clear frequency-impact gap within the literature. The findings further reveal a gradual shift toward authentic learning contexts, project/design pedagogy, and multidimensional learning outcomes; however, sustainability, interdisciplinary STEM, contextual learning, and authentic problem-solving remain insufficiently integrated within existing research. Therefore, future studies should prioritize developing and empirically evaluating integrative learning frameworks that combine authentic problem contexts, project-based learning, contextual knowledge, interdisciplinary perspectives, and sustainability-oriented issues to foster transferable problem-solving competencies capable of addressing complex environmental and societal challenges.

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