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A Systematic Literature Review on the Integration of the Nature of Science in Science Education to Support Scientific Literacy

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Abstract

The low level of students' scientific literacy remains a major issue in science education, as indicated by international assessment results and learning practices that still emphasize conceptual mastery without adequately addressing how scientific knowledge is constructed. One approach considered effective in addressing this issue is the integration of the Nature of Science in science learning, as it helps students understand the nature, processes, and characteristics of science more comprehensively. This study aims to examine and synthesize previous research on the integration Nature of Science in science learning to support the development of students' scientific literacy. This study employed a systematic literature review (SLR) method following the PRISMA procedure. Data were collected from the Scopus database, covering publications from 2021 to 2026, resulting in 26 articles that met the inclusion criteria. The findings indicate that the integration Nature of Science can be implemented through various approaches, including the development of teaching materials, explicit-reflective learning strategies, contextual approaches based on socio-scientific issues, laboratory activities, and teacher professional training. The integration Nature of Science shows positive contributions to improving students' scientific literacy, conceptual understanding, critical thinking skills, scientific argumentation, as well as metacognitive aspects and self-efficacy. However, the implementation of Nature of Science is still largely implicit and has not been systematically integrated into learning practices. Therefore, more structured and sustainable efforts are needed to explicitly integrate Nature of Science into science learning in order to optimally support the development of students' scientific literacy.

Keywords: *scientific literacy, science learning, Nature of Science*

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INTRODUCTION

The development of 21st-century skills has become a major focus in contemporary education. Modern education emphasizes the importance of equipping students with essential competencies such as critical thinking, problem-solving, and collaboration skills (Aziz et al., 2024). In the context of science education, the development of scientific attitudes is particularly important, as these attitudes serve as the foundation for students to engage in scientific processes and to understand empirical evidence objectively (Khairinaa et al., 2023). In line with these demands, scientific literacy has become a fundamental competency that every individual should possess in the 21st century. Scientific literacy is not limited to the mastery of scientific concepts but also encompasses the ability to understand, apply, and communicate scientific information in everyday life. Furthermore, it involves critical thinking skills, the ability to analyze problems, and the use of scientific methods to address various challenges (Parisu et al., 2025). Therefore, scientific literacy is considered an essential skill that needs to be developed to enable students to appropriately apply scientific knowledge in real-life contexts (Suryani et al., 2017).

The results of scientific literacy assessments conducted by the *Programme for International Student Assessment* (PISA) indicate that the level of scientific literacy among students in Indonesia remains relatively low. Data from assessments conducted in 2006, 2009, 2012, 2015, and 2018 show that Indonesian students' scientific literacy scores have not yet reached satisfactory levels (Yusmar & Fadilah, 2023). The most recent results from PISA 2022 further reveal that Indonesian students

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scientific literacy performance remains below the OECD average, with a score of approximately 383 compared to the OECD average of 485, and demonstrates a declining trend compared to previous cycles (Organisation for Economic Co-operation and Development [OECD], 2023). Although PISA is conducted every three years, the results for the next cycle (PISA 2025) have not yet been released; therefore, PISA 2022 remains the most recent reference for examining students scientific literacy. These findings indicate that students abilities to understand scientific concepts, interpret scientific phenomena, and apply scientific knowledge in everyday life still need significant improvement. One of the factors contributing to the low level of scientific literacy is the science learning process in schools, which tends to rely on conventional, teacher-centered approaches and primarily emphasizes conceptual mastery. In fact, scientific literacy extends beyond conceptual understanding to include scientific attitudes, the ability to apply scientific knowledge in real-life contexts, and skills in conducting scientific processes (Wijaya et al., 2025).

This condition indicates a gap in science learning, which continues to place greater emphasis on content mastery, while limited attention is given to understanding how scientific knowledge is constructed and validated. This gap highlights the importance of implementing science learning approaches that are not only content-oriented but also emphasize an understanding of the processes through which scientific knowledge is developed, commonly referred to as the *Nature of Science* (Handayani, 2025). The *Nature of Science* is a fundamental concept related to the epistemology of science, encompassing how scientific knowledge is generated, tested, and accepted within the scientific community. It includes several key characteristics, such as the understanding that scientific knowledge is tentative yet reliable, based on empirical evidence, involves human creativity and imagination, and is influenced by social and cultural contexts (Rahayu & Widodo, 2019).

Lederman emphasizes that understanding the *Nature of Science* is a crucial component of scientific literacy, as it enables individuals not only to understand what is known in science but also how such knowledge is generated and why it is accepted as scientific knowledge (Lederman & Lederman, 2014). Learning that integrates the *Nature of Science* goes beyond the delivery of scientific concepts by guiding students to understand how scientific knowledge is produced, tested, and applied (Viclara, 2025). Through this understanding, students are expected to develop a clear comprehension of scientific methods, the roles of observation and experimentation, and the development of scientific theories and laws. Consequently, they are better equipped to distinguish between science and pseudoscience and to recognize the relevance of science in everyday life.

Understanding the *Nature of Science* plays a crucial role in science education. Through this understanding, students not only learn scientific concepts but also gain insights into how scientific knowledge is developed, tested, and applied. Such understanding can facilitate students' comprehension of scientific concepts, increase their interest in science learning, and support their ability to make informed decisions related to scientific issues (McComas, 2004). In addition, an understanding of the *Nature of Science* enables students to recognize the connection between concepts and real-world contexts in science learning, thereby supporting the development of scientific literacy (Listiani, 2023). Therefore, fostering students' understanding of the *Nature of Science* is a key aspect of science education in developing scientifically literate individuals.

Numerous previous studies have examined the implementation of the *Nature of Science* in science education and its relationship with the development of students' scientific literacy. Several studies indicate that an understanding of the *Nature of Science* can positively contribute to the improvement of scientific literacy. However, the findings of these studies remain varied and are conducted across different educational contexts. In addition, some studies suggest that the integration of the *Nature of Science* in science learning is still relatively limited, particularly in the context of education in developing countries (Viclara, 2025). This condition indicates that research on the integration of the *Nature of Science* in science education is still dispersed across various studies with diverse approaches, and thus has not yet provided a comprehensive understanding.

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Therefore, this study aims to conduct a systematic literature review to analyze and synthesize existing research on the integration of the *Nature of Science* in science education to support the development of scientific literacy. In line with this objective, the study is guided by the following research questions:

1. How has research on the integration of the *Nature of Science* in science education evolved over time (RQ1)?
2. What forms of *Nature of Science* integration are implemented in science education (RQ2)?
3. What are the impacts of *Nature of Science* integration on students' scientific literacy (RQ3)?
4. What challenges are encountered in implementing *Nature of Science* integration in science education (RQ4)?

METHODS

Research Design

This study employed a systematic literature review (SLR) approach to map, analyze, and synthesize comprehensively previous studies related to the integration of the *Nature of Science* in science education to support the development of scientific literacy. The SLR approach was selected to ensure that the processes of identifying, selecting, and evaluating the literature were conducted in a systematic and transparent manner. The methodological framework of this study was designed in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which are widely recognized as a standard for conducting systematic reviews across various disciplines. Through this approach, the synthesis of the literature focused on examining the forms of *Nature of Science* integration in science education, the contexts of its implementation, and its contributions to the development of students' scientific literacy.

Data Sources and Search Strategy

The data used in this study were obtained from an international database, namely Scopus. This database was selected due to its extensive coverage of scientific publications, inclusion of high-quality peer-reviewed articles, and rigorous indexing standards, which ensure the reliability and credibility of the sources. In addition, Scopus is widely utilized in systematic literature review studies because of its ability to provide comprehensive and well-structured bibliographic data.

The literature search was conducted on March 10, 2026, at 20:39 (WIB), using a combination of relevant keywords: "Nature of Science" AND "science education" AND "scientific literacy." The use of the Boolean operator AND was intended to refine the search results to ensure greater relevance to the focus of the study. Furthermore, the search was limited to publications from the last five years (2021–2026) in order to capture the most recent developments in science education research.

Inclusion and Criteria

The selection of articles included in this study was determined based on predefined inclusion and exclusion criteria. The inclusion criteria were applied to identify studies relevant to the research focus, namely the integration of the *Nature of Science* in science education to support scientific literacy. Meanwhile, the exclusion criteria were used to filter out studies that did not align with the objectives of the study. The establishment of these criteria aimed to ensure that the selected articles were both relevant to the research objectives and met appropriate standards of scientific quality. The detailed inclusion and exclusion criteria used in this study are presented in Table 1.

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Table 1. Inclusion and Exclusion Criteria

Aspect	Inclusion Criteria	Exclusion Criteria
Topic	Studies discussing the integration of the *Nature of Science* in science education	Studies not addressing the *Nature of Science*
Research Focus	Studies related to students' scientific literacy	Studies not related to scientific literacy
Publication Type	Journal articles	Theses, books, proceedings, and review articles
Publication Year	2021-2026	Publications outside the specified period
Language	English and Indonesian	Languages other than English and Indonesian
Access	Full-text articles available	Articles without full-text access
Duplication	Unique articles	Duplicate articles

Study Selection Process

Articles that met the inclusion criteria were subsequently subjected to a stepwise selection process based on the PRISMA guidelines. The selection stages included identification, screening, eligibility assessment, and inclusion. During the identification stage, articles were retrieved from scientific databases using the predefined search keywords. Subsequently, the articles were screened based on their titles and abstracts to ensure their relevance to the research topic. Articles that passed the screening stage were further evaluated through full-text reading to assess their eligibility. The overall article selection process is illustrated in the PRISMA flow diagram presented in Figure 1.

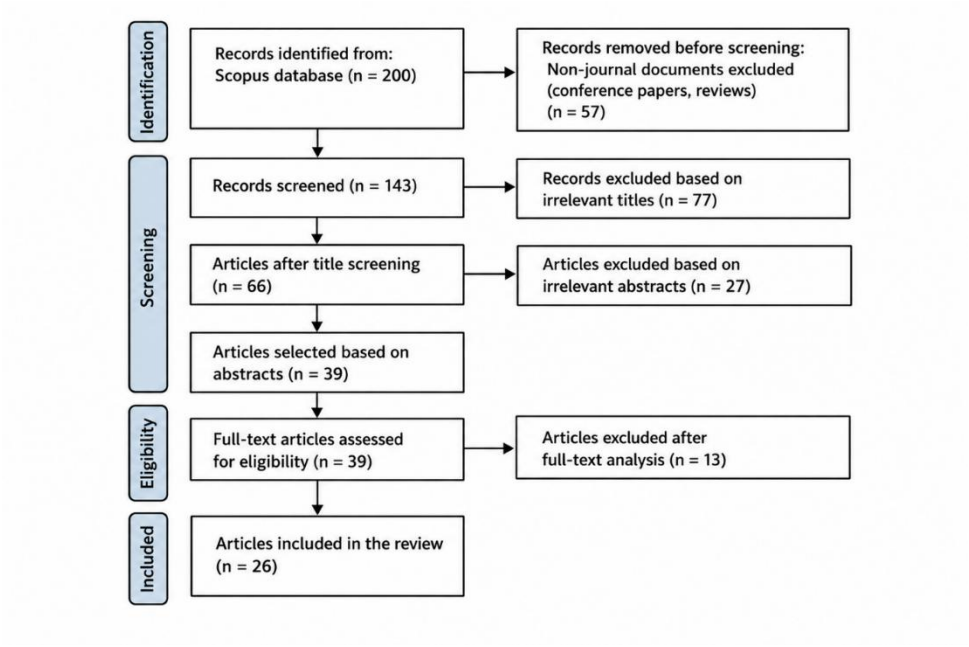


Figure 1. PRISMA Flow Diagram of the Article Selection Process

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Data Analysis Technique

Articles that passed the selection stage were systematically analyzed to identify key findings related to the integration of the *Nature of Science* in science education to support scientific literacy. The analysis process involved a thorough review of each selected article to extract essential information, including publication year, research methods, research subjects, and the focus of the study related to the implementation of the *Nature of Science* in science learning. The collected data were analyzed using a qualitative descriptive approach to identify research trends, patterns of *Nature of Science* integration in science education, and its contributions to scientific literacy. The results of the analysis were then presented in the form of tables, graphs, and descriptive narratives to provide a clearer understanding of the development of research in the studied topic. In addition, bibliometric analysis was conducted to map research trends and the relationships between keywords using VOSviewer software.

RESULT AND DISCUSSION

Result

Article Characteristics

A total of 26 articles were analyzed in this study using the PRISMA method, all of which were published within the last five years. The analyzed articles demonstrate a variety of research methods employed to examine the integration of the *Nature of Science* in science education. Most studies adopted quantitative approaches to measure the effects of *Nature of Science* integration on students' abilities, such as scientific literacy and conceptual understanding. In addition, several studies employed qualitative and mixed-methods approaches to explore learning processes as well as students' and teachers' understanding of the *Nature of Science* concept. This variation in research methods indicates that the study of *Nature of Science* integration has been investigated through diverse methodological approaches.

Table 2. Characteristics of the Reviewed Articles

No.	Authors	Year	Research Method	Research Subjects	Research Focus
1.	Khishfe	2023	Systematic Review	Research articles on science education	Reviews various instructional approaches to enhance students' understanding of the *Nature of Science*
2.	Cullinane & Erduran	2023	Qualitative Case Study	Pre-service science teachers in Ireland	Examines the impact of RFN-based workshops on understanding and implementation of the *Nature of Science* in lesson planning
3.	Zhuang et al.,	2021	Content Analysis / Document Analysis	5 high school physics textbooks in China	Analyzes the representation of the *Nature of Science* in physics textbooks

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No.	Authors	Year	Research Method	Research Subjects	Research Focus
4.	Laslo & Baram-Tsabari	2021	Content Analysis	Readers' comments on online news about animal experiments	Examines expressions of scientific literacy in online public discussions
5.	Yeh et al.,	2023	Content Analysis	3 high school physics textbooks	Analyzes how the *Nature of Science* is represented, including NOS aspects, clarity of presentation, and alignment with learning objective
6.	Garcia-Carmona	2021	Systematic Literature Review (PRISMA-based) with qualitative content analysis	88 articles from 17 education journals in Spain (2010–2019)	Examines how the *Nature of Science* is studied and taught, including research types, participants, NOS aspects, and learning context
7.	Gao et al.,	2025	Content Analysis	Biology curriculum documents in China	Analyzes the representation of the *Nature of Science* in curriculum standards and coherence across educational levels
8.	Manassero-Mas & Vázquez-AlonsoManassero-Mas & Vázquez-Alonso	2022	Quantitative Method	Elementary (Grade 6) and secondary (Grade 8) students	Examines the relationship between the *Nature of Science* and critical thinking skill
9.	Cobo et al.,	2022	Mixed methods	Pre-service science teachers	Investigates the effectiveness of contextual and integrated learning approaches in improving and sustaining understanding of the *Nature of Science*

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No.	Authors	Year	Research Method	Research Subjects	Research Focus
10.	Valencia et al.,	2023	Quantitative, quasi-experimental (pretest–posttest)	Pre-service teachers	Analyzes the effect of differences in science content knowledge on understanding of the *Nature of Science* before and after intervention
11.	Poor et al.,	2025	Mixed methods	14 scientists from various scientific fields	Examines scientists' views on the *Nature of Science* and their perspectives on the importance of communicating it to the public
12.	Munezero et al.,	2022	Quantitative (survey and statistical analysis)	Students (in the context of scientific literacy)	Analyzes factors influencing students' scientific literacy, such as learning strategies, motivation, and learning environment
13.	ShiShi	2023	Mixed Methods	14 scientists from various scientific fields	Examines scientists' views on the *Nature of Science* and their perspectives on the importance of communicating it to the public
14.	Kruit et al.,	2025	Quantitative (experimental, pretest–posttest design, multilevel analysis)	423 secondary education students (experimental and control groups)	Analyzes the impact of a web-based educational instrument based on socio-scientific issues (SSI) on argumentation skills, content knowledge, and understanding of the *Nature of Science*

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No.	Authors	Year	Research Method	Research Subjects	Research Focus
15.	Karaismailoglu et al.,	2025	Quantitative (survey using Structural Equation Modeling/SEM)	448 secondary school students	Examines the role of the *Nature of Science* as a mediator in the relationship between metacognition and science self-efficacy
16.	Lee & Park	2025	Academic literature on the Anthropocene	Literatur & sumber akademik tentang Anthropocene	Develops the concept of Anthropocene Literacy in science education, including the *Nature of Science* and multidisciplinary approaches
17.	Deng et al.,	2025	Meta-analysis	25 independent studies (K–12 & pre-service teachers)	Examines the effectiveness of Explicit-Reflective Teaching in improving understanding of the *Nature of Science* and analyzes moderating factors (duration, strategy, class size)
18.	Pelaez et al.,	2025	Mixed Methods	204 prospective elementary teachers (PETs) Filipina	Investigates pre-service teachers' views on six aspects of the *Nature of Science* using the SUSSI instrum
19.	Kim & Sermeus	2025	Content Analysis	Science educational videos on YouTube	Analyzes the presence and representation of the *Nature of Science* in science learning videos based on Lederman's framework

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No.	Authors	Year	Research Method	Research Subjects	Research Focus
20.	Kutluk et al.,	2025	Mixed methods	University students in STEM laboratory courses	Examines the effectiveness of the Designed-to-Fail Laboratory (DtFL) approach in improving understanding of the *Nature of Science* through structured failure
21.	Manassero-Mas & Vázquez-AlonsoManassero-Mas & Vázquez-Alonso	2021	Mixed methods	(pre-service teachers)	Analyzes the effectiveness of explicit-reflective *Nature of Science* instruction in improving NOS understanding and teachers' pedagogical compete
22.	Kadir et al.,	2025	Quantitative descriptive	150 Grade IX junior high school students (5 schools in Bombana, Indonesia)	Measures students' scientific literacy using the NOSLiT instrument based on *Nature of Science* unde
23.	Bytyqi-Damoni et al.,	2025	Qualitative (document analysis using Family Resemblance Approach/FRA)	Lower secondary school chemistry curriculum in Kosovo	Analyzes the representation of the *Nature of Science* in the chemistry curriculum and the balance of cognitive-epistemic and social-institutional aspects
24.	Chuene & Singh	2024	Qualitative	11 science teachers	Examines teachers' views on the *Nature of Science* and its implications for Pedagogical Content Knowledge (PCK)

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No.	Authors	Year	Research Method	Research Subjects	Research Focus
25.	Perez et al.,	2025	Bibliometric analysis (using Bibliometrix/Biblioshiny and VOSviewer)	1,225 documents from Web of Science and Scopus	Analyzes the development, trends, and research themes of scientific literacy in science education over 40 years
26.	Liu et al.,	2025	Quantitative	4,492 students (Grades 1–9) in China	4,492 students (Grades 1–9) in China

Research Publication Trends

The results of the analysis using Biblioshiny reveal the development of research publications related to the integration of the *Nature of Science* in science education over time.

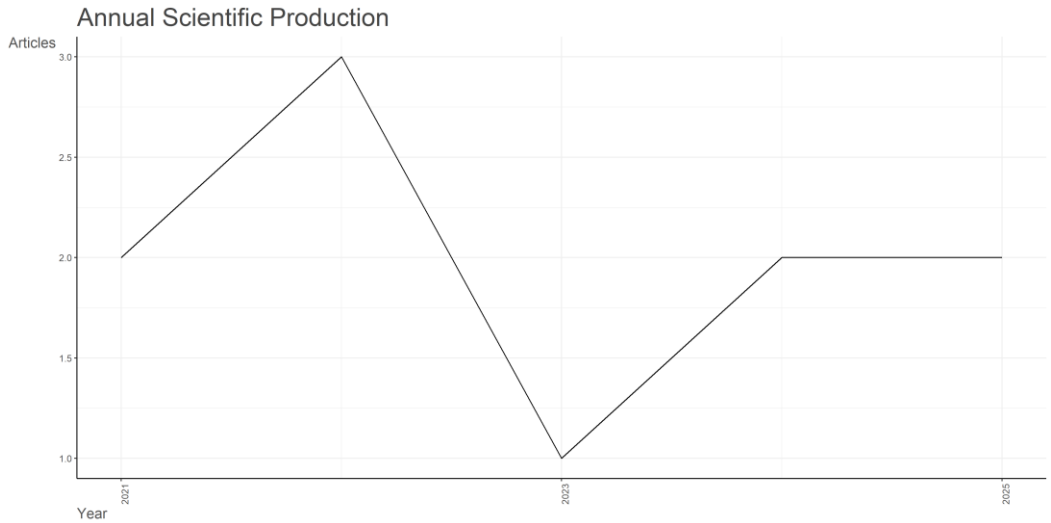


Figure 2. Trends in the number of publications per year (Annual Scientific Production)

Figure 2 illustrates the distribution of the number of articles published annually based on the studies analyzed in this review. The data show that there were two publications in 2021, which increased to three publications in 2022. In 2023, the number of publications declined to one article. Subsequently, the number of publications increased again to two articles in 2024 and remained stable in 2025 with the same number. Overall, the publication trend indicates that research on the integration of the *Nature of Science* in science education to support scientific literacy remains relatively limited. However, it demonstrates a stable pattern in recent years. This suggests that the topic continues to be relevant and holds significant potential for further development through future research.

Journal Source Distribution

The distribution of journals publishing the articles analyzed in this study is presented in Figure 3.

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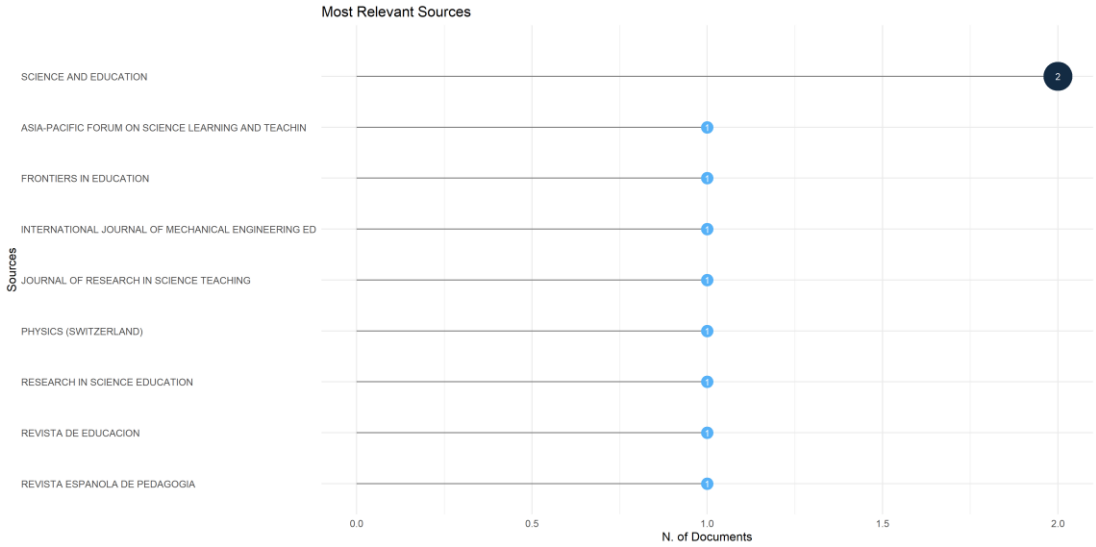


Figure 3. Journal Sources by Number of Publications

Figure 3 shows that the articles analyzed in this study were published across a range of international journals. *Science & Education* emerged as the most dominant source, with two articles. Meanwhile, other journals such as *Asia-Pacific Forum on Science Learning and Teaching*, *Frontiers in Education*, *International Journal of Mechanical Engineering Education*, *Journal of Research in Science Teaching*, *Physics (Switzerland)*, *Research in Science Education*, *Revista de Educación*, and *Revista Española de Pedagogía* each contributed one relevant article to the topic under investigation. These findings indicate that research related to the integration of the *Nature of Science* in science education is distributed across various scientific journals, although the contribution from each journal remains relatively limited.

Keyword Network Visualization

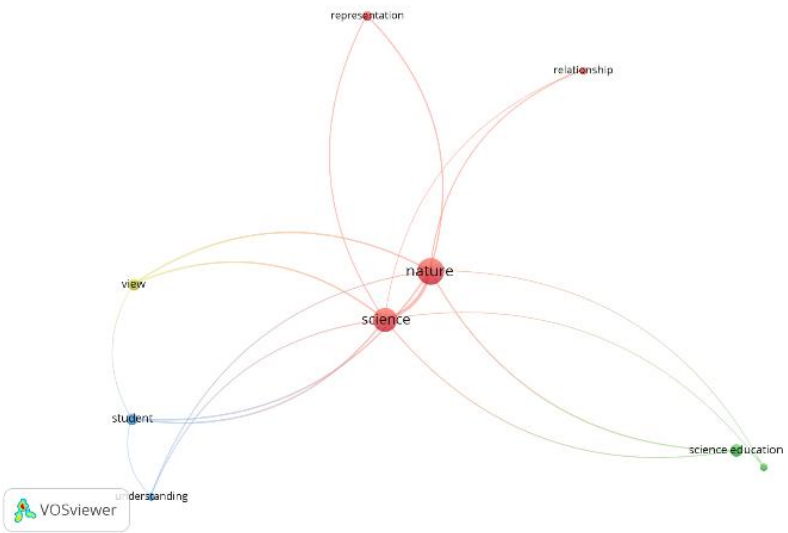


Figure 4. Network Visualization of Keywords

Figure 4 presents the results of the keyword network visualization analyzed using VOSviewer software. The figure shows that the keywords *science* and *nature* have the largest node sizes and are positioned at the center of the network. This indicates that these two keywords are the most frequently

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occurring themes in the analyzed articles. These central keywords are also strongly connected to several related terms, such as *science education*, *student*, *view*, *understanding*, *representation*, and *relationship*. This pattern suggests that studies on the *Nature of Science* primarily focus on students' understanding, perspectives on science, and its application within science education contexts. On the other hand, terms explicitly related to scientific literacy and instructional integration do not appear as dominant keywords. This finding indicates that research specifically addressing the integration of the *Nature of Science* in science education to support scientific literacy remains limited. Therefore, this topic presents significant opportunities for further research and development.

Keyword Density Visualization

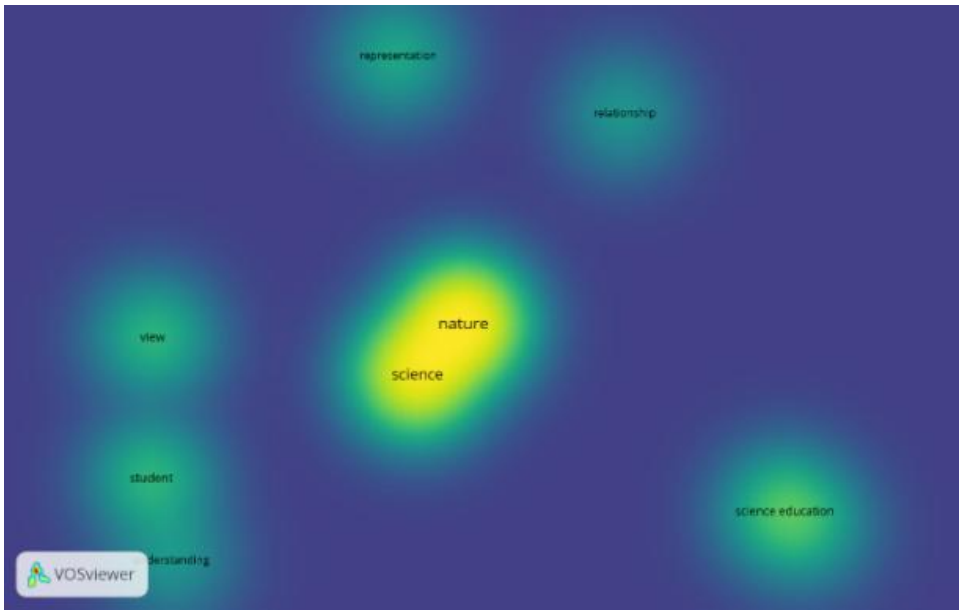


Figure 5. Keyword Density Visualization

Figure 5 presents the results of the keyword density visualization generated using VOSviewer software. In this visualization, the level of density is represented by color variations, where brighter colors (yellow) indicate a higher frequency of keyword occurrence, while darker colors represent lower frequencies. Based on the visualization, the keywords *science* and *nature* exhibit the highest density, as indicated by the brightest color at the center of the map. This suggests that these keywords serve as the primary focus in the analyzed articles. Other keywords, such as *science education*, *student*, *view*, *understanding*, *representation*, and *relationship*, show lower density levels and are distributed across different areas of the map. These findings indicate that such keywords appear less frequently and function as supporting themes within studies on the *Nature of Science*. Overall, the density visualization reinforces previous findings that research in this field is still dominated by the core themes of *science* and *nature*. Meanwhile, aspects related to instructional implementation and their connection to scientific literacy have not yet become central focuses, indicating opportunities for further research development.

Keyword Overlay Visualization

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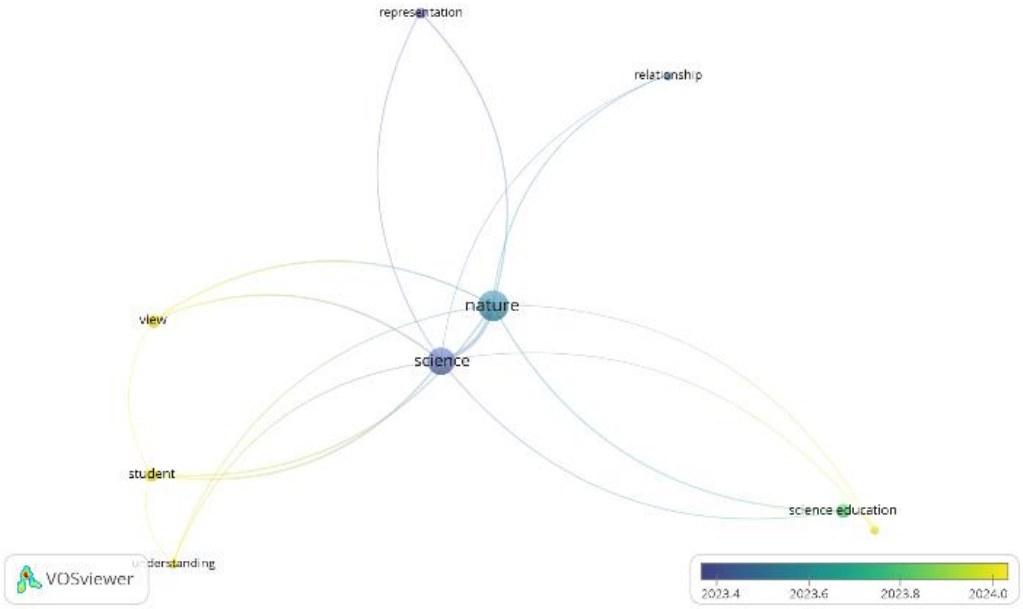


Figure 6. Keyword Overlay Visualization

Figure 6 presents the keyword overlay visualization generated using VOSviewer software. In this visualization, the color of each node represents the average year of keyword occurrence in the publications, ranging approximately from 2023 to 2024. Blue indicates earlier-occurring keywords, while yellow represents more recent ones. Based on the visualization, the keywords *science* and *nature* are positioned at the center of the network and show strong connections with other keywords. Their color gradient, which tends toward blue-green (around 2023), indicates that these topics have been the focus of research since the earlier period within the analyzed timeframe. Similarly, keywords such as *representation* and *relationship* also appear to have emerged relatively earlier. In contrast, keywords such as *science education*, *student*, *view*, and *understanding* are represented by brighter colors, approaching yellow (around 2024), indicating that these topics have gained more attention in recent studies. Overall, this visualization suggests a shift in research trends from a predominantly conceptual focus in the earlier period toward more applied and practice-oriented studies, particularly in the context of teaching and learning and student engagement in understanding the *Nature of Science*.

Discussion

Research Trends in the Integration of the Nature of Science (RQ1)

The analysis of the selected articles indicates that the number of publications on the integration of the *Nature of Science* in science education demonstrates a fluctuating trend over time. In 2021, two articles were published, followed by an increase to three articles in 2022. However, the number declined to one article in 2023. Subsequently, the number of publications increased again to two articles in 2024 and remained stable in 2025. This pattern suggests that research in this area remains relatively limited and has not yet experienced significant growth. Nevertheless, the consistent emergence of publications each year indicates that the integration of the *Nature of Science* in science education continues to be a relevant topic and holds potential for further development in future research.

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In general, research on the *Nature of Science* has been widely explored within the field of science education. In this context, the *Nature of Science* is understood as a concept related to the characteristics of scientific knowledge and the processes through which such knowledge is constructed and validated within the scientific community (Handayani, 2025). The *Nature of Science* is also considered a complex concept, as it encompasses philosophical, sociological, and historical dimensions, and is closely associated with how scientific knowledge is interpreted and evaluated Instruction oriented toward the *Nature of Science* is considered effective in fostering various student competencies, including understanding, insight, wisdom, and critical thinking skills. Moreover, such approaches contribute to enhancing students' scientific literacy and science process skills (Suratmi & Widodo, 2021).

However, the synthesis of the reviewed studies reveals a shift in the direction of research, moving from a predominantly conceptual focus toward practical implementation in instructional contexts and the evaluation of its impact on students. This shift is reflected in the increasing number of studies employing experimental and quasi-experimental designs to assess the effectiveness of instructional strategies in improving students' understanding of the *Nature of Science*, as demonstrated in previous studies (Kruit et al., 2025; Shi, 2023; Valencia Narbona et al., 2023). This trend indicates that the *Nature of Science* is no longer examined solely as a theoretical construct but is increasingly being implemented in actual classroom practices.

In addition, the findings indicate that research on the *Nature of Science* has increasingly evolved by linking it to various key variables in science education. The *Nature of Science* is no longer positioned as a standalone construct but is instead examined in relation to other competencies that support students' scientific development. Its connection to scientific literacy suggests that understanding the *Nature of Science* plays an important role in helping students interpret, evaluate, and apply scientific knowledge in various real-life contexts (Munezero et al., 2022).

Furthermore, the relationship between the *Nature of Science* and critical thinking skills indicates that a solid understanding of scientific principles can enhance students' ability to analyze arguments, evaluate evidence, and make data-driven decisions (Manassero-Mas & Vázquez-Alonso, 2022). Beyond cognitive aspects, recent studies have also linked the *Nature of Science* to affective and self-regulatory dimensions, such as metacognition and self-efficacy. These findings suggest that understanding the *Nature of Science* contributes to students' awareness of their own learning processes and strengthens their confidence in engaging with scientific concepts (Karaismailoglu et al., 2025).

In addition to publication counts and research findings, research trends can also be examined through the evolution of topics studied. Based on the keyword overlay visualization generated using VOSviewer, early-stage studies tended to focus on fundamental concepts such as *science* and *nature*. Over time, keywords related to instructional aspects such as *science education*, *student*, and *understanding* have increasingly emerged. This shift indicates a transition in research focus from conceptual discussions toward practical applications within educational contexts. Recent studies have also begun to explicitly connect the *Nature of Science* with scientific literacy. This is supported by findings demonstrating that understanding the *Nature of Science* is associated with improvements in students' scientific literacy (Kadir et al., 2025; Munezero et al., 2022; Shi, 2023). These results suggest that research is no longer limited to conceptual understanding but increasingly emphasizes its contribution to the development of scientific literacy. Furthermore, other studies indicate that the integration of the *Nature of Science* contributes to the development of scientific argumentation skills, critical thinking, and metacognitive abilities, all of which are essential components of scientific literacy (Karaismailoglu et al., 2025; Kruit et al., 2025). Overall, research on the integration of the *Nature of Science* in science education remains in a developmental stage, characterized by a relatively limited and fluctuating number of publications. Nevertheless, there is a clear tendency toward a shift in focus from conceptual exploration to instructional implementation and its connection to scientific

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literacy. This trend highlights the significant potential for further investigation and development in this area.

Forms of Integration of the Nature of Science in Science Education (RQ2)

The integration of the *Nature of Science* within science curricula has been implemented through various approaches. One of the most commonly used approaches is the distinction between explicit and implicit instruction. Explicit approaches involve directly addressing key aspects of the *Nature of Science*, such as the scientific method, the role of observation and experimentation, and the development of scientific theories and laws. In contrast, implicit approaches integrate the *Nature of Science* into everyday learning activities, such as laboratory work, discussions, and science projects (Viclara, 2025). The integration of *Nature of Science* aspects into science learning has been shown to enhance students' epistemological understanding. According to Khishfe (2014), the use of explicit-reflective approaches in teaching the *Nature of Science* can shift students' perspectives from simplistic epistemological views toward more sophisticated understandings of the nature of scientific knowledge.

The synthesis of the selected studies reveals that the integration of the *Nature of Science* in science education is characterized by a diversity of approaches. This integration is not limited to conceptual aspects but is also implemented through the use of instructional materials, the application of teaching strategies, and the design of scientific activities that actively engage students. This indicates that the *Nature of Science* is not merely positioned as learning content, but also as an integral approach embedded within the science teaching process. One of the most commonly identified forms of integration is through instructional materials, such as textbooks and other learning resources. In several studies, *Nature of Science* concepts are embedded within the content to support students' understanding of the nature of science. However, this form of integration remains suboptimal, as its presentation tends to be limited and unevenly distributed across different topics (Su et al., 2025; Zhuang et al., 2021). Similar findings are reported by Li et al. *(2023),* who argue that empirical evidence regarding the representation of the *Nature of Science* in textbooks is still limited. As a result, students' understanding of the *Nature of Science* tends to be fragmented, as it is not consistently reinforced throughout the learning materials.

The integration of the *Nature of Science* is also widely developed through contextual approaches that connect scientific concepts with real-life situations. A contextual approach emphasizes the relationship between learning content and everyday life, enabling teachers to support students in understanding concepts through relevant experiences (Risdiana et al., 2025). One of the most commonly applied approaches is *Socio-Scientific Issues* (SSI)-based learning. This approach links science education to socially relevant issues that are often current, controversial, and closely related to real-world contexts, thereby encouraging greater student engagement in learning science Findings from several studies indicate that this approach not only facilitates students' understanding of the characteristics and processes of science but also promotes scientific argumentation skills and enhances awareness of the relationship between science and society (Cobo et al., 2022; Kruit et al., 2025). Thus, context-based learning provides opportunities for students to construct a more meaningful and applicable understanding of the *Nature of Science*.

In addition, the integration of the *Nature of Science* has been advanced through various innovative approaches that emphasize reflective thinking and experiential learning. For instance, *Philosophy of Science* (POS)-based approaches are used to support students in understanding the epistemological foundations of science, including how scientific knowledge is constructed, tested, and revised (Shi, 2023). Moreover, specially designed laboratory activities, such as the *Designed-to-Fail Laboratory* approach, provide unique learning experiences by exposing students to situations involving failure or uncertainty in experiments (Kutluk et al., 2025). Through these experiences,

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students are able to recognize that scientific processes are not always linear or certain, but instead involve error, revision, and the interpretation of data.

The integration of the *Nature of Science* has also been identified in lesson planning and teacher professional development, for instance through training programs or workshops based on the *Family Resemblance Approach* (Cullinane & Erduran, 2023). *In addition, the integration of the Nature of Science has been examined across various learning resources, including textbooks, curriculum documents, and educational media such as instructional videos* (Gao et al., 2025; Kim & Sermeus, 2025; Yeh et al., 2023; Zhuang et al., 2021). However, findings from these studies indicate that the representation of the *Nature of Science* in such resources tends to remain implicit, inconsistent, and not yet systematically integrated.

Overall, the integration of the *Nature of Science* in science education demonstrates a shift toward more diverse and innovative approaches. Nevertheless, the synthesis also reveals an imbalance between the integration through instructional materials which tends to be implicit and less structured and the integration through instructional strategies, which are generally more explicit and effective. This finding highlights that the successful integration of the *Nature of Science* is not solely determined by the availability of learning materials, but also by the quality of instructional design that meaningfully connects *Nature of Science* concepts with students' learning experiences. Therefore, more systematic and integrated efforts are required to optimize the implementation of the *Nature of Science* in science education.

Impact of the Integration of the Nature of Science in Science Education (RQ 3)

The synthesis of 26 reviewed articles indicates that the integration of the *Nature of Science* in science education makes a significant contribution to improving the quality of learning and the overall development of students' competencies. These impacts are not limited to conceptual understanding but also extend to higher-order thinking skills, as well as affective aspects and students' self-regulation in the learning process. This suggests that *Nature of Science*-based instruction plays a broader role in shaping students' scientific understanding and attitudes. More specifically, the integration of the *Nature of Science* plays a crucial role in enhancing students' understanding of the nature of science itself. The *Nature of Science* is understood as an epistemological foundation that integrates multiple dimensions of science, including scientific processes, scientific knowledge as a product, scientific attitudes, and its application in real-life contexts (Mudviyanti et al., 2026). This improvement is particularly evident when instruction is designed using explicit and reflective approaches that directly emphasize the characteristics and processes of science (Kruit et al., 2025; Shi, 2023; Valencia Narbona et al., 2023). Explicit-reflective approaches in teaching the *Nature of Science* have been shown to be effective in enhancing scientific literacy, deepening conceptual understanding, and developing students' critical thinking skills (Mudviyanti et al., 2026). Through these approaches, students not only learn scientific products but also gain insight into how scientific knowledge is constructed, tested, and developed.

The integration of the *Nature of Science* also has a significant impact on the improvement of students' scientific literacy. In the context of 21st-century education, scientific literacy is considered an essential competency, as abilities in science and technology serve as a fundamental basis for individuals to function effectively in society (Asrizal & Festiyed, 2020). Scientific literacy enables students not only to understand scientific phenomena conceptually but also to apply scientific ideas appropriately in everyday life, thereby supporting problem-solving and evidence-based decision-making (Rizkita et al., 2016). Several studies indicate that students become more capable of explaining scientific phenomena, using evidence appropriately, and connecting scientific concepts to real-life contexts (Munezero et al., 2022).

Furthermore, the integration of the *Nature of Science* contributes to the development of critical thinking skills and scientific argumentation. Students become more proficient in analyzing

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information, evaluating evidence, and constructing data-based arguments, particularly in learning environments that incorporate socio-scientific issues (Manassero-Mas & Vázquez-Alonso, 2022). This demonstrates that the *Nature of Science* contributes not only to basic cognitive outcomes but also to higher-order thinking skills. In addition, the impact of *Nature of Science* integration is evident in metacognitive and self-efficacy aspects, where students show increased awareness of their thinking processes and greater confidence in learning science (Karaismailoglu et al., 2025). This indicates that *Nature of Science*-based instruction supports students in regulating their own learning processes more effectively.

Overall, these findings confirm that the integration of the *Nature of Science* makes a significant contribution to improving the quality of science education. However, these impacts do not occur automatically; rather, they are highly dependent on the pedagogical approaches employed. Without structured, explicit, and reflective implementation, the integration of the *Nature of Science* may not yield optimal outcomes. Therefore, more systematic efforts are required in designing *Nature of Science*-based instruction to ensure that its benefits can be maximized in a sustainable manner.

Challenges and Opportunities in the Integration of the Nature of Science (RQ4)

Despite the positive contributions of the *Nature of Science* integration in science education, the synthesis of 26 reviewed articles reveals that its implementation still faces several challenges. One of the primary issues relates to the suboptimal integration of the *Nature of Science* within curricula and instructional materials. Several studies indicate that the representation of *Nature of Science* aspects in textbooks and curriculum documents tends to be implicit, lacks systematic organization, and is not positioned as an explicit focus of instruction (Gao et al., 2025; Kim & Sermeus, 2025; Yeh et al., 2023; Zhuang et al., 2021). This condition results in the *Nature of Science* being insufficiently conveyed to students, as it often appears only implicitly within learning content. Consequently, students have limited opportunities to develop a deep understanding of the nature of science, including the characteristics of scientific knowledge, the role of empirical evidence, and the dynamic processes of scientific inquiry. This finding suggests that without structured and explicit planning, the integration of the *Nature of Science* in curricula and instructional materials is not yet able to effectively support the development of comprehensive scientific understanding among students.

In addition, the level of understanding among teachers and pre-service teachers regarding the *Nature of Science* varies considerably. Several studies reveal that limitations in both conceptual and pedagogical understanding of the *Nature of Science* hinder its effective implementation in classroom practice (Cullinane & Erduran, 2023). This indicates that not all teachers are adequately prepared to integrate the *Nature of Science* effectively into instruction. As a result, teaching practices often fail to incorporate the *Nature of Science* in a planned and explicit manner. Consequently, students are not provided with learning experiences specifically designed to foster an understanding of the nature of science, including how scientific knowledge is constructed, the role of evidence, and the dynamic nature of scientific processes. Therefore, teachers' limited understanding emerges as a key factor influencing the depth of students' understanding of the *Nature of Science*.

On the other hand, challenges in the implementation of the *Nature of Science* are also evident in classroom practices. Although explicit-reflective approaches have been shown to be more effective in enhancing students' understanding, their application remains limited and inconsistent. Several studies indicate that when the *Nature of Science* is taught implicitly, its impact on students' understanding is relatively weaker compared to explicit and reflective instruction (Kruit et al., 2025; Shi, 2023; Valencia Narbona et al., 2023). These challenges are influenced by several factors, including limited instructional time, dense curriculum demands, and the lack of professional development opportunities for teachers in teaching the *Nature of Science*. As a result, despite the

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strong potential of explicit-reflective approaches to deepen students' understanding, their practical implementation continues to face significant constraints.

Despite these challenges, the literature review highlights significant opportunities to enhance the effectiveness of *Nature of Science* integration in science education. One promising strategy is the implementation of innovative instructional models, such as *project-based learning* and contextual approaches based on *socio-scientific issues* (SSI). These approaches enable students to connect scientific concepts with real-world problems, making learning more relevant and meaningful. In addition to deepening students' understanding of the *Nature of Science*, these strategies have been shown to improve critical thinking skills, scientific argumentation, and evidence-based decision-making (Cobo et al., 2022; Kruit et al., 2025).

In conclusion, although the integration of the *Nature of Science* in science education continues to face various challenges, the opportunities for its development remain substantial. To achieve optimal implementation, more planned, systematic, and sustained efforts are required. These efforts include the development of instructional materials that present the *Nature of Science* explicitly and in a structured manner, the enhancement of teachers' competencies through professional training and workshops, as well as the adoption of innovative instructional strategies that connect *Nature of Science* concepts with meaningful and relevant real-world contexts. Such an integrated and consistent approach not only supports teachers in effectively delivering the nature of science but also enables students to engage in more meaningful learning experiences. As a result, students' understanding of the *Nature of Science* and their scientific literacy can be enhanced, allowing them not only to memorize scientific facts but also to understand the processes, characteristics, and applications of science in everyday life.

CONCLUSION

This study demonstrates that the integration of the *Nature of Science* in science education plays a crucial role in supporting the development of students' scientific literacy. The findings address the proposed research questions by showing that research trends on *Nature of Science* integration over the past five years remain relatively limited and fluctuate over time, although they have begun to shift toward more contextual and applied approaches. The forms of integration are implemented through various strategies, including the development of instructional materials and curriculum, explicit-reflective teaching approaches, socio-scientific issues (SSI)-based learning, laboratory activities, and the enhancement of teacher competencies. Furthermore, the integration of the *Nature of Science* has a positive impact on students' scientific literacy, conceptual understanding, critical thinking skills, scientific argumentation, as well as metacognitive awareness and self-efficacy. However, its implementation still faces several challenges, particularly the tendency for *Nature of Science* to be presented implicitly in curricula and instructional materials, as well as variations in teachers' understanding of the concept. These findings highlight that *Nature of Science* integration needs to be implemented in an explicit, structured, and contextual manner to effectively support the development of scientific literacy.

This study contributes by providing a comprehensive synthesis of research trends, forms of integration, impacts, and challenges related to the implementation of the *Nature of Science* in science education, which may serve as a reference for future research in the field of science education. However, this study has several limitations, including the use of a single database (Scopus) and the restriction of the publication period to the last five years. Therefore, future studies are recommended to expand data sources by incorporating additional databases and employing a broader range of keywords. Moreover, further empirical research is needed to examine the effectiveness of various *Nature of Science* integration models across different educational contexts, as well as to support the development of more systematic instructional materials and the continuous professional development of teachers. In conclusion, the integration of the *Nature of Science* in science education holds strong

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potential to enhance students' scientific literacy when implemented in a planned and sustained manner.

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