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Explicating explicit reflection in nature of science education: a systematic literature review

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For over two decades, "explicit reflection" has been a cornerstone concept in Nature of Science education. Many studies underscore the crucial role of Explicit Reflection in effective Nature of Science education, yet its ubiquity is accompanied by ambiguity in its definition and application. In this study, the aim is to comprehensively map the evolving meanings of Explicit Reflection in Nature of Science education. Conducting a systematic review, articles providing definitions for Explicit Reflection in Nature of Science education between 2000 and 2023, were examined following PRISMA guidelines. 61 definitions that adhered to our predefined criteria were systematically identified and selected. Subsequently, a data analysis process was conducted involving both discourse analysis and thematic synthesis. Using discourse analysis, both persistent themes and evolving patterns were identified, shedding light on the dynamic character of Explicit Reflection within the context of Nature of Science education. In parallel, during the thematic synthesis, a taxonomy of 25 descriptive themes was developed and further distilled into four analytical categories. These four key analytical themes encompass: "the meaning of explicit", "the meaning of reflection", "learning environment" and "cognitive process dimensions". Two types of Explicit Reflection: the student-centered and teacher-centered types, were constructed. From these, student-centered definitions of Explicit Reflection incorporate higher cognitive process dimensions and offer a more comprehensive definition. In conclusion, this study clarifies the multifaceted nature of Explicit Reflection in Nature of Science education, providing a nuanced framework that distinguishes between student-centered and teacher-centered approaches. By offering a detailed taxonomy and highlighting the cognitive depth of student-centered definitions, this work lays the groundwork for more precise implementation and future research in Nature of Science pedagogy.

KEYWORDS

science education, nature of science, explicit reflection, systematic review, student reflection, cognitive process dimensions, student-centered

1 Introduction

"Nature of Science" (NoS) education has long been recognized as a fundamental component of comprehensive science education and scientific literacy (AAAS, 1993; NGSS, 2013; NRC, 2000). It is a concept used to denote the sociology and epistemology of science and assumptions scientists make as they develop their scientific knowledge, as well as issues like what science is and how it works (Clough, 2007; Lederman, 1992). Given its central role in scientific literacy, NoS education has been the focus of a wide range of studies exploring

diverse approaches to foster students' understanding of NoS (Cofré et al., 2019). Decontextualized approaches, for example, draw students' attention to NoS through the use of analogies to scientific practices, while contextualized NoS instruction uses historic or contemporary cases of scientific experiments or discoveries as tools to learn about science. The crux of these approaches is stimulating explicit reflection (ER) (van Griethuijsen et al., 2015).

In a critical review in 2000, Abd-El-Khalick and Lederman coined the terms "implicit" and "explicit" approaches toward NoS. They identified that an implicit approach implies that an understanding of NoS can be facilitated through exposure to science content and "doing science". Conversely, the explicit approach emphasizes that comprehension of NoS arises from educational methods incorporating elements from the history and philosophy of science and/or targeted instruction on various aspects of NoS (Abd-El-Khalick and Lederman, 2000).

That paper highlighted that successful NoS education needs explicit instruction and requires students to reflect on their experiences. Since then, the concept of "explicit reflection"[1] has become a commonly used term in NoS education research. Many other researchers have further stressed its significance, including Krajewski and Schwartz (2014) and Lederman (2007). However, the popularity of ER is only equaled by its vagueness because it is conceptualized in many ways. For instance, whereas Aydin et al. (2013) suggests that ER entails NoS education is *"specifically planned for, taught, and assessed"* (p. 990), Matkins and Bell (2007) rather emphasize that, by using ER in NoS education, students *"reflect upon the similarities and differences between classroom science and practicing scientists"* (p. 138.) Though the authors of both papers aim to explain the meaning of ER, their definitions vary. Furthermore, numerous studies fail even to provide a definition of the concept (see Çil and Çepni, 2012; Deniz et al., 2020), and, as the concept has been used for decades, its meaning may have changed throughout this period.

Thus far, the meaning(s) and evolution of the concept "ER" in NoS education remain uncharted. Gaining a deeper understanding of its meaning(s) could enhance communication among the various stakeholders utilizing the term, including educators, policymakers, scientists, and science communicators. As such, the primary objective of this study is to comprehensively map out the various meanings and evolution of the concept of ER in NoS education. A systematic review of relevant literature will be undertaken to achieve this goal, focusing on articles that provide explicit definitions. This study aims to illuminate the clouded field of ER research by analyzing and categorizing the definitions provided in these articles.

2 Theoretical framework

2.1 Nature of science

As a key concept in science education studies, NoS has a broad variety of definitions ranging from "what science is and how it works" (Clough, 2007) to "the epistemology and sociology of science or the values and beliefs inherent to scientific knowledge and its development" (Lederman, 1992). Beyond these general characterizations, no consensus exists among philosophers of science, historians of science, scientists, and/or science educators on a specific definition (Abd-El-Khalick and Lederman, 2000). To reflect the lack of belief in the existence of a single nature of science, the term "Nature of Science" or NoS has been chosen for use throughout this paper rather than the more stylistically appropriate "the Nature of Science" (Abd-El-Khalick and Lederman, 2000).

Different NoS frameworks are used in the NoS education literature. These indicate the content about NoS that should be taught in schools. In NoS research, two views can be roughly distinguished: the consensus view and the non-consensus view. The consensus view is that it is possible to formulate a list of NoS ideas on which science educators and scientists agree (e.g., "the Lederman 7" and "McComas' NoS ideas"). The non-consensus view is that it is hard to agree on fundamental NoS ideas for education (e.g., the "features of science" approach, the "family resemblance approach" or "the whole science model") (Erduran and Dagher, 2014; Höttecke and Allchin, 2020; Matthews, 2012). Supporters of the non-consensus view advocate teaching about the complex and contextual sides of NoS (Clough, 2007). This study encompasses all articles that delve into the concept of NoS within their research, regardless of whether they adopt a consensus or non-consensus perspective. Both are categorized as "research on NoS".

2.2 NoS and the learning environment

With regard to NoS education, the distinction between teacher-centered and student-centered learning environments was identified as a pivotal theme. A teacher-centered learning environment is an instructional approach in which the educator assumes a central and directive role in the teaching and learning process. In this approach, they are primarily responsible for imparting knowledge and information to the students, who are more passive recipients of the teacher's instruction (Kennedy and Barnes, 1994). Addressing the issue of excessive teacher talk in the classroom in this approach, Kennedy and Barnes (1994) advocate for an increase in learner talk to enhance engagement and active participation.

In a student-centered environment, teachers act as facilitators, guiding and encouraging students and giving them choices in their learning and assignments. Teachers are no longer the gatekeepers of information but rather a resource for learners to obtain and grasp knowledge. Student-centered learning environments encompass various forms, including "messing around", "hands-on learning" or "guided discovery", "learning through problem-solving", "curiosity-driven inquiry", and "theory improvement inquiry" (Bereiter and Scardamalia, 1996, pp. 499–500). Despite such diversity, these forms share common features, often presenting students with authentic tasks to induce relevant learning experiences (Grabinger, 1996).

Recent literature portrays student-centered learning environments as more suitable for effective NoS education than teacher-centered approaches (Kember et al., 2010). Emphasizing student-centered approaches encourages open discussions, inquiry-based activities, and problem-solving tasks, fostering curiosity, critical thinking, and a deeper understanding of NoS. Teacher-centered learning

1 In the literature on NOS education "explicit reflection" is often also referred to as "the explicit reflective approach" or "explicit reflective instruction". This research has opted to use the more neutral term "explicit reflection".

environments may hinder students from adopting a deep approach to studying (Entwistle, 2003). However, student-centered environments are less likely to induce surface approaches, offering a more conducive setting for meaningful learning experiences (Gow and Kember, 1993). Empirical studies corroborate the advantages of student-centered instruction in teaching NoS; students report higher satisfaction and demonstrate significant improvements in their understanding when taught in such a manner (Khazaei et al., 2018; Minnaert et al., 2007; Müller and Louw, 2004; Smit et al., 2014).

The contrast between student-centeredness and teacher-centeredness in NoS education underscores the significance of adopting student-centered approaches to facilitate meaningful learning experiences. By leveraging authentic tasks and encouraging active learner involvement, educators can create an environment that nurtures a profound comprehension of NoS.

2.3 NoS and cognitive process dimensions

Bloom's Taxonomy of Educational Objectives, developed by Benjamin Bloom in 1956, is a renowned classification system that aims to promote cognitive development by guiding students toward more sophisticated levels of learning. It comprises six cognitive-learning categories, ranging from foundational knowledge acquisition to complex cognitive processes (Bloom et al., 1956).

In the context of NoS education, the revised Bloom's Taxonomy plays a vital role in cultivating students' thinking abilities. This version, proposed by Anderson and Krathwohl (2001), distinguishes between "the Knowledge Dimension" and "the Cognitive Process Dimension". The Knowledge Dimension includes factual, conceptual, procedural, and metacognitive knowledge, while the Cognitive Process Dimension consists of the dimensions "remembering", "understanding", "applying", "analyzing", "evaluating", and "creating" (Anderson and Krathwohl, 2001).

According to Allchin (2011), current NoS education in mainstream settings tends to heavily emphasize the lower levels of the Cognitive Process Dimension of the Revised Taxonomy, specifically "remembering" and "understanding". Students are frequently assessed on their recall and comprehension of NoS tenets, but the development of higher-order thinking skills, such as analyzing, evaluating, and creating NoS understanding, is often lacking (Allchin, 2011).

To bridge this gap and align with the aspirations of NoS education, science educators need to elevate their instructional practices. Research suggests that by targeting the higher levels of Bloom's Taxonomy, educators may foster deeper analytical and critical thinking skills among students, enabling them to engage with NoS concepts more effectively (Allchin, 2011; Almeida et al., 2023; Yacoubian, 2015). A shift towards emphasizing the processes of analyzing, evaluating, and creating in NoS education will empower students to think critically about scientific practices, evaluate scientific claims, and synthesize information from diverse sources.

3 This study

This study aims to provide a comprehensive overview of the different meanings of ER in NoS education, while also exploring the evolving discourse surrounding it. To achieve this, a systematic review was conducted, focusing on the following questions: (1) Which different meanings of ER in NoS education exist in the academic science education literature? and (2) How has the discourse within the definitions of ER evolved over time?

4 Methodology

A systematic review was conducted to achieve a comprehensive overview of the literature. In accordance with standards for systematic literature reviews, this review is characterized by a more rigorous and structured process compared to traditional reviews (Meerpohl et al., 2012). The aim is to be transparent, objective, and replicable by basing the process on a clearly defined research question and following a well-structured and well-documented search protocol as well as clearly defined inclusion and exclusion criteria that determine which studies to include (Meerpohl et al., 2012). This study's systematic literature review follows the guidelines defined in the PRISMA statement (Preferred Reporting Items for Systematic reviews and Meta-Analyses) (Page et al., 2021). This study used these guidelines to minimize bias and ensure the validity and reliability of the findings. A systematic literature review is the most well-equipped method to give a thorough outline of this research area, identify gaps in the literature, and highlight areas for future research.

4.1 Literature search and selection

An overview of how the literature was chosen according to the PRISMA flow diagram can be found in Figure 1. A "report" is one research item, such as an article or a book chapter.

The electronic databases Web of Science, the Education Resources Information Center (ERIC), EBSCO, JSTOR, and Scopus were explored to identify literature within this review's scope. The databases were selected for their relevance and extensive coverage of educational research. In 2000, Abd-El-Khalick and Lederman conducted a pivotal review distinguishing between explicit and implicit approaches to NoS education. Notably, they were the first to introduce the term "explicit reflection," emphasizing reflection as a core element for effective NoS education. This marked a shift in the field, as subsequent research began to adopt and build upon the concept of ER. To ensure the inclusion of the most recent and pertinent studies, articles published from 2000 onwards were focused on. Boolean search terms were utilized, as detailed in Table 1, to facilitate the identification of relevant literature.

Overall, the academic database search yielded 302 reports. After removing 138 duplicates using the computer program *EndNote 20*, and 32 manually, the full texts of the remaining articles were retrieved. Two articles could not be accessed and were therefore excluded. The sources, titles, and abstracts of the remaining 130 records were initially screened, and then the articles were carefully read to determine whether they met the inclusion criteria. The following inclusion criteria were used: (i) contains a description or definition of ER related to NoS education, (ii) is a theoretical or empirical research article, and (iii) is written in English. Of the 130 reports, 17 were non-English, 20 were on unrelated topics, and 39 were related to NoS education but did not define or describe ER even though it was mentioned in their title or abstract. After these exclusions, 54 reports remained.

In addition to electronic databases, the PRISMA guidelines also provide the option to include searches of registers and other sources

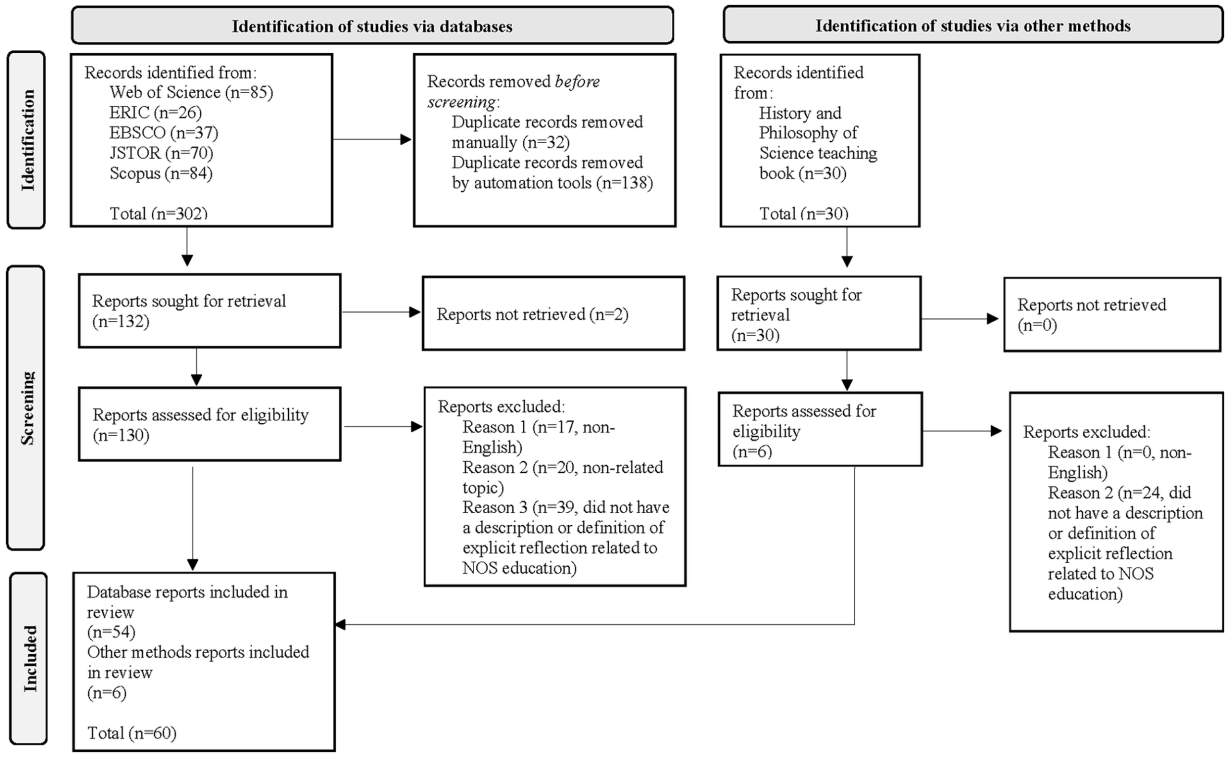

FIGURE 1
Flow diagram of literature search and selection of this systematic review following PRISMA (Page et al., 2021).

TABLE 1 The identification of studies in electronic databases through Boolean search terms.

Electronic database	Boolean search term	Hits	Date
Web of Science	"Nature of Science" (Title) and "Explicit Reflection" (All Fields) or "Explicit Reflective" (All Fields)	85	30/09/2023
ERIC	title: "Nature of Science" title:("Explicit Reflection" OR "Explicit Reflective")	26	30/09/2023
EBSCO	AND "Nature of Science" Title AND "Explicit Reflection" Title OR "Explicit Reflective" Title	37	30/09/2023
JSTOR	"Nature of Science" AND "Explicit Reflection" OR "Explicit Reflective"	70	30/09/2023
Scopus	(TITLE ("Nature of Science") AND TITLE-ABS-KEY ("Explicit Reflection") OR TITLE-ABS-KEY ("Explicit Reflective"))	84	30/09/2023

(Figure 1). Chapters of "Nature of Science in Science Instruction: rationales and strategies" by McComas (2020) were included in the study. This book is 745 pages long and contains 39 chapters, and it claims to be *"the most complete and accessible one-source work available on nature of science instruction."* Many influential researchers in the field of NoS education participated in its writing. The following search terms were used to identify the relevant sections: "explicit", "reflection", and "reflective". This resulted in the selection of 30 chapters. All were written in English, but 24 did not give a definition or description of ER, although it was mentioned. Therefore, six remained.

In addition to the electronic database search, a hand search was conducted of articles published in leading journals of science education, including *Journal of Research in Science Teaching, Science & Education, International Journal of Science Education, and Research in Science Education* (Page et al., 2021). This was done to ensure that the most trustworthy and relevant studies in science education were included to develop the conclusions of this review (Gough and Thomas, 2016). No new articles were found that met the inclusion criteria, indicating that the current pool was generally sufficient.

Combining the database articles ($n = 54$) and the book chapters ($n = 6$) resulted in a total of 60 reports that met all criteria for inclusion in this review.

4.2 Definition identification

It was initially assumed that each article would present a single definition of ER. However, Duschl and Grandy (2013, p. 2111) gave two definitions for ER in the context of NoS education. The first definition advocates that teachers should explicitly connect consensus statements to features of science lessons and activities, whereas the second suggests that students should engage in domain-specific scientific practices over extended curriculum units, spanning weeks or even months. This is why a total of 61 definitions of ER were identified and referenced from the 60 distinct articles.

4.3 Data

The data analysis for this systematic review involved a rigorous approach, consisting of two distinct methodological steps: descriptive analysis and thematic synthesis.

4.3.1 Descriptive analysis

For the descriptive analysis, a comprehensive search was conducted for relevant data in the selected articles, including author name, publication year, title, abstract, and source (journal or book chapter), to establish a general overview of their content. The general description was then refined by searching each article for its research population and educational level. This process afforded a broad insight into their overarching characteristics.

4.3.2 Thematic synthesis

To categorize the meanings of ER and the discourse on this concept over time, all 61 definitions were analyzed in depth following the protocol of thematic synthesis developed by Thomas and Harden (2008). These authors argued that thematic synthesis provides a tested way to synthesize qualitative parts of research in a transparent manner and achieve higher-order thematic categories. The generation of new themes beyond the descriptive content of articles is a crucial characteristic and should lead to the creation of a whole greater than its constituent parts. Three stages in thematic synthesis are outlined which provide the framework for the synthesis in this paper.

4.3.3 Stage 1: Free line-by-line coding

The process was started by collecting relevant primary studies that contained definitions or discussions related to ER in NoS education. The text units from these studies were extracted and entered into a database for further analysis. A line-by-line coding of the extracted text was performed, assigning codes to capture key concepts, phrases, or statements related to ER. This coding process allowed for the construction of initial descriptive themes that reflected the different aspects and interpretations of ER in NoS education.

4.3.4 Stage 2: Development of descriptive themes

Following the line-by-line coding, these initial codes were organized into related areas to form descriptive themes. Codes with similar meanings were grouped, and connections between codes were explored to establish relationships and patterns within the data. A coded line was considered part of a descriptive theme if it occurred in 5% or more definitions. This threshold was chosen to balance inclusivity with clarity, ensuring that themes reflected recurring patterns across the dataset without compromising analytical focus or coherence. The organization of descriptive themes was accomplished through a constant comparison approach, referring back to the original text units to ensure accuracy and consistency. For instance, two text units mentioning "explicit" were identified: one referring to explicit as being intentionally targeted and planned for, and another emphasizing the specific planning and assessment of NoS within ER. These text units were linked by the descriptive theme "explicit = planned for," indicating a shared meaning of "explicit" in relation to intentional planning (see Figure 2).

Building upon the identified descriptive themes, a discourse analysis of ER in the context of NoS education was undertaken to delve into the evolution of themes over time. This discourse analysis aligns with the principles of Foucault (1970), emphasizing that the meaning of most social phenomena derives from their contextual elements. Therefore, comprehending the usage of ER among scholars necessitates a deep understanding of the encompassing context, of which the discourse on ER is an integral part. This study adopts an approach akin to diachronic discourse analysis, in that it examines how the discourse around Explicit Reflection (ER) in Nature of Science (NoS) education has developed over time. By organizing the data into distinct time segments (2000–2023), the analysis focuses on identifying patterns of continuity and change in how ER is defined across different periods. However, it is important to note that this approach does not offer the full depth and breadth typically associated

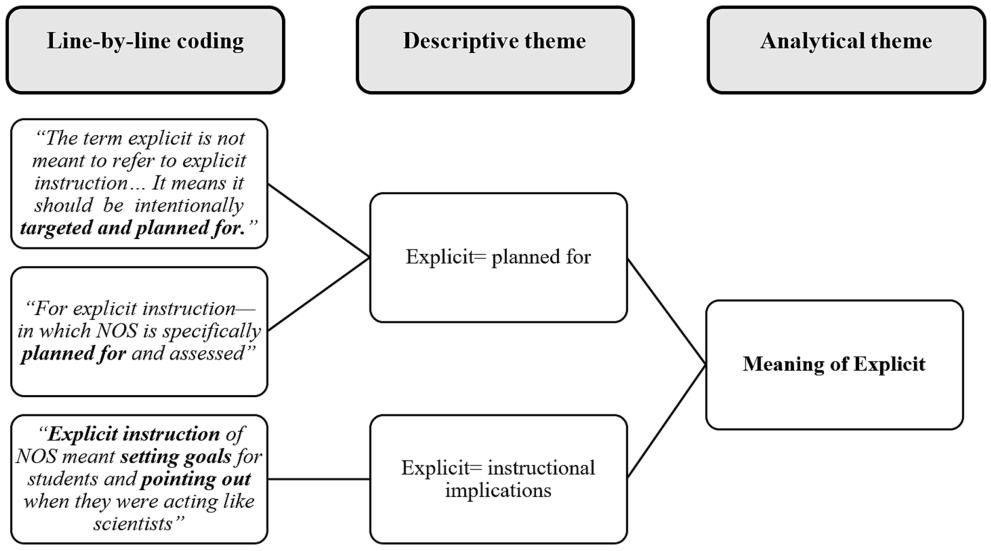

FIGURE 2
Thematic synthesis workflow illustration.

with diachronic discourse analysis. The relatively short timespan and narrow thematic focus limit the extent to which broader historical, social, or institutional trends can be inferred. Rather than aiming to reconstruct long-term historical developments, this analysis emphasizes shifts in definitional emphasis and conceptual framing over time within a bounded academic discourse.

A balanced segmentation analysis was used to explore the evolution of the definitions of ER in the discourse. They were segmented into relatively consistent groups, each comprising 15 or 16 definitions. The decision to divide the articles into groups of this size was a deliberate choice to ensure a balanced and equitable analysis of the discourse on ER in NoS education. Such uniform segmentation allows for comparative analyses of different descriptive themes across time periods with consistent article numbers, facilitating the identification of changes and consistencies in discourse without sample size biases. This approach led to four groups: 2000–2010 (the first 16 definitions), 2011–2014 (the second 15), 2015–2021 (the third 15), and 2022- September 2023 (the last 15). This method strikes a balance between practicality and representativeness while mitigating concerns related to varying publication outputs.

4.3.5 Stage 3: Generation of analytical themes

At this stage, the research aimed to go beyond the individual findings of selected studies and generate higher-level concepts or analytical themes that synthesize the meaning of ER in NoS education. The development of analytical themes involved inferring implications, connections, and broader interpretations from the descriptive themes. Three of the researchers engaged in extensive discussions. They iteratively refined the analytical themes until they accurately encompassed all the initial descriptive themes and provided insights beyond the individual study findings. For instance, the descriptive theme of "explicit = planned for" was mentioned earlier. Another meaning given to explicit inside the text units was the descriptive theme "explicit = instructional implications." These two descriptive themes were then incorporated into the analytical theme labeled "Meaning of explicit" (see Figure 2).

4.3.6 Reflexivity

This study employed inductive coding. Although inductive coding is often described as allowing themes to "emerge" from raw data, the process here was not one of passive discovery. Rather, codes were actively constructed, shaped by the researchers' theoretical backgrounds and prior assumptions. To minimize the risk of narrow interpretation, close collaboration was maintained throughout phases three, four, five, and six of the analysis process (Braun and Clarke, 2019), incorporating multiple perspectives. While the researchers share common interests in science education, their diverse academic backgrounds and theoretical orientations contributed a range of insights to the analysis. As such, the findings of this study should be understood in light of the researchers' positionalities and academic contexts.

The research team brought expertise from various fields: the first author specializes in NoS education and sustainability, the second in NoS education and philosophy, the third in biology education, and the fourth in school policy and education for sustainable development. This diversity ensured that the data was examined from multiple angles, enriching the final themes through critical discussion and reflection.

5 Results

5.1 Descriptive results

Figure 3 illustrates the evolution of the use of ER in the NoS education research included in this systematic review. A notable increase in the number of articles can be seen in the years 2013 ($n = 8$), 2020 ($n = 8$), and 2022 ($n = 9$). Note that for the year 2020, six of these articles originated from the same book that was incorporated into this research: "Nature of Science in Science Instruction: Rationales and Strategies," edited by William McComas.

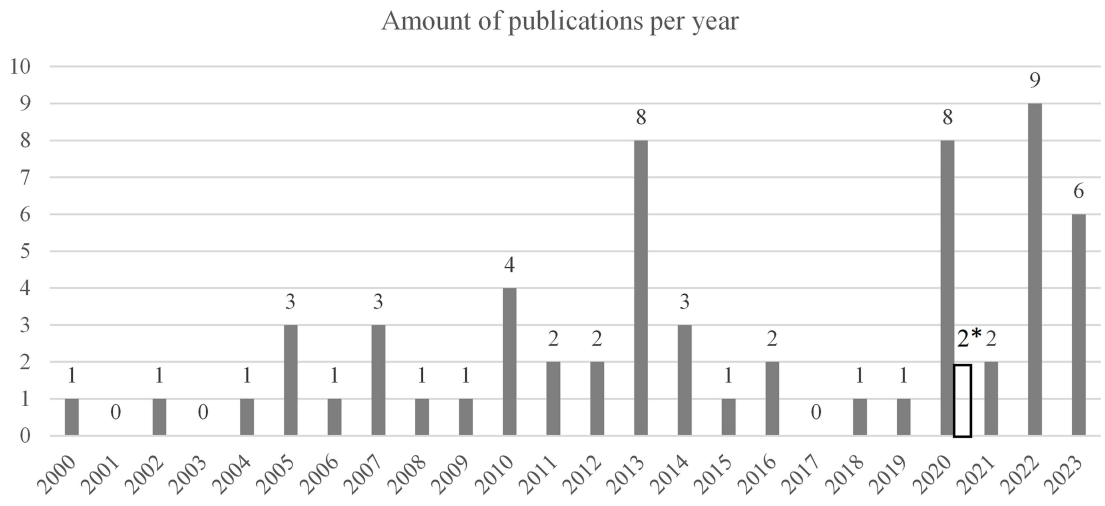

FIGURE 3
Overview of the distribution of the articles included in this study based on publication year. 2*, for the year 2020, is the number of publications that would be selected if no books were included in the systematic review.

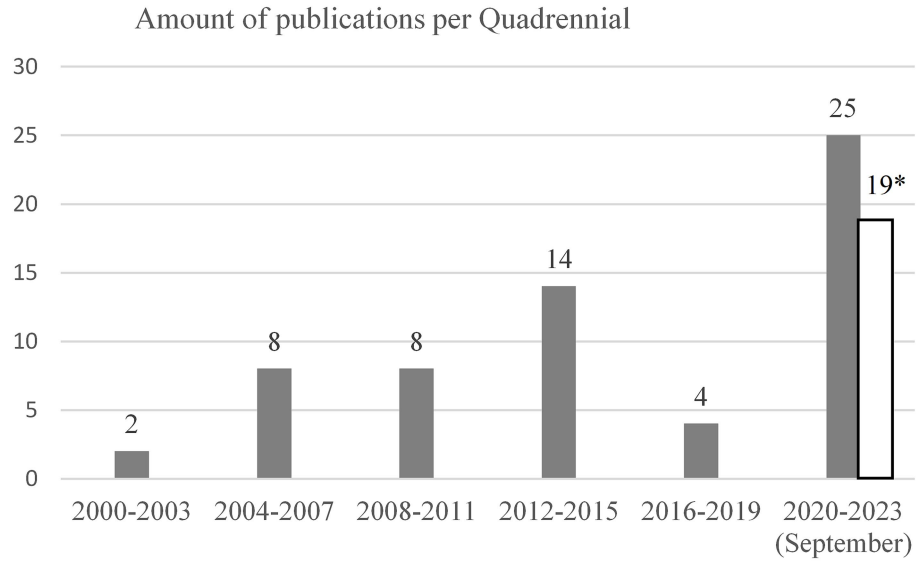

FIGURE 4
Overview of the distribution of the articles included in this study over 6 quadrennial periods. 19*, for the quadrennial 2020–2023, is the number of publications that would be selected if no books were included in the systematic review.

Thus, based on the database search, only two articles were published in the year 2020 that met the selection criteria.

To gain a more comprehensive understanding of trends, the data were grouped into six four-year periods: 2000–2003, 2004–2007, 2008–2011, 2012–2015, 2016–2019, and 2020–2023 (up to September). The outcomes of this temporal segmentation, as illustrated in Figure 4, indicate notable patterns in the prevalence of articles containing definitions for ER within the domain of NoS education.

Only two articles meeting the selection criteria were identified in the initial quadrennial period (2000–2003). This number increased to 8 articles in the subsequent periods of 2004–2007 and 2008–2011. A notable surge occurred during 2012–2015, with 14 relevant articles indicating heightened scholarly attention to ER in NoS education. However, this growth was followed by a decline during 2016–2019, with only four articles meeting the criteria. Conversely, the most recent period (2020–2023) witnessed a substantial increase, with 25 articles identified. Notably, six of these articles emanated from a book that was incorporated into the study. Even excluding these book-derived contributions, a substantial number of 19 articles* remained, highlighting a significant rise in research focus on ER within NoS education in recent years.

These findings collectively delineate the dynamic evolution of scholarly engagement with ER in the context of NoS education. They depict periods characterized by subdued research activity contrasted with phases marked by surges in academic engagement.

5.2 Descriptive analysis

5.2.1 Research population

Of the 60 articles, 53 (88%) specified their research population, while the remaining seven (12%) predominantly consisted of theoretical discussions without explicitly mentioning a defined research population. Three distinct categories were identified among the 53 articles with a defined research population. Nineteen articles (32%) focused on in-service teachers as the primary research population, investigating the effects of ER on NoS education within this group. Eighteen (30%) researched pre-service teachers, exploring how ER could enhance their understanding of the NoS during their training. The remaining 16 (27%) involved students as the research population, examining the impact of ER on their development of NoS concepts (Table 2).

TABLE 2 Distribution of the research population overall included articles.

Research population	Number of articles	Percentage of total
In-service teachers	19	32%
Pre-service teachers	18	30%
Students	16	27%
No research population (theoretical)	7	12%

5.2.2 Educational level

The examination of educational levels featured in the 60 selected studies identified five distinct categories: "kindergarten," "elementary," "middle school," "high school," and "higher education." Of the articles, 53 (88%) explicitly delineated their intended educational level. Some studies included multiple educational levels, which were appropriately classified under the "all" levels category.

Of the 53, the distribution across various school levels was as follows: "elementary education" 27%, "middle school" 20%, "higher education" 15%, "all educational levels" 13%, "high school" 12%, and "kindergarten" 2% of the total. Specific school levels could not be ascertained for the remaining 12% of articles, primarily because they predominantly comprised theoretical discussions rather than empirical studies that defined explicit educational targets (Table 3).

TABLE 3 Distribution of the educational levels overall included articles.

Education level	Number of articles	Percentage of total
Kindergarten	1	2%
Elementary	16	27%
Middle school	12	20%
High school	7	12%
Higher education	9	15%
All	8	13%
No educational level (Theoretical)	7	12%

5.3 Thematic synthesis

An initial examination of their general characteristics was conducted before embarking on the thematic synthesis of the 61 ER definitions. This analysis identified a remarkable diversity. The shortest definition comprised a concise 14 words, while the most expansive definition extended over 326 words, underscoring the significant variation within the landscape of ER definitions in NoS education.

Furthermore, the analysis unveiled recurring patterns in the terminologies used across these definitions. Notably, certain words recurred with higher frequency than others. Among the most frequently appearing terms were "learners," "activity," "NoS," "reflection," and "instruction."

5.3.1 Stages 1 and 2: Free line-by-line coding and descriptive themes

As a result of the analysis and categorization of the free line-by-line coding, 25 distinct descriptive themes were constructed, forming the foundational framework for discerning key elements characterizing ER definitions within NoS education. The descriptive themes are presented in Table 4.

Notably, some definitions of ER were found to use the term *"explicit"* to define ER itself, or the word *"reflection"* to explain the concept of ER. These instances are captured in Table 4 under the descriptive themes *"Word 'explicit' used to define ER"* and *"Word 'reflection' used to define ER"*. Such cases are particularly significant, as they reveal potential circularity, i.e., explaining a concept by using (part of) the concept itself in its definition.

5.3.1.1 Evolution in discourse about "explicit reflection": balanced segmentation analysis

The evolution in discourse on ER in NoS education reflects a dynamic landscape marked by consistent trends and shifting emphases and perspectives. This section delves deeper into the results derived from the balanced segmentation analysis.

The findings presented in Table 5 can be categorized into two groups: descriptive themes that exhibit fluctuations and those that have remained relatively consistent over time. Firstly, three descriptive themes show fluctuations over time. For this analysis, fluctuations entail variations in the occurrence of a descriptive theme equal to or surpassing 40% between the segment with the highest occurrence and that with the lowest occurrence. This threshold was chosen as a pragmatic indicator of meaningful change, large enough to highlight substantial shifts in theme prevalence across time segments, while avoiding overinterpretation of minor variations. Although not statistically derived, this criterion serves as a heuristic to identify patterns that stand out in the context of this qualitative synthesis. Notably, these variations may not necessarily denote a consistent trend of increase or decrease across all time segments, emphasizing the significance of substantial shifts in theme prevalence without implying a uniform directional change throughout the analyzed periods. The most significant fluctuation (48%) is observed between segments 1 (2000–2010) and 4 (2022–2023) in the descriptive theme "instruction". Notably, this theme is prevalent in over 50% of all articles in the first three time segments but declines to 27% in the final period. The second largest fluctuation (47%) is noted between segments 3 (2015–2021) and 4 (2022–2023) in the descriptive theme "discussion". While "discussion" appears in less than 50% of definitions in the initial three segments, it rises to 67% in the final segment. Finally, the descriptive theme "understanding NoS" demonstrates a noteworthy fluctuation between segments 2 (2011–2014) and 4 (2022–2023), differing by 40%. In the initial three

TABLE 4 Summary of identified descriptive themes.

No	Descriptive theme (alphabetically)
1	Activity
2	Aspects of Nature of Science (synonyms for aspects: ideas, issues, tenets)
3	Discussion
4	Explicit = Curricular implications
5	Explicit = It should be an instructional outcome (synonyms: objective, target)
6	Explicit = No implicit Teaching (synonyms: not as context alone, no auxiliary outcome)
7	Explicit = Not a didactive teaching strategy/pedagogical approach
8	Explicit = Planned for (synonym: planning)
9	Explicit = Specifically drawing attention to NoS (synonyms for specifically: Overtly, Explicitly)
10	Explicit = Teacher points out /overtly addresses the NoS aspects
11	Instruction
12	Iterative (synonyms: ample of opportunities)
13	Learners (synonyms: students, participants, pupils)
14	NoS is assessed (synonym: assessment)
15	Not just repeating the lecture (synonym: not just repeating what is told/ reiterated)
16	Questions
17	Reflection = Own NoS ideas vs. new information
18	Reflection = Relate to what scientists do/ make connections
19	Reflection = Thinking
20	Reflection = Within a NoS framework
21	Teacher guides
22	Understanding NoS
23	The word "Explicit" is used to define ER
24	The word "Reflection" is used to define ER
25	Writing

TABLE 5 Heatmap showing how descriptive themes of ER in NoS education have changed over time, represented as a percentage of total occurrences within each time segment.

Descriptive themes (alphabetically)	1st segment (2000–2010)	2nd segment (2011–2014)	3rd segment (2015–2021)	4th segment (2022–2023)
Activity	63%	67%	40%	53%
Aspects of Nature of Science	88%	87%	87%	100%
Discussion	31%	47%	20%	67%
Explicit = Curricular implications	0%	13%	7%	7%
Explicit = It should be an "instructional outcome"	31%	27%	20%	20%
Explicit = No implicit teaching	25%	13%	7%	33%
Explicit = Not a didactive teaching strategy	19%	20%	7%	7%
Explicit = Planned for	38%	40%	27%	33%
Explicit = Specifically drawing attention to NoS	44%	33%	27%	53%
Explicit = Teacher points out the NoS aspects	19%	27%	13%	13%
Instruction	75%	53%	73%	27%
Iterative	6%	20%	7%	0%
Learners	88%	87%	87%	93%
NoS is assessed	13%	20%	0%	13%
Not just repeating the lecture	19%	13%	20%	13%
Questions	25%	40%	20%	7%
Reflection = Own NoS ideas vs. new information	6%	7%	7%	13%
Reflection = Relate to what scientists do	38%	40%	20%	13%
Reflection = Thinking	13%	20%	20%	7%
Reflection = Within a NoS framework	19%	27%	20%	7%
Teacher guides	6%	13%	13%	0%
Understanding NoS	44%	20%	27%	60%
Word "explicit" used to define ER	50%	33%	13%	40%
Word "reflection" used to define ER	44%	47%	40%	53%
Writing	13%	0%	7%	0%
Number of definitions per segment	16	15	15	15

Darker colors represent a higher occurrence.

segments, "understanding NoS" appears in less than 45% of definitions, dropping to 20% in the second time segment. Conversely, it exceeds 60% of all definitions on ER in NoS education in the final segment.

A particularly noteworthy observation is that these fluctuations predominantly emerge in the final time period (2022–2023). This pattern suggests the possibility of a shift in emphasis within the discourse on ER in NoS education. The increased focus on "discussion" and "understanding NoS", alongside the decline of "instruction", may signal a transition from prioritizing the delivery of planned instruction by the teacher toward approaches that emphasize dialogic engagement and conceptual understanding of NoS by the students.

Secondly, some descriptive themes show notable consistency over the four time segments. From these, "aspects of NoS" and "learners" occur frequently with percentages of 87% or higher across all time segments. The descriptive themes "activity" and "word explicit used to define ER" show moderately high occurrences, between 40 and 67% across all time segments. The 18 remaining descriptive themes have a relatively low occurrence in the definitions for ER in NoS education over all the time segments. This consistency provides valuable insights into enduring aspects of ER discourse within NoS education, suggesting foundational principles or enduring areas of emphasis that transcend different time periods.

These findings emphasize the dynamic nature of the meaning of ER. Although it consistently revolves around "aspects of NoS" and the engagement of "learners" with NoS education, there has been a noticeable shift in scholarly focus. The research emphasis has transitioned from prioritizing "instruction" to placing greater importance on fostering a deeper "understanding of NoS" and promoting interactive "discussion" within the didactical approach. This shift could reflect an evolving perspective on effective pedagogy and highlight an ongoing refinement of strategies to enhance ER experiences in NoS education. Notably, the most pronounced changes consistently occurred between segment 4 (2022–2023) and one of the preceding three segments, underscoring significant shifts in the conceptualization of ER within NoS education in recent years. These trends highlight the dynamic nature of discussions of ER.

5.3.2 Stage three: analytical themes

The next stage of the analysis was the development of analytical themes, a crucial stage involving extracting deeper insights, making connections, and deriving broader interpretations from the initial descriptive themes.

In total, four analytical themes were developed through this process, each shedding light on distinct aspects of ER in NoS education:

1. The meaning of explicit
2. The meaning of reflection
3. The learning environment
4. Cognitive process dimensions (bloom revised)

This section will provide a comprehensive discussion of each analytical theme, delving into their significance and implications for NoS education.

5.3.2.1 The meaning of explicit

In analyzing the 61 definitions, diverse interpretations of the term "explicit" were observed within the context of ER in NoS education. Of these, 29 provided definitions that categorized "explicit" as an intentional and planned focus on NoS education integrated within the curriculum. Conversely, 27 defined "explicit" in the context of instructional implications for NoS education.

Where the term "explicit" is defined as "intentionally planned," the emphasis is on the idea that "explicit" does not merely imply didactic or direct instruction but underscores the deliberate and purposeful nature of incorporating NoS education into the learning process. For example, Çil's (2014) definition:

> *"…the term explicit is not identical to didactic or direct instruction. It emphasizes that learning about NoS should be planned intentionally for learning science concepts or content and complex science theories."* (p. 340)

However, when "explicit" is defined as "having instructional implications," it implies that a certain type of explicit or direct instruction is necessary. For example, Witucki et al. (2023) state that:

> *"Explicit refers to a teaching approach where the NoS concepts are discussed openly where students' attention is drawn directly to the concept."* (p. 7)

From the remaining five, one definition did not align with either of the two established categories (Scharmann et al., 2005). According to Scharmann et al., "explicit" signifies that NoS should be treated as a standalone topic within a science course. Although this may share some similarity with the idea that "explicit" means "intentionally planned for," there is a nuanced distinction. In the "intentionally planned for" concept, the emphasis lies on integration within the curriculum, ensuring that NoS is taught alongside other science content. However, Scharmann et al.'s definition of "explicit" takes on the specific meaning that NoS is a distinct science topic taught independently.

> *"Explicit, meaning that it should be an independent topic taught within a science course and not left to emerge implicitly through exposure to science concepts."* (p. 28)

In addition, four definitions did not overtly identify the meaning of "explicit" in their description of "explicit reflection" for NoS education.

The distribution of the definitions for this analytical theme is shown in Table 6.

5.3.2.2 The meaning of reflection

Diverse conceptualizations of the term "reflection" were observed in the analysis (Table 7). Most surprisingly, 26 (43%) of the 61 definitions did not provide a specific meaning. Among the remaining 35 (57%), two distinct trends were distinguished, highlighting different perspectives on the role and purpose of reflection in NoS education.

Fourteen (23%) underscored the importance of reflection as a means of facilitating concept building, which refers to the process of constructing a comprehensive understanding of NoS. Concept building of NoS involves the thoughtful consideration of the various aspects, principles, or components that constitute it. An example of "reflection as concept building of NoS" comes from Howe (2009):

> *"Reflective learning underscores that students must be challenged to develop their own conceptual understanding of the NoS tenets."* (p. 397)

Twenty-one (34%) definitions were categorized under, reflection meaning the "transfer between learning activity and NoS", where reflection is understood as a process that facilitates the transfer of learning. In these definitions, reflection involves applying knowledge, skills, or experiences gained during a specific (school) learning activity to broader contexts related to the exploration and understanding of science. Rather than remaining confined to the immediate learning task, reflection, in these definitions, enables learners to connect their classroom experiences to scientific practices and epistemological aspects

TABLE 6 Occurrence distribution of analytical theme "meaning of explicit".

Meaning of explicit		
Category	Number of definitions	Percentage of total
Explicit as "intentionally planned"	29	47%
Explicit as "having instructional implications"	27	44%
Explicit as "a standalone topic"	1	2%
Nothing mentioned	4	7%

TABLE 7 Occurrence distribution of analytical theme "meaning of reflection".

Meaning of reflection		
Category	Number of definitions	Percentage of total
Reflection as concept building of NoS	14	23%
Reflection as transfer between learning activity and NoS	21	34%
Nothing mentioned	26	43%

of science. The definition of Akerson et al. (2007) exemplifies this type of reflection:

> *"Reflective NoS instruction requires learners to think about how their work illustrates the NoS and how their inquiries are similar to or different from the work of scientists."* (p. 753)

Whereas "concept building of NoS" centers on developing a deep, foundational understanding of NoS itself, definitions that frame reflection as a "transfer between the learning activity and NoS" emphasize the allocation of knowledge and experiences gained through school learning activities to contexts resembling the work and thinking of scientists. This latter perspective highlights a broader use of learned principles, extending beyond the original learning setting, to promote a more applied and contextualized understanding of NoS. In contrast, definitions that focus solely on concept building of NoS emphasize the development of core understandings within the immediate learning context, without necessarily extending to broader applications.

5.3.2.3 The learning environment

Of the 61 definitions analyzed, 35 (57%) adopted a teacher-centered perspective, highlighting the teacher's role in facilitating ER. Conversely, 26 (43%) emphasized the student's involvement in the reflective process. Among the definitions that presented a teacher-centered perspective, Wan and Subramaniam (2023) suggest that:

> "*The explicit approach refers to teaching NoS directly through open discussions so as to reflect on some aspects of NoS."* (p. 1057)

In this delineation, the emphasis is placed on the teacher, and it remains unclear whether the student, the teacher, or both are expected to engage in reflection on the aspects of NoS. An example of a student-centered definition is given by Angle (2020):

> *"… [an] approach [that] emphasizes student awareness of certain NoS aspects in relation to the science-based activities in which they are engaged, and student reflection on these activities from within a framework comprising these NoS aspects."* (p. 686)

Within all of the teacher-centered definitions, a strong emphasis is placed on the educator's role in guiding ER on NoS concepts: the teacher takes the lead in facilitating discussions on NoS topics. It is not always clear if the students participate in the reflections, or if it is the teacher's reflection that is targeted. The teacher's facilitation drives the initiation and direction of the reflective activities.

Conversely, the student-centered definitions shift the focus towards active student engagement in the reflective process. The approach centers around students' awareness and understanding of specific NoS aspects within the science-based activities they are involved in. Consequently, students play a more autonomous role in driving the reflective process.

5.3.2.4 Cognitive process dimensions (bloom revised)

A Pragmatic Master List of Action Verbs for Bloom's Taxonomy by Newton et al. (2020) was used to categorize the definitions within the different Cognitive Process Dimensions.

As an example, one of the definitions that was written on the lower Cognitive Process Dimension of "understanding" is from McDonald (2010):

> *"An explicit NoS instructional approach deliberately focuses learners' attention on various aspects of NoS during classroom instruction, discussion, and questioning."* (p. 1137)

This falls within the "understanding" dimension of Anderson and Krathwohl (2001) because it emphasizes the process of comprehending and focusing on various aspects of NoS during classroom activities. The use of terms such as "focuses learners' attention" and "deliberately" suggests that the instructional approach aims to facilitate students" understanding of NoS concepts. The focus is on providing students with insights into different aspects of NoS, aiming for comprehension and awareness rather than critical analysis or evaluation (Anderson and Krathwohl, 2001).

A definition containing the "evaluating" dimension comes from Howe (2009), who describes it as follows:

> *"Explicit learning means that through some aspect of instruction, one or more of the relevant NoS tenets are directly targeted for students to evaluate. Reflective learning underscores that students must be challenged to develop their own conceptual understanding of the NoS tenets."* (p. 397)

Howe's definition belongs to the "evaluating" dimension as it strongly emphasizes the process of assessment and critical analysis of NoS tenets. Using the term "evaluate" and the phrase "challenged to develop their own conceptual understanding" indicates that the students are expected to critically examine NoS concepts and make judgments about their validity and relevance. This definition explicitly states that students are required to target NoS tenets for assessment, suggesting a higher-order cognitive process that involves weighing the merits and limitations of NoS ideas.

When examining the 61 definitions, it was observed that no definitions fell within the "creating" category. Three were categorized under the "evaluating" category, indicating that they focused on prompting students to assess and critically analyze NoS concepts. Seventeen were classified in the "analyzing" category, emphasizing the process of breaking down NoS ideas into their component parts for a deeper understanding. Three were placed within the "applying" category, emphasizing the practical application of NoS knowledge. Twenty-one were found within the "understanding" category, where students needed to comprehend and interpret NoS principles. Lastly, 17 definitions were grouped under the "remembering" category, signifying that they primarily focused on students retaining and recalling NoS information.

The distribution of definitions across the Cognitive Process Dimensions of the revised Bloom's taxonomy is depicted in Figure 5.

In this categorization, the three upper dimensions were designated as "high" Cognitive Process Dimensions, and the three lower ones as "low". Consequently, 33% of all definitions of ER were described on a higher Cognitive Process Dimension, while 67% were described on a lower dimension.

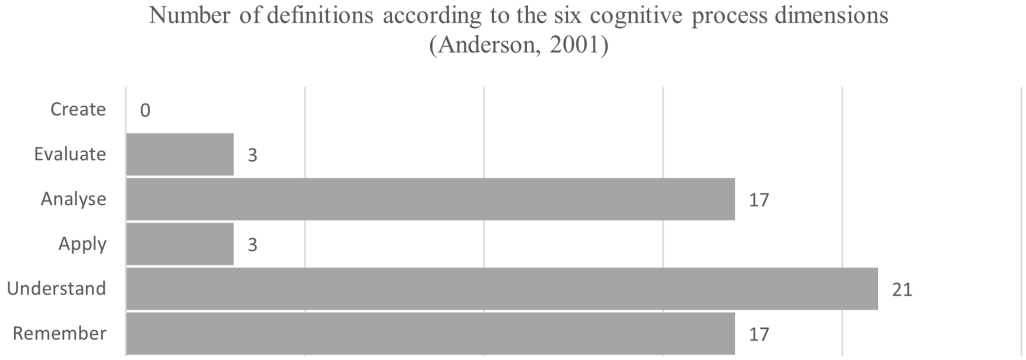

FIGURE 5
Distribution of definitions across cognitive process dimensions of bloom's revised taxonomy (Anderson and Krathwohl, 2001).

TABLE 8 Analytical themes and categories identified within the definitions on ER in NoS education.

Meaning of explicit	Meaning of reflection	Learning environment (Khazaei et al., 2018)	Cognitive process dimensions (revised taxonomy of bloom)
Planned for (47%)	Concept building of NoS (23%)	Student-centered (43%)	High (33%)
Instructional implication (44%)	Transfer learning activity and NoS (34%)	Teacher-centered (57%)	Low (67%)
Did not specifically define "explicit" (7%)	Did not specifically define "reflection" (43%)		

TABLE 9 The two types of ER: student-centered and teacher-centered definitions.

Type of ER	Meaning of explicit		Meaning of reflection		Cognitive process dimensions	
Type 1: Student-centered (26 definitions)	Planned (54%)	Instructional implications (38%)	Transfer between learning activity and NoS (62%)	Concept building of NoS (35%)	Lower cognitive process dimensions (38%)	Higher cognitive process dimensions (62%)
Type 2: Teacher-centered (35 definitions)	Planned (43%)	Instructional implications (49%)	Transfer between learning activity and NoS (49%)	Concept building of NoS (14%)	Lower cognitive process dimensions (89%)	Higher cognitive process dimensions (11%)

Both types are characterized by three analytical themes – meaning of explicit, meaning of reflection and cognitive process dimensions – underlined are the characteristics that occur most per type.

5.3.3 Thematic synthesis overview

Table 8 summarizes the fundamental insights gained from the analysis of the definitions of ER in NoS education. It briefly reviews the analytical themes and their corresponding categories, shedding light on the multifaceted nature of ER definitions. These themes unveil diverse perspectives and nuanced dimensions solely related to how ER is conceptualized within NoS education, like the learning environment, cognitive processes, and interpretations of "explicit" and "reflection".

5.3.3.1 The thematic synthesis through the lens of the "learning environment"

Three of these four themes can be considered relatively neutral, in the sense that existing publications do not exhibit a discernible preference for any specific mode of expression concerning ER in NoS education. However, for one particular theme, the "learning environment," a discernible preference was documented in the literature. This aligns with the promotion of a student-centered learning environment instead of a teacher-centered one.

Consequently, the "learning environment" theme was chosen as a lens through which to examine the remaining three analytical themes: the "meaning of explicit," the "meaning of reflection," and the "Cognitive Process Dimensions". This approach was used to enable the consideration of the implications of the prevailing literature's inclination toward a student-centered learning environment, as well as trends occurring in the expression of the other analytical themes when categorized based on learning environment.

The results are summarized in Table 9, which delineates the trends within analytical themes when focused on either student-centered or teacher-centered definitions. This categorization highlights the distinct characteristics associated with each perspective. Henceforth, these distinct viewpoints are referred to as "the two types of ER definitions": student-centered (type 1) and teacher-centered (type 2), each with its own unique characteristics.

There were 26 student-centered type definitions. "Explicit" was defined as "planned" in 54% of instances, with 38% mentioning "instructional implications." Regarding the meaning of "reflection", 62% linked it to "the transfer of knowledge between learning activities and NoS", and 35% emphasized concept building in NoS. In the

domain of Cognitive Process Dimensions, 38% focused on lower cognitive processes, while 62% emphasized higher cognitive processes.

The teacher-centered type comprised 35 definitions. "Explicit" was mostly characterized as "instructional implications" (49%), with 43% mentioning the "planned" aspect. For the meaning of "reflection", 49% related it to the transfer of knowledge between learning activities and NoS, while 14% connected it to concept building of NoS. Teacher-centered definitions predominantly focused on lower Cognitive Process Dimensions (89%), with only 11% writing according to higher Cognitive Process Dimensions.

Notably, there were discernible differences between the types of ER definitions with regard to two of the three identified themes. Particularly notable is that student-centered definitions tended to conceptualize ER within a higher Cognitive Process Dimension. Furthermore, they demonstrated a higher level of precision in defining both "explicit" (92%) and "reflection" (97%). In contrast, teacher-centered definitions conspicuously prioritized the definition of "explicit" (92%), yet exhibited a lower level of clarity in defining "reflection" (63%). These findings robustly underscore the proposition that adopting a student-centered approach for defining ER in the context of NoS education is more apt and efficacious, particularly with respect to articulating the reflective component.

6 Discussion

In this section, critical findings related to ER are explored in the context of NoS education. Firstly, it was discovered in the methodology that over half of the 123 articles (63 articles) utilizing "explicit reflection in NoS education" in their title or abstract did not provide any definition of ER. Secondly, the research identified significant diversity in length, which ranged from 14 to 326 words, and content. Such a variety of content led to the development of 25 descriptive themes and four analytical themes: the meanings of "explicit" and "reflection," "the learning environment," and the distribution of ER definitions across Cognitive Process Dimensions. Finally, the evolution of the discourse on ER in NoS education within the 61 definitions was mapped out. Notably, the diverse meanings of ER underscore the necessity for a shared vocabulary or framework to analyze its significance in fostering effective NoS education.

6.1 Descriptive results

Based on historical trends, a future can be anticipated in which research on ER within the context of NoS education is poised for sustained growth and deeper exploration. The rise in scholarly interest observed in the most recent period (2020–2023) could continue, leading to a larger body of research. Such a growing emphasis on ER may foster interdisciplinary collaboration among educational psychologists, science educators, and curriculum developers, facilitating innovative approaches to its implementation. While cyclical fluctuations might persist, reflecting evolving academic interests and changing educational priorities, future research is expected to contribute to the development of new theoretical frameworks and models, offering structured insights into this concept.

In terms of the research population, it became evident that 53 of the 60 articles examined featured a well-defined research population. Among these, the division was notable: 30% of the studies concentrated on students, 34% on pre-service teachers, and the largest segment, 36%, was dedicated to in-service teachers. This underscores the significance research places on teachers to play a role in the implementation and understanding of ER in the NoS education landscape.

Turning to the educational levels explored in the studies, 53 of the 60 articles specified the school grade they targeted. The results paint a rich tapestry of educational diversity, with 15% of the research addressing all educational levels. Elementary education emerges as most prominent, capturing 30% of the research focus, followed by middle school at 23%, and higher education at 17%. High school and kindergarten educational levels, however, received less attention, appearing in only 8 and 2% of the articles, respectively. This distribution suggests that the selected definitions may primarily reflect how ER is conceptualized in early and middle educational settings. As such, the findings may be less representative of how ER is understood or applied in secondary education, where students might be more developmentally prepared to engage with higher-order dimensions of reflection (Abd-El-Khalick, 2011).

The broad spectrum of educational contexts in which ER has been examined shows its potential as a versatile tool for augmenting students" understanding of NoS concepts, transcending age and educational levels. Moreover, including pre-service and in-service teachers as research subjects underscores scholars' recognition of the significance of offering training and professional development to educators to integrate ER into their teaching practices. However, the noticeable underrepresentation of research on students, particularly at the high school and kindergarten levels, suggests the need to address the existing research gaps in these domains.

In conclusion, the descriptive findings underline the diversity of research populations and educational levels in literature on ER in NoS education, accentuating its relevance and adaptability across many educational contexts and levels. This should prompt researchers to investigate further the untapped potential of ER in NoS education at all stages of learning.

6.2 Thematic synthesis

The identification of 25 descriptive themes among the definitions of ER in NoS education highlights the rich diversity in the discourse surrounding this concept. This discussion will delve deeper into these descriptive themes, highlighting trends uncovered through the application of two distinct analytical methods: the quadrennial period analysis and the balanced segmentation analysis. By examining these themes, valuable insights were gained into the evolving perspectives on ER in NoS education.

6.2.1 Evolution of ER discourse

The results of this study displayed a portrayal of the evolution of discourse surrounding ER within the realm of NoS education literature. A dynamic landscape characterized by both consistent trends and notable fluctuations in descriptive themes over time was discerned through a balanced segmentation analysis.

Some of the descriptive themes that appeared consistently throughout the literature are, in many ways, unsurprising. References to "aspects of NoS" and "learner" are arguably foundational building blocks of any definition of ER in this context. After all, a definition of

ER that does not reference the Nature of Science itself or the individuals to whom it applies would risk being conceptually incomplete. These elements provide the essential framework that grounds ER in both subject matter and audience.

The persistent use of the word "explicit" in ER definitions across all time segments raises concerns about definitional clarity. If the concept of ER is routinely explained by using the term "explicit", it risks circularity. Definitions should illuminate; they should provide conceptual access to something unfamiliar, not obscure it in tautologies. The continued reliance on the word "explicit" may reflect ongoing conceptual uncertainty within the field about what is precisely meant by explicitness in this context.

What is particularly notable, however, is the steady presence of the theme "activity" across all time periods, appearing at moderately high frequencies. This recurring emphasis suggests a widespread recognition within the field that engaging students actively is necessary to make abstract NoS concepts more accessible and meaningful. NoS has long been described as one of the more conceptually challenging domains in science education for both teachers and learners (Abd-El-Khalick and Lederman, 2000). The inclusion of "activity" in ER definitions may reflect efforts to bridge this abstractness by embedding reflection in tangible classroom practices. This emphasis aligns well with broader movements in science education promoting inquiry-based learning and active engagement (Duschl, 2008; Osborne, 2014). Inquiry approaches are often viewed as pedagogical strategies for making science more authentic and meaningful, and this may be mirrored in ER definitions.

The fluctuations observed across the time segments offer further insights into evolving priorities in the discourse on ER. One of the most striking shifts is the decline in references to "instruction" in the most recent period. This decline raises intriguing questions: Are researchers deliberately distancing themselves from terminology that might imply a top-down, teacher-led delivery model? One possibility is that continued dissatisfaction with the effectiveness of purely instructional approaches to fostering NoS understanding has led scholars to emphasize interaction and student engagement more explicitly in their definitions of ER. After all, instruction can easily be interpreted as unidirectional, knowledge flowing from teacher to student, while reflection inherently requires cognitive engagement by the learner. This shift may also explain the corresponding rise in prominence of "discussion" in the most recent literature. Unlike instruction, discussion inherently implies reciprocity: an exchange of ideas. Indeed, this increasing emphasis on dialogic engagement parallels well-established pedagogical arguments in science education advocating for the centrality of argumentation, dialogue, and discourse in learning science (Osborne, 2010; Duschl, 2008). Definitions of ER that foreground discussion may therefore signal an effort to reposition ER as an interactive process where students co-construct meaning about NoS, rather than passively receiving instruction about it.

The increased attention to "understanding NoS" in the most recent segment is also revealing. This emerging emphasis may represent a shift from focusing solely on the pedagogical design of ER (e.g., planned instruction or associated activities) toward more direct acknowledgment of its intended educational purpose: the development of students' conceptual understanding of NoS. Earlier definitions may have implicitly assumed this outcome, but its growing explicit inclusion in recent literature suggests a sharpening of focus around the ultimate goal of ER. It may indicate a maturing of the discourse around ER, with definitions becoming more deliberate in articulating not just how reflection should be facilitated, but why it should occur.

In summary, the evolution of ER definitions in NoS education appears to reflect both consolidation around core elements and an ongoing search for conceptual precision. While certain foundational aspects remain stable, recent shifts suggest an increasing emphasis on student-centered, dialogic approaches to fostering understanding of NoS.

6.2.2 The meaning of ER in literature

Within the corpus of 61 definitions related to ER in NoS education, a comprehensive analysis distinguished four distinct analytical themes. These provide an essential framework for understanding the multifaceted dimensions of ER in this context. This section will illuminate each analytical theme, offering a detailed exploration of their individual characteristics and implications.

Concerning the meaning of explicit, the results of this study highlight the different interpretations and definitions of the term "explicit" in the context of NoS education. The majority of the articles analyzed understood ER as intentional planning and targeting of the topic within the curriculum, rather than an instructional approach. Nevertheless, a considerable number of articles viewed ER as an instructional element, emphasizing the need for explicit teaching and didactic approaches to teaching NoS. These findings demonstrate the need for further exploration and clarification of the term "explicit reflection" in NoS education.

The primary observation on the meaning of reflection is that it is frequently absent from specific definitions within ER discourse in NoS education. This point will be explored further later in the discussion. Also, it was observed that definitions that did give an explanation of what was meant by the concept of "reflection" as a tool for NoS education follow two distinctive paths. Firstly, reflection was seen as a means to foster a profound conceptual understanding of NoS principles, encouraging critical thinking and internalization of concepts. This constructivist approach emphasized active engagement and the establishment of a solid foundation of NoS knowledge. Secondly, it could serve as a tool for transferring NoS knowledge from the classroom to real-world scientific practices, bridging the gap between theory and application. This approach highlights the practical relevance of NoS education, preparing learners to effectively apply NoS principles in scientific contexts. Future researchers may consider integrating these two dimensions, defining reflection in NoS education as a multifaceted process encompassing both conceptual building and knowledge transfer, thereby offering a comprehensive and balanced approach.

Given that reflection is so often overlooked in ER definitions, such a lack of clarity poses a potential hindrance in the development of effective NoS education. It is imperative to clarify the meaning of reflection in this context to ensure that instructional strategies align with intended learning outcomes. Based on this analysis, it is recommended that future studies provide a clear definition of reflection within their definitions of ER in NoS education, as it is such a key element.

The study's findings indicated a lack of consensus regarding the learning environment in definitions of ER. Some position students as the central focus, emphasizing reflection as an action undertaken by the students themselves. However, most definitions (57%) place the teacher at the center of the reflective process, implying that the teacher, rather than the student, is responsible for reflecting on NoS. Whilst teacher reflection on NoS is undoubtedly valuable, effective NoS education primarily targets the learner. We do not believe that researchers intend to suggest that teachers alone should engage in reflection. However, the ambiguity in some definitions could lead to this interpretation. To avoid

such confusion, it would be beneficial for definitions of ER to explicitly highlight student-centered reflection, thereby ensuring clarity and alignment with the goals of effective NoS education.

This emphasis on student-centered ER aligns with the broader literature on effective learning environments for NoS education. Research consistently highlights the importance of student-centered settings that offer authentic tasks, encourage open discussions, promote inquiry-based activities, and cultivate problem-solving skills to facilitate meaningful learning experiences (Bereiter and Scardamalia, 1996; Grabinger, 1996). Such environments align with constructivist pedagogy and prioritize active learner involvement in the learning process (Gow and Kember, 1993; Kember et al., 2010). Extensive empirical support confirms that students exhibit enhanced satisfaction and understanding of NoS concepts when exposed to student-centered learning (Minnaert et al., 2007; Smit et al., 2014). By aligning definitions of ER with these educational ideals, the field can better support NoS learning experiences that are both significant and effective.

The distribution of ER definitions across the Cognitive Process Dimensions (Anderson and Krathwohl, 2001), as identified in the analysis, highlights an important consideration for NoS education. The theoretical framework, as articulated by Allchin (2011) and supported by contemporary educational theories, underlines the importance of cultivating critical thinking skills among students. While understanding NoS principles is essential, the greater pedagogical benefit comes from helping students think critically about these concepts. Such a deeper level of engagement leads to a more profound understanding, moving beyond simple memorization or recognition.

The findings of this study suggest that many definitions within the articles analyzed primarily address lower Cognitive Process Dimensions, such as "remembering" and "understanding." They often focus on tasks like identifying, recalling, relating, and recognizing NoS concepts. Fewer definitions engage higher cognitive processes like "analyze," "evaluate," or "synthesize," which encourage students to engage in more complex activities such as appraising, assessing, comparing, critiquing, and creating. This observation calls attention to the way the definitions are constructed. Scholars may unintentionally reinforce a focus on memorization by using action verbs tied to lower-order cognitive skills. However, by choosing action verbs that reflect higher-order cognitive processes – such as "evaluate," "critique," "compare," and "synthesize" – they can encourage research on student learning that moves beyond simple knowledge retention and focuses on deeper, more analytical thinking.

At the same time, it is worth considering whether such higher-order processes are equally feasible across all educational levels. Definitions of ER may need to be tailored to what is developmentally appropriate for learners at different ages. As Abd-El-Khalick (2011) notes, the cognitive demands of reflection should align with students' developmental stages. Developing level-appropriate definitions of ER could therefore be a fruitful line of research for those working at the intersection of NoS and science education.

6.3 Thematic synthesis overview

The thematic synthesis provides a comprehensive overview of the varied discourses surrounding ER in NoS education. It underscores the critical need for clear and standardized ER definitions, especially given that 63 out of 123 articles with ER in their title or abstract lacked such definitions and were therefore excluded from this study.

To enhance the synthesis of this complex topic, it was examined through the lens of the learning environment, shedding light on distinct discourse patterns in definitions of ER. Notably, student-centered ER definitions prioritized action verbs that reflect higher-order cognitive processes, which may be more beneficial when the goal is to foster critical thinking in NoS education. This type also demonstrated greater clarity, offering more often definitions for both the concepts of "explicit" and "reflection". In contrast, teacher-centered ER definitions frequently emphasized "instructional implications," highlighting a focus on teaching methods rather than the creation of meaningful learning experiences.

In conclusion, the thematic synthesis outlined two types of ER definitions: student- and teacher-centered. It highlighted inconsistencies in interpretations, accentuating the requirement for authors to carefully curate their definitions for research on ER in NoS education.

7 Future research

To address the issues outlined above and advance understanding of ER in NoS education, future studies should consider four key priorities:

Firstly, scholars should provide a clear definition of ER within the context of NoS education research, moving beyond one-sentence definitions. Secondly, they should select action verbs that align with the intended Cognitive Process Dimension, judiciously considering whether they accurately reflect the desired level and depth of reflection. Thirdly, the definition of ER should be framed within a targeted learning environment, whether student-centered or teacher-centered. Researchers should be mindful of the implications this choice carries: is the goal to encourage reflection primarily from the educator, or, as has been assumed here, is the reflection meant to be student-driven? Finally, it is essential to define both "explicit" and "reflection" within the ER context to reduce ambiguity and establish a common foundation for research and practice.

Given that ER has predominantly been defined in a teacher-centered manner, often using action verbs associated with lower-order cognitive processes, it would be valuable to explore the impact of defining ER from a student-centered perspective in the future, using action verbs linked to higher-order cognitive processes. Such research could, for instance, shed light on how these varying definitions might influence teachers' pedagogical approaches when they encounter them.

8 Conclusion

The findings of this research emphasize the complexity surrounding ER in the context of NoS education. This is reflected in the diverse range of meanings attributed to ER, which were categorized into 25 descriptive and four analytical themes, ranging from "explicit" meaning "direct" or "planned" NoS education, to reflection on "higher" and "lower Cognitive Process Dimensions". Based on these findings, we recommend that definitions of ER in NoS education should be student-centered and designed to engage learners in higher-order cognitive processes. Additionally, to enhance conceptual clarity, definitions of ER should avoid circularity, specifically, they should not rely on the terms "explicit" or "reflection" when defining ER itself.

The importance of ER in effective NoS education is well-established in the academic literature. However, this review highlights a significant challenge: the wide variation in ER's conceptualization. It raises the question of whether researchers have consistently investigated the same phenomenon, potentially leading to discrepancies in findings and hindering the development of a cohesive body of knowledge in this field. Therefore, the key message to future research on ER in NoS education is to be explicit about explicit reflection.

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LB: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. JS: Writing – review & editing, Funding acquisition, Conceptualization, Supervision. RP: Writing – review & editing, Supervision. PP: Writing – review & editing, Supervision.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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