

Beyond the Surface: Exploring Explicit Reflection in Nature of Science Education

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ABSTRACT

In science education, the concept of Nature of Science (NoS) is considered crucial to foster scientific literacy. Numerous studies underscore the significance of one key-component in effective Nature of Science education: Explicit Reflection. However, capturing the concept of Explicit Reflection presents a series of challenges. Research indicates that employing questions is a viable method to instigate reflection, yet the implementation of this approach exhibits considerable variability. Furthermore, the diverse interpretations of NoS education itself, ranging from the consensus view to more open perspectives, further complicate the educational landscape. This study addresses these challenges using two methodologies: a systematic literature review and expert content validation for the categorization of Nature of Science frameworks. Our findings show that articles favoring student-centered definitions of Explicit Reflection demonstrate more proficiency in their instructional approach to Nature of Science education by posing more and effective questions, with a particular emphasis on specific aspects of Nature of Science. In contrast, articles emphasizing teacher-centered definitions of Explicit Reflection present fewer and less effective questions within their instructional approach to Nature of Science education, often focusing on generalized reflections unrelated to Nature of Science. Furthermore, articles adopting Nature of Science frameworks categorized as *closed towards defining Nature of Science* are more likely to align with the patterns of articles that had a teacher-centered definition of Explicit Reflection. In contrast, articles containing frameworks that were more *mixed* or *open towards defining Nature of Science* mostly aligned with the patterns of articles having a student-centered definition of Explicit Reflection. To conclude, this study unveils the intricate relationship between the various meanings of Explicit Reflection, the conceptualization of Nature of Science, and Nature of Science questions. It promotes clarity in the field, facilitating a shared understanding of Nature of Science education and Explicit Reflection, vital for cohesive and impactful science education and research.

Keywords: Nature of Science, Explicit Reflection, NoS questions, Science Education, Systematic Review

Introduction

Within the realm of science education, the concept of Nature of Science (NoS) is deemed fundamental. NoS encompasses the values, assumptions, and essence of what science is and how it operates (Clough, 2006; Lederman, 1992). It is widely acknowledged that NoS education is instrumental for nurturing scientific literacy (AAAS, 1993; NGSS, 2013; NRC, 2000). Ever since Abd-El-Khalick and Lederman's influential review in 2000, the concepts of *implicit* and *explicit* approaches towards NoS education were coined. These concepts stress the importance of clear NoS instruction and the need for students to reflect on their learning experiences. As a result, the term *Explicit Reflection* (ER) has become widely used in NoS education research, with researchers like Krajewski and Schwartz (2014) and Lederman (2007) highlighting its significance.

There is considerable diversity in the definition of ER within the field of NoS education. For instance, while Aydin et al. (2013) emphasized that ER entails specific planning, teaching, and assessment in NoS education, Matkins and Bell (2007) focused on students reflecting upon the distinction between classroom science and the practices of real-world scientists. The variation in these definitions adds complexity to the teaching and understanding of ER within the context of NoS.

In light of the inherent challenges associated with ER (Gandolfi, 2017; Lederman, 1992), this article aims to address two of these challenges found within the literature.

Challenge 1: The Importance of Questioning

There are many ways to elicit reflection, but one common approach is to use questions targeted at ER (Kruse et al., 2020). Questions are the prompts that make students reflect and develop a rich conceptual understanding of NoS (Voss et al., 2022). Kruse et al. (2020) showed that a significant number of questions expected to evoke ER often fall short of their intended purpose. Instead, they tend to generate self-reflection among students, as opposed to a more profound reflection upon the very essence of NoS, which remains the heart of the matter.

Challenge 2: Consensus in NoS Education

The lack of consensus on what should be taught about NoS adds to the complexity of ER. On one side, the *consensus view* proponents believe in a set of NoS aspects that form the basis for instructing students about the fundamentals of NoS (Lederman et al., 2002; McComas & Clough, 2020). On the other side, adversaries assert that the consensus view offers too narrow of a perspective of NoS (Irzik & Nola, 2011; Kaya et al., 2016; Matthews, 2012). This divergence in conceptualizations prompts a pertinent question: when scholars and academics hold differing interpretations of NoS for science education, does this variation extend to their views on ER in NoS education? Do they approach it from distinct angles and conceptualize it in varying ways? The proliferation of diverse conceptualizations can inadvertently create confusion, not only among educators but also among researchers. Such confusion, if left unaddressed, can undermine the collective efforts to enhance the effectiveness of NoS education and research. Therefore, it is important to move towards transparency in the field.

The Goal of Our Study

Through a systematic review of existing literature, our goal is to provide clarity and a comprehensive understanding of the use of ER within the realm of NoS education research. In particular, our study seeks to address the challenges that surrounds ER and its application in NoS

education in two ways. First, we aim to unveil the connection between the numerous meanings attributed to ER and the types of questions that facilitate ER. Secondly, we explore the potential divergence between different NoS frameworks, and assess if and how an article's conceptualization of NoS influences its approach to ER and the choice of questions.

Theoretical Framework

Meanings of ER

Since Abd-El-Khalick and Lederman (2000) introduced the distinction between implicit and explicit instruction, the need for learners to reflect on their NoS experiences has gained prominence. Consequently, *explicit reflection* (ER) has emerged as a fundamental concept within NoS education research, emphasized by scholars such as Krajewski and Schwartz (2014) and Lederman (2007). However, ER's popularity is matched by its lack of a precise definition. It takes on various meanings. For instance, Aydin et al. (2013) suggested that ER involves NoS education that is “specifically planned for, taught, and assessed” (p. 990), Matkins and Bell (2007) rather emphasized that by using ER in NoS education, students “reflect upon the similarities and differences between classroom science and practicing scientists.” (p. 138). Therefore, while both authors aimed to elucidate the concept of ER, disparities in their definitions emerge. Furthermore, numerous studies fail to even provide any definition of the concept (Cil & Cepni, 2012; Deniz et al., 2020).

To study the different meanings of ER, Boven et al. (2025) conducted a systematic literature review that resulted in a concise summary that delineates **four analytical themes for ER** and their corresponding categories, providing insights into the multifaceted nature of ER. These themes unveil diverse perspectives and nuanced dimensions related to how ER is conceptualized within NoS education. The four analytical themes found are: *Meaning of Explicit*, *Meaning of Reflection*, *Learning Environment* and *Cognitive Processes Dimensions* (see Table 1).

Table 1

Analytical Themes of ER and Their Different Interpretations (Boven et al., 2025)

Meaning of Explicit	Meaning of Reflection	Learning Environment	Cognitive Process Dimensions (Anderson & Krathwohl, 2001)
Planned for	Concept building of NoS	Student-centered	High
Instructional implication	Transfer activity and NoS	learning Teacher-centered	Low

The same study identified **two types of ER**: student-centered and teacher-centered perspectives. The findings indicate that definitions aligned with a student-centered perspective (Type 1) more accurately reflect the initial intent of ER, which is to foster a critical understanding of NoS,

thereby contributing to the development of scientific literacy. Type 1 definitions were found to provide a more comprehensive account of ER, emphasizing higher cognitive process dimensions as outlined by Anderson and Krathwohl (2001) compared to those definitions with a teacher-centered (Type 2) perspective on ER (Figure 1).

Figure 1

The Two Types of ER: Student-centered and Teacher-centered

Type of ER	Meaning of Explicit	Meaning of Reflection	Cognitive Process Dimensions (Anderson and Krathwohl, 2001)
Type 1: Student-centered	Planned	Transfer learning activity between NoS and	Higher cognitive process dimensions
Type 2: Teacher-centered	Instructional implications	Transfer learning activity between NoS and	Lower cognitive process dimensions

Note. Both types of ER are characterized by three analytical themes – Meaning of Explicit, Meaning of Reflection and Cognitive Process Dimensions. This table is the synthesized version based on Boven et al. (2025).

NoS Questioning Approach

In the realm of science education research, the use of different types of NoS questions has garnered attention as a means to foster ER. Scholars like Kruse et al. (2020) and Voss et al. (2022) have explored the impact of question types on student thinking about NoS.

In the study by Kruse et al. (2020), four historical short stories were presented to 6th-grade students, accompanied by different NoS questions. The question types included: general reflection questions, general NoS questions, specific NoS questions targeting particular NoS ideas, and specific NoS questions with additional preamble (Table 2). The findings revealed that students tended to address more NoS ideas when asked specific questions with or without a preamble. In contrast, a significant decrease in the number of NoS ideas addressed was observed for general NoS questions, and students rarely addressed NoS ideas when asked general reflective questions. The study concluded that, therefore, specific NoS questions, with or without preamble, are more effective in drawing students' attention to a wide variety of accurate NoS ideas compared to more general questioning approaches.

Similarly, Voss et al. (2022) explored the nature of student responses to different questions. They distinguished general reflection questions and NoS-specific questions, which were further categorized as evaluative, convergent, and divergent questions (Table 2). Their study collected data through writing, and students were presented with a story combined with varying question types. The

findings indicated that the type of question influenced student responses significantly. Much like the findings of Kruse et al. (2020), responses to the general reflection questions were largely unrelated to NoS, indicating their limited effectiveness in teaching NoS concepts. Evaluative questions tended to elicit normative or, according to the authors, misconception responses, while divergent questions allowed for a wider range of views, including some misconceptions (from a consensus viewpoint, see consensus vs non-consensus view, later in this article). Convergent questions, biased towards consensus NoS views, often resulted in normative responses.

In conclusion, the findings from both Kruse et al. (2020) and Voss et al. (2022) suggest that specific NoS questions, presented in a divergent or convergent manner, are preferred for NoS education (Table 1). Divergent questions encourage students to explore a broader range of NoS perspectives and may be favored by those who do not align with the consensus view. In contrast, convergent questions guide students toward a consensus view understanding of NoS.

Other types of NoS questions appear to be less effective. For instance, while general NoS questions may serve as informal assessments of student thinking and initiate NoS discussions, they are less effective in promoting deeper engagement with NoS concepts (Kruse et al., 2020). Furthermore, evaluative questions, although suitable for assessment purposes, do not seem to stimulate significant development of NoS ideas among students (Voss et al., 2022).

Importantly, the two studies both emphasized the limited effectiveness of general reflection questions with no clear link to NoS in fostering meaningful NoS discussions in the classroom. Therefore, their use should be avoided or minimized.

Table 2

Summary of the Types of Questions to Evoke Explicit Reflection in NoS Education as Categorized by Kruse et al. (20) and Voss et al. (2022)

Author	Type of Question	Example	Result
Kruse et al. (2020) and Voss et al. (2022)	General reflection questions	“Based on what you just read, what do you notice or want to remember?”	Rarely/ No NoS ideas addressed
Kruse et al. (2020)	General NoS questions	“How is doing science like composing music?”	Low amount of NoS ideas addressed
	Specific NoS questions	“How does the need to make sense of data account for disagreements among scientists and the inventive character of science?”	High amount of NoS ideas addressed
	Specific NoS questions + additional preamble	“Note that the data is not telling the scientists what to think. Instead, scientists have to develop ideas that will account for the data... How does the need to make sense of data account for disagreements among scientists and the inventive character of science?”	High amount of NoS ideas addressed
Voss et al. (2022)	Evaluative questions	“Do you think that scientific knowledge involves only observable facts? Do you think that scientists use their inferences along with their observations?”	Normative or misconception responses
	Divergent questions	“How were we being like scientists in what we just did?”	Wider range of NoS views, some misconceptions
	Convergent questions	“Why do you think being creative is important for science?”	Normative, consensus view responses

Conceptualization of NoS

Consensus Versus Non-consensus View

One of the driving factors behind the discussion of NoS in science education has been the recognition of misconceptions about NoS held by both students and teachers (Cofré et al., 2019; Lederman, 1992). The consensus view of NoS has emerged as a valuable tool to list, clarify and possibly address these alternative conceptions. The consensus view gives a simplified image of NoS for educational purposes, it serves as a means to communicate accurate NoS ideas to K-12 students (Abd-El-Khalick et al., 1998). The consensus view entails a set of key aspects that have achieved widespread agreement among scientists and the academic community providing a foundation for NoS instruction in schools offering clarity and simplicity in addressing NoS (Kruse et al., 2020).

The seven key aspects identified within the consensus view include (Abd-El-Khalick and Lederman, 2000):

- 1) **Science is Empirical:** This aspect highlights the foundational role of empirical evidence in scientific knowledge. It underscores the principle that scientific claims should be grounded in observable phenomena.
- 2) **Science is Creative and Imaginative:** It recognizes the creative nature of scientific inquiry, emphasizing that scientific discoveries often involve innovative thinking and imaginative problem-solving.
- 3) **Science is Theory-Laden:** This aspect acknowledges that scientific knowledge is laden with theoretical constructs and paradigms, which guide scientific investigations and interpretations.
- 4) **Science is Embedded in Society and Culture:** It emphasizes that scientific knowledge is influenced by social, cultural, and historical contexts. Science is not isolated but interconnected with the broader societal and cultural landscape.
- 5) **Science is Tentative:** This aspect underscores the provisional and dynamic nature of scientific knowledge. It highlights that scientific theories and models are subject to revision as new evidence emerges.
- 6) **No One Method to Science:** It acknowledges that there isn't a single universal scientific method. Science employs a variety of methods and approaches to investigate the natural world.
- 7) **Differences between Theories and Laws:** It differentiates between scientific theories and laws, emphasizing that these serve distinct purposes within the scientific enterprise.

These seven aspects are often referred to as the *Lederman 7*. Notably, the name, the Lederman 7, was given by other researchers as an attribution to Norman G. Lederman's importance in the field, while Lederman himself referred to the framework as *Aspects of NoS*. Many subsequent NoS frameworks have drawn inspiration from or built upon the Lederman 7.

A substantial body of scholars endorse the consensus view (Abd-El-Khalick, 2001; Akerson et al., 2007; Bell et al., 2011; Hanuscin, 2013; Khishfe, 2015; McComas, 2020; Schwartz & Crawford, 2004) with notable academics, such as Norman Lederman, Fouad Abd-El-Khalick, and William McComas, offering their distinctive interpretations of the consensus view. Moreover, the consensus view has left an indelible mark on science education standards, finding adherence in respected institutions from the United States of America like the National Science Teaching Association (NSTA, 2020) and the former National Research Council (NRC, 2000), now known as the Next Generation Science Standards (NGSS, 2013).

One of the newest approaches to the consensus view comes from McComas (2020). McComas' NoS ideas reflect many of the recommendations widely offered but is unique in that related NoS elements are clustered into three bigger domains labeled *the tools and products of science*, *the human elements of science*, and *science knowledge and its limits*. Within each domain there are three major sub-elements or key NoS aspects. They are connected as follows:

- **Tools and products of science:** *evidence is vital, laws and theories are related but distinct and shared methods;*
- **The human elements of science:** *creativity is everywhere, subjectivity and bias are present, interaction with society and culture;*
- **Science knowledge and its limits:** *distinction from engineering and technology, tentativeness, durability and self-correction and science has limits.*

The consensus view of NoS offers an accessible entry point for teaching NoS in K-12 settings. However, it is not without criticisms. While the consensus view simplifies NoS for pedagogical purposes, it faces criticism for its oversimplification and lack of nuance. Critics argue that it overlooks

the differences between scientific disciplines and omits many intricacies of the scientific process (Allchin, 2017; Matthews, 2012).

Furthermore, proponents of the consensus view have been criticized of promoting an essentialist approach to NoS, which oversimplifies the rich diversity of scientific practices and worldviews across various disciplines (Wan et al., 2013). According to Wan et al. (2013) it provides a framework through which NoS is described monolithically as it 'is' or 'ought' to be. This can lead to students forming new stereotypes or alternative conceptions that may hinder a more nuanced understanding of NoS.

Given the critiques on the consensus view, researchers have turned their attention to alternative perspectives, distinct from the consensus paradigm. These **non-consensus approaches** include, among others, Clough's question approach (2007), the epistemic and non-epistemic approach of García-Carmona and Acevedo-Díaz (2018) and the family resemblance approach (FRA) (Dagher & Erduran, 2016; Erduran & Dagher, 2014; Irzik & Nola, 2011, 2014).

Clough's NoS questions (2007) aim to address the distortion of NoS tenets, encouraging their investigation rather than mere instruction in science classrooms. NoS issues are presented as questions to avoid the notion of a final form of science. Some of his thought-provoking questions include: "In what sense is scientific knowledge tentative? In what sense is it durable?", "How does private science differ from public science? In what ways are they similar?", and "In what sense is scientific knowledge invented? In what sense is it discovered?" (p. 33).

The epistemic and non-epistemic aspects of NoS framework, proposed by García-Carmona, and Acevedo-Díaz (2018), offer a balanced integration of epistemic and non-epistemic elements drawn from an exhaustive review of literature on the philosophy, sociology, history of science, and science education related to NoS. The epistemic factor is categorized into *nature of the scientific process* and *nature of scientific knowledge*, while the non-epistemic factors are further divided into *factors internal to the scientific community* and *factors external to the scientific community*. Within these categories, they propose many NoS themes to be discussed such as *the role of research questions*, *gender influence* and *role of media in science dissemination*.

Irzik and Nola (2011, 2014) introduced the **family resemblance approach** (FRA) to offer a more nuanced perspective on understanding NoS. In their framework, science is viewed as a complex system encompassing both cognitive-epistemic and social-institutional elements. They likened various scientific disciplines to a family, highlighting shared characteristics while also acknowledging unique traits within each discipline (Kaya et al., 2019, p. 24). Instead of presenting NoS as a set of fixed statements, the FRA provides a system of categories meant to be explored within specific scientific domains and historical contexts. According to the authors, the FRA promotes a dynamic, creative, and adaptable understanding of NoS. However, the FRA is also not without flaws as it presents challenges for implementation in educational settings, especially considering that science teachers already find it challenging to implement the consensus view of NoS (Bugingo et al., 2022).

Open Versus Closed NoS Approaches

To categorize NoS frameworks, closed approaches can be distinguished from open approaches. According to Irzik and Nola (2011) the closedness of NoS comes in three forms:

Firstly, the conceptualization of NoS presents a narrow perspective, intentionally omitting aspects that lack consensus to enhance clarity. However, this selective approach can render NoS topics undiscussable. For instance, asserting, there is no single scientific method, fails to acknowledge the existence of overarching methodologies, like the hypothetico-deductive method, and general methodological principles that guide scientific practices. Neglecting such foundational principles raises questions about science's self-corrective nature in the absence of methodological rules. Furthermore,

excluding scientific inquiry is done in an artificial way, leaving out aspects of scientific inquiry means leaving out important aspects of what makes science, science, which is in fact, NoS.

Secondly, the portrayal of NoS conveys a monolithic-view of science, disregarding the inherent disparities among various scientific disciplines and projecting an impression of rigidity and timelessness.

Finally, the conceptualization of NoS lacks a comprehensive and systematic unity. The interconnections among NoS components are not clearly delineated, leading to noticeable tensions. For instance, when recognizing that science is socially and culturally embedded, a challenge arises regarding how it manages to produce universally valid knowledge applicable across diverse cultures and societies. In contrast, according to Irzik and Nola (2011) more open approaches to NoS exemplify a dynamic, creative, and open-ended NoS.

This Study

In this study, we investigate the multifaceted meanings of ER in the context of NoS education. We address two research questions:

RQ 1: How does the type of ER (student-centered or teacher-centered) relate to both the questioning approach aimed at achieving ER and the conceptualization of NoS in academic NoS literature?

RQ2: How does the conceptualization of NoS (open, mixed, closed) relate to both the four analytical themes of ER and the questioning approach aimed at achieving ER in academic NoS literature?

Methodology

To expand upon the systematic literature review of Boven et al. (2025), we employed the same corpus of literature which was collected through the PRISMA method (Page et al., 2021) and included 60 articles.

We applied the holistic analysis approach of Lieblich et al. (1998) to conduct a thorough examination of the various interpretations of ER within the context of the articles themselves. Holistic analysis entails a meticulous exploration of recurring themes across different articles. This method emphasizes that each ER definition should not be examined in isolation but rather considered in conjunction with the entirety of the article, contributing to a more profound and nuanced exploration of the subject matter at hand. We utilized the holistic analysis approach to identify all the essential elements within the selected articles to address our research questions (Lieblich et al., 1998), including:

- 1) Identifying and analyzing all the questions employed inside the articles used to achieve ER about NoS
- 2) Identifying and analyzing all NoS frameworks used inside the articles to understand how each article conceptualizes NoS

NoS Questioning Approach

As a key part of our methodology, we catalogued all questions in the articles that were used to elicit ER about NoS. To achieve this, we read all 60 articles in full to identify every relevant question. In our analysis, we considered not only the questions explicitly stated in each article but also those that were mentioned indirectly or implied by the authors.

As an illustrative example of this approach: Akerson et al. (2000) use in their article a total of five questions to elicit ER. Additionally, the authors integrate NoS activities introduced by Lederman and Abd-El-Khalick (1998) in the publication: *Avoiding De-Nature Science: Activities that Promote Understanding of the NoS*, which incorporate 17 questions aimed at eliciting ER. Therefore, for the article of Akerson et al. (2000), we consider both their own five questions and the 17 questions of Lederman and Abd-El-Khalick (1998), as part of their questioning approach, resulting in a combined total of 22 questions.

We considered a single question as one unit when it possessed the capacity to function independently. To elucidate this, we refer to an example from the work of Witucki et al. (2023), who proposed the following question for eliciting ER: “Do scientists use their imagination/creativity? If so, then how? If not, then why not?” (p. 27). In our analysis, this question was regarded as a singular unit, even though it encompasses three distinct components. It is worth noting that the components “*If so, then how?*” and “*If not, then why not?*” lack independent significance and meaning in isolation; hence, they were treated as integral constituents of the overarching question.

To facilitate a structured and meaningful categorization of the identified questions, we utilized the categorization frameworks provided by Kruse et al. (2020) and Voss et al. (2022) as outlined in Table 2 in our theoretical framework. This systematic categorization process enabled us to analyze the questioning approach of the articles in a comprehensive and organized manner, in alignment with the goals of our research.

Conceptualization of NoS: Expert Content Validation

In this study, the categorization of NoS frameworks is aimed at providing a comprehensive understanding of the diverse perspectives within the NoS field. We conducted our analysis using the NoS frameworks present within the 60 articles. Frameworks were identified through a comprehensive read-through of all the articles, with articles lacking explicit mention of a framework excluded from the analysis. However, special consideration was given to one article authored by Duschl and Grandy (2013), titled “Two Views About Explicitly Teaching Nature of Science”, which presented two distinct NoS frameworks. Within this article, the authors not only provided two discrete perspectives on ER but also delineated contrasting outlooks regarding the conceptualization of NoS. These dual-NoS conceptualizations corresponded to two separate NoS frameworks. Consequently, we treated these dual conceptualizations of NoS, as elucidated in Duschl and Grandy's article, as distinct entities within our analytical framework.

After all the frameworks were identified, we categorized them into three distinct groups - open, mixed, and closed towards NoS – following the definition of Irzik and Nola (2011) for the concepts of *closedness* and *openness*. Closed frameworks reflect a narrow perspective on NoS, characterized by a monolithic-view of science and a lack of comprehensive and systematic unity. Open frameworks, on the other hand, demonstrate a dynamic, creative, and open-ended approach to NoS. Mixed frameworks incorporate elements from both perspectives.

Expert Selection

We selected four experts specializing in research on NoS education. Each expert was chosen for their expertise in the field, with one specializing in science teacher education, another currently pursuing a doctoral dissertation on NoS education, a third engaged in post-doctoral research on science communication, and the fourth serving as a lecturer in philosophy and science education. To ensure impartiality in the categorization of the frameworks, none of the selected experts had

participated in the creation of any of the frameworks under assessment. Additionally, two of the experts were external to the study, while the other two were authors of the study.

Expert Content Validation of NoS Frameworks

To ensure an unbiased assessment, the four NoS experts independently evaluated the NoS frameworks. The evaluation process was carried out in a blinded manner. This means that the experts were provided with excerpts from the framework descriptions with all identifying information redacted. This approach guaranteed impartiality in the evaluation, as the experts were unaware of the specific framework names and authors.

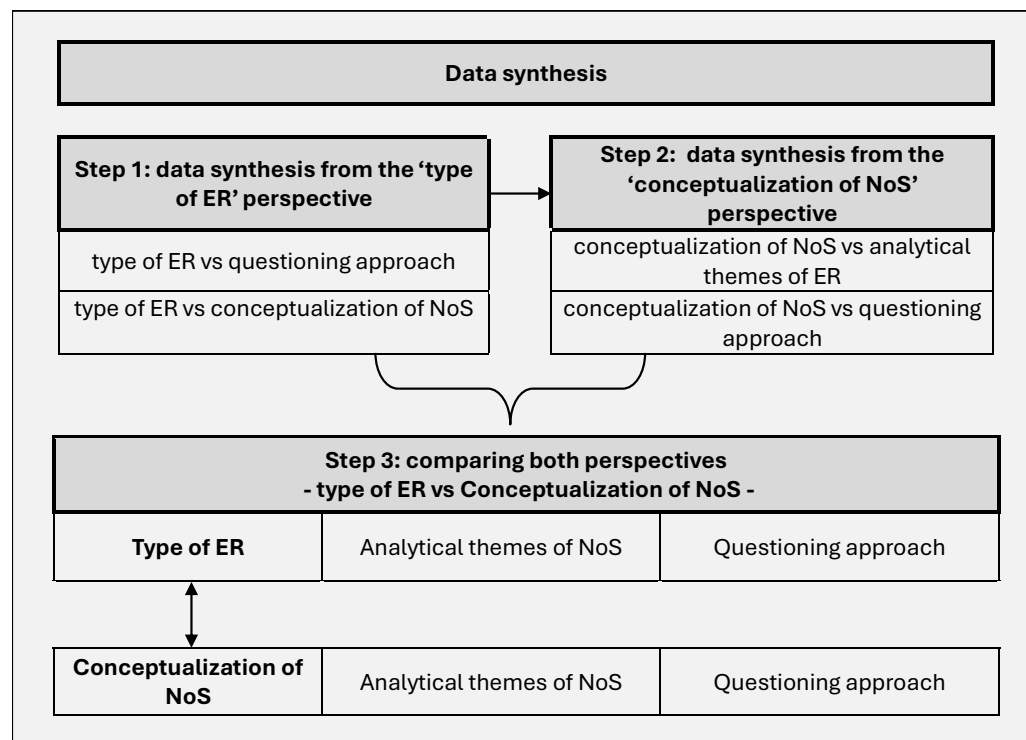
Initially, the evaluations resulted in minor discrepancies ($\kappa=.85$) in the categorizations of the frameworks. However, through rigorous discussions and deliberations, a consensus was reached about the categorization among the experts. The consensus-building process was instrumental in ensuring that the final categorizations accurately reflected the experts' collective assessment.

Data Synthesis

After collecting and categorizing the relevant data, we synthesized the findings to identify patterns, connections, and potential disparities. We followed a three-step approach shown in Figure 2.

Figure 2

The Three-step Approach for the Data Synthesis



In step one, we looked at the data from the *type of ER* perspective based on the framework provided by Boven et al. (2025) (Figure 1), which includes student-centered and teacher-centered ER, along with their respective characteristics. This step involved two sub-steps. First, we compared the type of ER and the questioning approach by examining the variety of question types used to stimulate ER (Table 2.) and comparing them across articles that align with either student-centered (type 1) or teacher-centered (Type 2) definitions of ER. Second, we compared the type of ER (student- or teacher-centered) with the conceptualization of NoS as open, mixed, or closed. This conceptualization of NoS was determined in the expert content validation.

In step two, we examined the data through the lens of *the conceptualization of NoS* (open, mixed, closed). This step comprised two sub-steps. Firstly, we compared the conceptualization of NoS in articles with the analytical themes used to define ER based on the framework provided by (Boven et al., 2025) (Figure 1). Secondly, we compared the conceptualization of NoS in articles with the questioning approach, scrutinizing the variety of question types employed to stimulate ER on NoS (Table 2) across articles aligning with open, mixed, or closed approaches to conceptualizing NoS. In the final step, step three, we conducted a comparative analysis of the synthesized data from both perspectives: *type of ER* and *conceptualization of NoS*, seeking alignment or discrepancies in patterns among both perspectives.

Results

NoS Questioning Approach

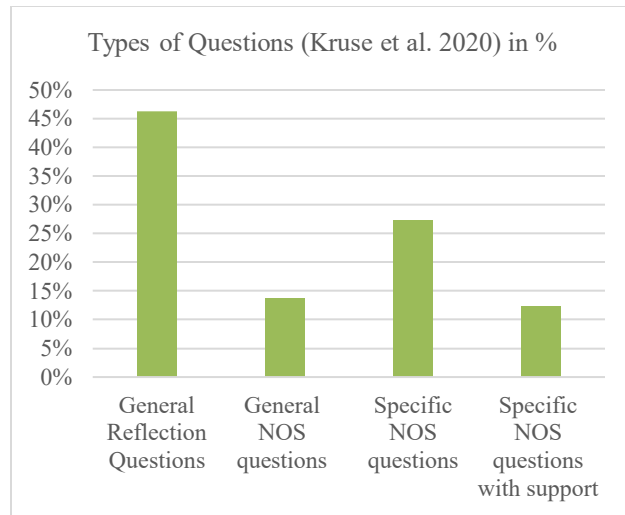
Within the 60 articles related to NoS education, 47 mentioned at least one question for encouraging ER on NoS. In total 589 questions were identified. Kruse et al. (2020) and Voss et al. (2022) have one category in common, the non-NoS questions named *general reflection questions*. We found that 277 questions (47%) fell under the classification of general reflection questions.

Additionally, using Kruse et al.'s definitions, we identified 82 questions (14%) as general NoS questions, 158 questions (27%) as specific NoS questions, and 71 questions (12%) as specific NoS questions with supportive information (preamble) (Figure 3).

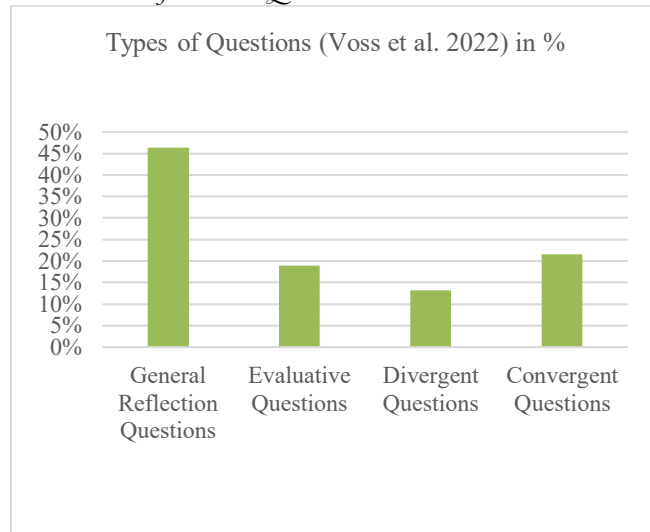
Moreover, applying the categorization by Voss et al. (2022), we determined that 112 questions (19%) were evaluative NoS questions, 77 questions (13%) were divergent NoS questions, and 123 questions (21%) were convergent NoS questions (Figure 4).

Figure 3

Distribution of the 589 Questions Used in the 47 Articles Following Kruse et al.'s Categorization (2020)

**Figure 4**

Distribution of the 589 Questions Used in the 47 Articles Following Voss et al.'s Categorization (2022)



Conceptualization of NoS

Among the 60 articles included in this systematic review, we identified eight distinct frameworks for understanding NoS. These frameworks ranged from being developed in 2000 to 2020. Chronologically these frameworks were: *The Lederman 7* (2000), *NRC* (2000), *Clough's questions* (2007), *FRA* (2011), *NGSS* (2013), *Epistemic and non-epistemic NoS* (2018), *NSTA* (2020) and *McComas' NoS ideas* (2020) (Table 3). Five of these frameworks are recognized as NoS consensus view frameworks, namely, *The Lederman 7*, *NSTA*, *McComas' NoS ideas*, *NRC*, and *NGSS*. The remaining three frameworks, *Clough's questions*, *FRA* and *Epistemic and non-epistemic NoS*, are recognized as non-consensus view frameworks (Abd-El-Khalick & Lederman, 2000; Clough, 2007; Clough & Olson,

2008; García-Carmona & Acevedo-Díaz, 2018; Irzik & Nola, 2011; McComas, 2020; NGSS, 2013; NRC, 2000; NSTA, 2020).

Table 3

The Eight Identified NoS Frameworks

NoS framework	Number of articles
NoS consensus view framework	
The Lederman 7 (Abd-El-Khalick and Lederman, 2000)	28
NSTA (NSTA, 2020)	8
McComas' NoS ideas (McComas, 2020)	7
NRC (NRC, 2000)	3
NGSS (NGSS, 2013)	2
Total	48
NoS non-consensus view framework	
Clough's questions (Clough, 2007)	3
FRA (Irizik and Nola, 2011)	2
Epistemic and non-epistemic NoS (García-Carmona and Acevedo-Díaz, 2018)	2
Total	7
No framework mentioned	6

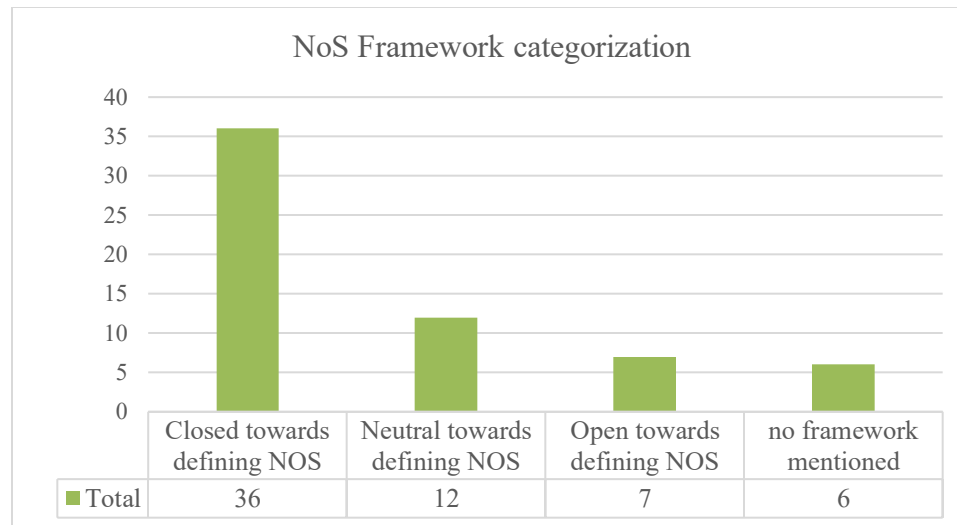
Among the 60 selected articles, The Lederman 7 emerged as the most frequently used NoS framework (46%), while NGSS (3%), FRA (3%) and Epistemic and non-epistemic NoS (3%) were the least commonly employed. Additionally, six articles did not mention a specific NoS framework. It is to be observed that the NoS consensus view is the most used approach in research on ER in NoS education.

In the expert content validation process of classifying frameworks into *closed*, *mixed*, and *open* categories for the conceptualization of NoS, both The Lederman 7 and the NSTA NoS frameworks were categorized as closed. This category, comprising a total of 36 articles, emerged as the most prevalent within the literature included in this study. The mixed category encompassed the NRC, 'NGSS', and 'McComas' ideas' NoS frameworks, constituting a total of 12 articles. Conversely, the open category, which included Clough's questions, FRA, and the Epistemic and non-epistemic NoS frameworks, was the least utilized, featuring only seven articles. Figure 5 provides an overview of the distribution of articles across these different categories.

The analysis indicates that a significant portion of the articles defining ER for NoS education predominantly utilized NoS frameworks with relatively closed definitions for NoS, leaving less space for complexity and context.

Figure 5

Distribution of the NoS Frameworks over the Three Categories -Closed, Mixed, Open- towards NoS, as Defined by the Four NoS Experts



Data Synthesis

The data synthesis presents an overview of (1) the types of questions used to elicit ER on NoS and (2) how NoS was conceptualized in each article, based on expert content analysis.

A total of 589 questions were analyzed, drawn from the 47 articles that included at least one question (13 articles included no questions). Each question was first categorized as either NoS-related (i.e. addressing General or Specific NoS content) or non-NoS-related (i.e. General Reflection, with no explicit reference to NoS). This distinction is mutually exclusive: questions were either classified as NoS-related or not. For NoS-related questions, a second layer of classification was applied: each question was further categorized as Evaluative, Divergent, or Convergent, with only one of these three applied per question. For definitions of each question type and examples, see Table 2, which outlines the coding framework used to guide the categorization process.

The second part of Table 4 reports how NoS frameworks were interpreted within each article, categorized as Closed, Mixed, or Open, based on expert content analysis. Six articles did not reference a NoS framework.

Table 4*Summary of the Findings of the Holistic Analysis*

Questioning approach	% of articles ^a
(Kruse et al, 2020; Voss et al, 2022)	
General Reflection	47
(Kruse et al, 2020)	
General NoS Question	14
Specific NoS Question	39
(Voss et al, 2022)	
Evaluative Questions	19
Convergent Question	21
Divergent Question	13
Conceptualization of NoS (Expert Content Analysis)	% of articles ^b
Closed	65
Mixed	22
Open	13

^a The percentage is based on all articles that included questions. 13 articles did not include any questions and are therefore not included in this summary. The overall total of questions included in all articles was 589 questions.

^b The percentage is based on all articles that included a NoS framework. As mentioned earlier, 6 articles did not include any NoS framework and are therefore not included in this summary

RQ1.1: The Type of ER vs the Questioning Approach

To address the initial aspect of research question one, we analyzed each of the 60 articles to examine the relation between the type of ER, whether it was student- (Type 1) or teacher-centered (Type 2), with the questioning approach employed to evoke ER on NoS. We observed notable

differences in the utilization of questions between articles with Type 1: student-centered (n=26) and Type 2: teacher-centered definitions of ER (n=35). Articles adhering to Type 1 employed a total of 305 questions, of which 181 (59%) were related to NoS. On average, these articles contained twelve questions (SD=8,77), with seven focusing on NoS. In contrast, articles with a Type 2 definition of ER featured 267 questions in total, with 126 (47%) of them addressing NoS. On average, these articles contained eight questions (SD=7,67), with four centered on NoS, which was a significantly lower proportion compared to the articles containing a Type 1 approach towards defining ER ($p=0.0043$).

When we specifically analyzed the NoS-related questions in articles with a Type 1, student-centered approach, we observed that 75% of them were specific NoS questions, targeting particular aspects of NoS (Table 5). For instance, questions such as *"Do you think scientists need creativity?"* were prevalent. The remaining 25% consisted of general NoS questions, such as *"How were you acting like a scientist today?"*. This categorization was based on the criteria outlined by Kruse et al. (2020). Utilizing the framework proposed by Voss et al. (2022), we further categorized the NoS-related questions. Articles with a Type 1 approach to ER predominantly featured convergent NoS questions (45%), followed by evaluative (31%) and divergent (24%) NoS questions.

Considering articles adopting a Type 2, teacher-centered, approach to ER, the majority (71%) of NoS-related questions were specific in nature, primarily targeting distinct NoS aspects. The remaining 29% encompassed general NoS questions, as per Kruse et al.'s criteria. When employing Voss et al.'s framework, these articles mainly included evaluative NoS questions (41%), followed by convergent (32%) and divergent (27%) NoS questions. The observed variations in the categorization of NoS questions between the two types of ER didn't differ significantly.

Table 5

Summary of the Questioning approach Categorized According to the Two Types of ER

Questioning approach	Type 1: Student-centered		Type 2: Teacher-centered	
	n	%	n	%
(Kruse et al, 2020)				
General NoS Question	45	25	37	29
Specific NoS Question	136	75	89	71
Total	181	100	126	100
(Voss et al, 2022)				
Evaluative Questions	56	31	52	41
Convergent Question	81	45	40	32
Divergent Questions	44	24	34	27
Total	181	100	126	100

Note. A total of 26 articles were related to Type 1 and a total of 35 articles were related to Type 2. Definition for ER Based on (Boven et al., 2025).

RQ1.2: The Type of ER vs the Conceptualization of NoS

To address the second aspect of research question one, we conducted a comparison for each of the 60 articles. This comparison involved examining the type of ER, whether it was student- (Type 1) or teacher-centered (Type 2), with the way NoS was conceptualized in the article (Open, Mixed, Closed) (Table 6). The predominance of NoS frameworks categorized as *closed towards defining NoS* is a notable trend, and both student- and teacher-centered definitions of ER predominantly align with frameworks classified as such. In articles where a student-centered definition of NoS was employed, the alignment with the closed approach was observed 54% of the time. For articles with a teacher-centered NoS definition, the alignment with the closed approach occurred in 63% of the cases.

Table 6

Summary of the Findings of the Conceptualization of NoS Related to the Learning Environment

Type of ER	NoS conceptualization			Did not specify a NoS framework
	Open towards defining NoS	Mixed towards defining NoS	Closed towards defining NoS	
Type 1: Student-centered	19%	19%	54%	8%
Type 2: Teacher-centered	6%	20%	63%	11%

R.Q.2: The Conceptualization of NoS vs the Four Analytical Themes of ER and the Questioning Approach

To address research question two, we analyzed each of the 60 articles to examine the relation between the conceptualization of NoS, whether it was open, mixed or closed with both the four analytical themes for ER (Table 1) and the questioning approach employed to evoke ER on NoS. We observed notable differences (Table 7). In the articles with a framework that is more open towards the conceptualization of NoS (n=7), ER is predominantly understood as a planned learning activity (100%) in which a transfer is made to NoS elements (87%), lower cognitive process dimensions are emphasized (71%), and the learning environment is written in a student-centered way (71%). The questioning approach to evoke ER on NoS involves an average of 13 questions, mostly specific (75%), convergent NoS questions.

In the articles with a framework that is more mixed towards the conceptualization of NoS (n=12), ER is largely understood as a planned learning activity (67%) in which a transfer is made to NoS elements (58%), higher cognitive process dimensions are emphasized (58%), and the learning environment is written in a teacher-centered way (58%). The questioning approach includes an average of eight questions, mostly specific (75%), convergent NoS questions.

In the articles with a framework that is more closed towards the conceptualization of NoS (n=36), ER is largely understood as an instructed learning activity (58%) in which a transfer is made to NoS elements (53%), lower cognitive process dimensions are emphasized (72%), and the learning

environment is written in a teacher-centered way (61%). The questioning approach includes an average of nine questions, mostly general reflection questions (57%).

Table 7

Summary of the Relationship Between the Conceptualization of NoS, the Four Analytical Themes of ER and the Questioning Approach

Conceptualization of NoS ^a	Analytical themes of ER (Boven et al., 2025)				Questioning Approach
	Meaning of Explicit	Meaning of Reflection	Cognitive process dimensions	Learning Environment	
Open (n=7)	Planned (100%)	Transfer between learning activity and NoS (86%)	Lower cognitive process dimensions (71%)	Student- centered (71%)	Avg. 13 questions, mostly specific (75%) convergent NoS questions
Mixed (n=12)	Planned (67%)	Transfer between learning activity and NoS (58%)	Higher cognitive process dimensions (58%)	Teacher- centered (58%)	Avg. 8 questions, mostly specific (71%) convergent NoS questions
Closed (n=36)	Instructional implications (58%)	Transfer between learning activity and NoS (53%)	Lower cognitive process dimensions (72%)	Teacher- centered (61%)	Avg. 9 questions, mostly general reflection questions (57%)

^a Only articles with a conceptualization of NoS (n=55) are included in this overview.

Patterns between articles: the type of ER and the conceptualization of NoS

In the last step of this study, we conducted a comparative analysis of the synthesized data from both perspectives: *type of ER* and *conceptualization of NoS*, seeking alignment or discrepancies in patterns among both perspectives. The findings show that articles adhering to a more closed approach to conceptualizing NoS demonstrated similarities with articles adopting a teacher-centered perspective (Type 2) in defining ER (Figure 6).

Figure 6

Comparison of the Articles Adhering to Type 2 ER and a Closed Conceptualization of NoS

Type of ER	→	Meaning Explicit	of	Meaning Reflection	of	Cognitive Process Dimensions	Questioning Approach
Type 2: Teacher-centered	→	Instructional implications		Transfer between learning activity and NoS		Lower cognitive process dimensions	8 questions on average, mostly general reflection questions not related to NoS
Conceptualization of NoS	→	Meaning Explicit	of	Meaning Reflection	of	Cognitive Process Dimensions	Questioning Approach
Closed	→	Instructional implications		Transfer between learning activity and NoS		Lower cognitive process dimensions	9 questions on average, mostly general reflection questions not related to NoS

Additionally, articles adopting a mixed stance on conceptualizing NoS exhibited patterns akin to those of articles employing a student-centered approach to define ER (Figure 7).

Figure 7

Comparison of the Articles Adhering to Type 1 ER and a Mixed Conceptualization of NoS

Type of ER	→	Meaning Explicit	of	Meaning Reflection	of	Cognitive Process Dimensions	Questioning Approach
Type 1: Student-Centered	→	Planned		Transfer between learning activity and NoS		Higher cognitive process dimensions	10 questions on average, mostly specific convergent NoS questions
Conceptualization of NoS	→	Meaning Explicit	of	Meaning Reflection	of	Cognitive Process Dimensions	Questioning Approach
Mixed	→	Planned		Transfer between learning activity and NoS		Higher cognitive process dimensions	8 questions on average, mostly specific convergent NoS questions

Lastly, when examining the patterns within articles employing a more open approach to conceptualizing NoS, we observed a closer alignment with articles that employed a student-centered approach to define ER. Nevertheless, it is worth noting that these articles often framed their ER definitions in terms of lower cognitive process dimensions, a characteristic more commonly associated with teacher-centered definitions and not typical of student-centered ones (Figure 8).

Figure 8

Comparison of the Articles Adhering to Type 1 ER and an Open Conceptualization of NoS

Type of ER	Meaning Explicit	Meaning Reflection	Cognitive Process Dimensions	Questioning Approach
Type 1: Student-Centered	Planned	Transfer between learning activity and NoS	Higher cognitive process dimensions	10 questions on average, mostly specific convergent NoS questions
Conceptualization of NoS	Meaning Explicit	Meaning Reflection	Cognitive Process Dimensions	Questioning Approach
Open	Planned	Transfer between learning activity and NoS	Lower cognitive process dimensions	13 questions on average, mostly specific convergent NoS questions

Discussion

In this section, we delve into the key findings of our study and discuss their implications within the context of ER in NoS educational literature.

NoS Questioning Approach

The findings of our study highlight the significance given to asking questions to evoke ER about NoS. When analyzing all 60 articles, only 13 articles did not mention any questions. Building on Kruse et al.'s (2020) research, our analysis categorized questions into three types: *General Reflection*, *General NoS question*, *Specific NoS Question*. The findings of our study revealed a prominent emphasis on general reflection questions such as, “*How did you develop this inquiry plan?*” (Zion et al., 2020). These questions, however, tend to convey NoS ideas implicitly rather than explicitly. It is crucial for future research in this area to align with the intended explicitness of ER by employing more specific NoS questions (Kruse et al., 2020). These specific NoS questions are according to (Voss et al., 2022) best asked in a convergent way to achieve consensus view answers from students (e.g. “*Why is well-established science knowledge often so durable and enduring?*” (Parrish et al., 2020)) or in a divergent way to achieve a wider range of NoS views (e.g. “*What makes a good scientist?*” (Dunlop and De Schrijver, 2020)). Such approaches hold promise for enhancing the effectiveness of NoS education and fostering a deeper understanding of NoS concepts among learners (Kruse et al., 2020; Voss et al., 2022). Only 34% of the questions analyzed were classified as either convergent (21%) or divergent (13%). Consequently, 66% of the

questions used across all articles were less effective in promoting deeper engagement with NoS concepts, as defined by Kruse et al. (2020) and Voss et al. (2022).

Conceptualization of NoS

Our systematic review identified eight distinct NoS frameworks, categorized into two groups: those aligning with the NoS consensus view and those not. The prevalence of articles adhering to the consensus view underscores its dominance in research, primarily utilizing widely accepted NoS principles.

Regarding the notion that consensus view frameworks are oversimplified, closed and rigid toward defining NoS (Allchin, 2011, 2017; Clough, 2007; Irzik and Nola, 2011, 2014; Matthews, 2012), our study partially supports this. The McComas NoS ideas, NRC, and NGSS frameworks fall under the ‘mixed towards defining NoS’ category, while the Lederman 7 and NSTA are categorized as *closed towards defining NoS*. None of the consensus view NoS frameworks were categorized as *open towards defining NoS*, therefore, offering partial confirmation.

This pattern implies that consensus-based frameworks, while providing structure and pedagogical clarity, may simultaneously constrain the complexity and diversity of scientific practices presented in classrooms. As such, there appears to be a trade-off between accessibility and epistemic richness, where pedagogical clarity may come at the expense of conceptual depth and inclusiveness. This systematic review also reveals that many articles on ER in NoS education predominantly employed NoS frameworks with relatively closed NoS definitions. This trend may prompt important discussions about how using different NoS frameworks affects the depth and scope of ER in NoS education.

These findings hold significant implications for researchers and educators in NoS education. Researchers should be aware of how selected NoS frameworks influence the interpretation and implementation of ER. Educators should consider these findings when designing NoS education curricula, acknowledging that *closed* frameworks dominate educational practice. However, the potential benefits of integrating *mixed* and *open* frameworks to foster nuanced discussions and understanding of NoS should not be underestimated.

Data Synthesis

RQ1.1: The Type of ER vs the Questioning Approach

The key findings from our analysis reinforce the notion proposed by Boven et al. (2025) that articles having student-centered definitions of ER (Type 1 ER) have distinct advantages over their teacher-centered (Type 2 ER) counterparts. Firstly, we observed that articles employing a student-centered definition of ER exhibited a propensity to ask a significantly higher number of questions aimed at promoting ER in the context of NoS. This quantitative difference in the use of questions underscores the greater emphasis placed on active engagement and reflective practices within the articles with a student-centered approach to ER (Type 1 ER). Secondly, our analysis revealed that articles embracing a student-centered definition of ER not only posed more questions but also asked more effective questions, in particular, focusing on specific convergent NoS questions (Kruse et al., 2020; Voss et al., 2022).

In contrast, articles that adhered to a teacher-centered definition of ER asked significantly fewer questions, with most being general reflection questions, which are, according to Kruse et al. (2020), less effective. The predominance of general reflection questions, which are not explicitly related to NoS, indicates a potential misalignment between the questions posed and the specific goals

of NoS education. This suggests that articles with teacher-centered definitions of ER may not effectively promote in-depth, NoS-focused reflection among students.

In sum, our findings provide the confirmation that supports the superiority of articles utilizing student-centered definitions of ER (Type 1 ER). The richer question-asking environment and the focus on specific, convergent NoS questions underscore the effectiveness of this approach in promoting ER about NoS.

RQ1.2: The Type of ER vs the Conceptualization of NoS

Our analysis of the relationship between the type of ER and the conceptualization of NoS in 60 articles revealed interesting insights. Contrary to our initial expectation, which posited that articles using student- versus teacher-centered definitions for ER might conceptualize NoS differently, we found that both types of ER predominantly align with *closed* frameworks for defining NoS.

Additionally, our analysis revealed that among student-centered articles, 38% adhered to mixed or open NoS frameworks, whereas only 26% of teacher-centered articles did so. This difference suggests that student-centered approaches may offer a slightly greater diversity in conceptualizing NoS compared to teacher-centered approaches.

These findings underscore the importance of critically evaluating the relationship between ER types and NoS conceptualizations. While the alignment between ER types and NoS conceptualization is not absolute, it does provide valuable insights into prevailing trends in NoS education literature.

R.Q.2: The Conceptualization of NoS vs the Four Analytical Themes of ER and the Questioning Approach

The findings from our analysis show that articles having an open or mixed approach to conceptualizing NoS have distinct advantages over their closed approach counterparts. Firstly, we observed that articles employing an open or mixed conceptualization of NoS exhibited a propensity to ask a significantly higher number of questions aimed at promoting ER in the context of NoS compared to the articles with a closed conceptualization of NoS ($p=0.0001$). This quantitative difference in the use of questions underscores the greater emphasis placed on active engagement and reflective practices within the articles with an open or mixed conceptualization of NoS. Secondly, our analysis revealed that articles embracing an open or mixed conceptualization of NoS not only posed more questions but also asked more effective questions, in particular, focusing on specific convergent NoS questions (Kruse et al., 2020; Voss et al., 2022). In contrast, articles that adhered to a closed conceptualization of NoS asked significantly fewer questions, with most being general reflection questions, which are, according to Kruse et al. (2020), less effective.

Moreover, articles with an open conceptualization of NoS predominantly defined ER in a student-centered manner, which aligns with the preferred approach. Conversely, articles with a mixed conceptualization of NoS tended to emphasize ER on higher cognitive process dimensions, offering a potential benefit in promoting deeper engagement with NoS concepts. In contrast, articles with a closed conceptualization of NoS often adopted a less preferred approach, defining ER in a teacher-centered manner and focusing on lower cognitive process dimensions.

In conclusion, our analysis highlights the advantages of articles with an open or mixed approach to conceptualizing NoS over their closed approach counterparts.

Patterns Between Articles: the Type of ER and the Conceptualization of NoS

The comparisons drawn between our findings on *the type of ER* and *the conceptualization of NoS* reveal a compelling interplay between both. These insights help us delve into the nuanced dynamics that shape NoS education and encourage further exploration of their implications for both science education and research.

On the one hand, we observe an alignment between more closed NoS frameworks and teacher-centered ER definitions. This suggests that articles embracing established and conventional NoS tenets often favor a teacher-centered approach to ER. This alignment emphasizes the strong connection between traditional NoS conceptualizations and pedagogical practices that emphasize the role of the teacher in guiding students' reflection on NoS. This tendency may be rooted in the notion that teacher-centered approaches are generally seen as more prescriptive and didactic, aligning with more traditional and restrictive views of NoS.

On the other hand, articles adopting a mixed or open stance on NoS tend to align more with articles that have a student-centered perspective on ER. This suggests that these open and mixed frameworks, with their dynamic and more flexible NoS conceptualizations, resonate with the principles of student-centered ER. This alignment emphasizes the strong connection between innovative, open NoS conceptualizations and pedagogical practices that prioritize students.

These findings call for a shift in how researchers report about NoS interventions and instruction, away from rigid, transmissive models of science education and toward more student-centered, reflective approaches. In the hope that this encourages teachers, teacher educators, and curriculum developers to foster classroom environments that emphasize:

- Targeted NoS questioning that invites deep reflection, avoiding general reflection prompts;
- Open conceptualization of science, where science is not portrayed as a fixed body of facts but as a social, human, and collaborative enterprise;
- Student agency, enabling learners to grapple with the meaning, implications, and boundaries of science themselves, rather than receiving these ideas prepackaged.

The findings translate into clear guidance for the design of curricula and the formation of educational policy. Firstly, curriculum designers and educators should explicitly prioritize the use of Mixed and Open NoS frameworks to structure content, as these intrinsically harmonize with superior, student-centered pedagogical practices. Secondly, to translate the theoretical explicitness of ER into practice, instructional materials must feature a significantly higher frequency of specific NoS questions (e.g., Convergent or Divergent types) and actively minimize the use of non-NoS-related General Reflection questions. Finally, educational policies should critically re-evaluate existing standards that rely on purely Closed NoS conceptualizations. The data suggests that for NoS education to effectively evolve, the field must adopt frameworks that accommodate the nuance and complexity necessary to support true student-centered, reflective practice, thereby driving systemic educational improvements.

Limitations

While this study offers insights into the relationship between the conceptualization of ER, NoS frameworks, and questioning approaches, several limitations must be acknowledged.

First, although our analysis systematically identified and categorized the quantity and types of questions used to evoke ER, we did not assess the quality or classroom implementation of these questions. The presence of specific, divergent or convergent NoS questions in an article does not necessarily indicate their effective use in practice. It is unlikely that all questions asked by teachers during interventions or NoS lessons are reported in publications, given the dynamic and interactive nature of classroom discourse, which often includes follow-up questions, clarifications, extensions,

and spontaneous prompts. Without observational or empirical data on how these questions are posed, received, and discussed in actual educational settings, conclusions regarding their pedagogical effectiveness remain necessarily limited.

Second, our classification of ER definitions into *student-centered* and *teacher-centered* types, as well as the categorization of NoS frameworks as *open*, *mixed*, or *closed*, necessarily involved an element of interpretive judgment. Although we employed expert content validation to strengthen reliability, these categories are not always rigid or mutually exclusive. In several cases, articles demonstrated hybrid characteristics, making classification complex. This subjectivity may have influenced the patterns observed and calls for cautious interpretation of our typologies.

Third, this study does not fully consider the contextual diversity in which ER and NoS education occur. The selected articles span a range of countries, educational levels, and instructional settings, yet our analysis did not explicitly differentiate findings based on these variables. By not controlling for or analyzing these contextual factors, our synthesis may obscure important nuances and limit the generalizability of our conclusions across different educational environments.

Taken together, these limitations suggest that further empirical and context-sensitive investigations are necessary to deepen and validate these insights.

Future Research

Our study opens avenues for future research in the realm of NoS education and ER. There are four key areas that warrant further investigation.

Firstly, conducting a **comparative analysis** of NoS education approaches using closed, mixed and open NoS conceptualizations can shed light on the benefits and challenges associated with each. Examining the extent to which NoS frameworks influence ER practices and student engagement can deepen our understanding of effective pedagogical strategies.

Secondly, empirical **longitudinal studies** can offer insights into the long-term impact of various NoS conceptualizations and ER definitions on students' NoS understanding and their development as reflective thinkers. Tracking students over time and analyzing their progress can provide a comprehensive view of NoS education outcomes.

Thirdly, investigating the **evolution of NoS conceptualizations** and their implications for science education practices is a promising area of research. How and why NoS conceptualization has evolved, and how these changes have influenced ER approaches, is a topic that warrants exploration.

Finally, research examining the implications of NoS conceptualization and ER definitions for **educational policies and curricula** is essential. Understanding how these factors impact the design and implementation of science education programs can inform policy decisions and improve the quality of NoS education.

Conclusion

In this systematic review, we have delved into the intricate relationship between the conceptualization of NoS, the types of ER, and their implications for science education. Our study has unveiled critical insights into the way NoS education is approached and practiced, focusing on the significance of the questioning approach to evoke ER about NoS and the interplay between the type of ER, as student- or teacher-centered, and the conceptualization of NoS.

Notably, we observed that articles that embrace student-centered definitions of ER demonstrated some advantages over their teacher-centered counterparts. They asked more questions,

particularly those aligned with specific convergent NoS aspects, fostering a more engaging and reflective environment within NoS education (Kruse et al., 2020).

Furthermore, our exploration into the world of NoS conceptualizations revealed the dominance of closed NoS frameworks that align with teacher-centered ER definitions. In contrast, the less frequently used, but more open and mixed NoS frameworks harmonize with a student-centered approach to ER. In conclusion, our study underscores the need for ongoing research and discussion surrounding NoS education. Perhaps the era of traditional, closed approaches to NoS is coming to an end, paving the way for more open or mixed frameworks in the future. We can't help but wonder—if we were to conduct the same study in ten years, what results would we find?

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