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ARTICLE

A Comparative Epistemic Network Analysis of the Nature of Science in Turkish National Physics Curriculum and International Baccalaureate Diploma Programme Physics Curriculum

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Abstract
This study aimed to analyze and compare the nature of science (NOS) aspects represented in the most recent editions of the International Baccalaureate Diploma Programme (IB DP) physics curriculum and the Turkish national physics curriculum. The Family Resemblance Approach (FRA) was employed as the theoretical framework for identifying and coding the NOS aspects, while epistemic network analysis (ENA) was used to model and compare the relational structure among these aspects across the two curricula. The findings showed that both curricula predominantly represented NOS through the cognitive-epistemic categories in the FRA, which reflects the global trend of underemphasizing the social-institutional categories of science in K-12 science curricula and textbooks. The Turkish physics curriculum concentrated its references to NOS in the scientific practices and social values of science categories. The most critical finding was the lack of any reference to the FRA's social certification and dissemination category in the Turkish physics curriculum. The ENA results revealed that the IB DP physics curriculum offers a more holistic epistemic network structure by establishing strong connections between the aims and values of science and the scientific methodology. The social-institutional categories, on the other hand, were positioned on the periphery of the network and disconnected in both curricula. Overall, these findings indicated that the Turkish curriculum risks presenting physics as a narrowly framed discipline, detached from its institutional, ethical, and philosophical context, while the IB DP curriculum offered a more holistic epistemic network by establishing stronger connections between the aims and values of science and its methodology.

Keywords Nature of science · Physics education · Curriculum · Family resemblance approach · Epistemic network analysis

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1 Introduction

In science education, one of the fundamental components of educating students to be scientifically literate is for them to develop a sophisticated understanding of the nature of science (NOS) (Lederman, 1992). The concept of scientific literacy, a central goal of science education worldwide, is defined as the capacity of citizens to engage thoughtfully and critically with science-related issues in order to make informed decisions (Osborne, 2023). A vital component of this is an advanced understanding of the NOS, which extends beyond scientific content to include how knowledge is constructed and justified. In today's era of rapidly advancing technology and widespread digital information, including content generated by artificial intelligence, gaining this holistic perspective of science is more critical than ever. Comprehensive frameworks such as the Family Resemblance Approach (FRA) emphasize not only the cognitive-epistemic features of science but also its vital social-institutional dimensions, which are essential for students to critically evaluate the origin, validity, and reliability of scientific claims in the modern public sphere (Erduran & Dagher, 2014). As a construct, the NOS encompasses the epistemological and ontological principles underlying scientific knowledge, the evolution of scientific methods, and the sociocultural context of science as an institution. Since the 1980 s, the importance and central role of the NOS in science teaching and learning have been extensively emphasized in both the literature and curriculum documents (Driver et al., 1996; McComas et al., 1998). Research on the NOS in science education from the past to the present has focused on various lines of inquiry such as students' conceptions of the NOS (Cheung & Erduran, 2023), the most effective teaching methods for developing a conceptual NOS understanding (e.g., the effectiveness of explicit-reflective approaches) (e.g., Lederman, 1992), and the representation of various NOS aspects in science textbooks (e.g., Park et al., 2019).

The limitations of traditionally accepted views of the NOS in the literature, for example the consensus view (Lederman et al., 2002), in fully capturing the rich and dynamic structure of scientific practice, along with their susceptibility to ongoing philosophical debates, have prompted scholars over the past two decades to seek more comprehensive and holistic models for characterizing the NOS (Allchin, 2011; Matthews, 2012). In response to this methodological need, the FRA was first introduced in the philosophy of science context (Irzik & Nola, 2011, 2014). Erduran and Dagher (2014) expanded and reconceptualized the FRA to provide a more comprehensive account of the NOS. The FRA aimed to holistically conceptualize the NOS as two overarching interacting systems: the cognitive-epistemic system and the social-institutional system. Thus, the FRA provides a powerful analytical framework for in-depth contextualization of various aspects of the NOS in a holistic way, offering more than a list of isolated principles (Erduran & Dagher, 2014).

In recent years, international curriculum analyses using the FRA framework have revealed a striking common trend in science education. Studies show that science curricula in many countries primarily focused on the cognitive-epistemic dimensions of the NOS, yet the social-institutional aspects, which encompass the social, ethical, economic, and political contexts of science, were not adequately or consistently represented (e.g., Cheung, 2020; Kaya & Erduran, 2016; Xie et al., 2025). This situation increases the risk of students viewing science solely as a body of knowledge and methods, leading to a lack of understanding of the social context of science as a human enterprise, which is a fundamental dimension of scientific literacy.

The significance of the present study stems from the need for comparative curriculum analyses that systematically examine how the NOS is represented across different educational settings and cultural contexts. Comparative studies play a central role in the science education literature by enabling the identification of shared patterns and contextual differences in curricular priorities. Since its foundation in 1968, the International Baccalaureate (IB) programs for K-12 education have been offered in many countries worldwide. For example, targeting students aged 16–19 (i.e., upper secondary), the IB Diploma Programme (DP) has been implemented in 155 different countries across the world in 2023 (International Baccalaureate Organization [IBO], 2025a). Despite its widespread recognition and implementation both in Türkiye and internationally, the IB DP physics curriculum has not yet been examined in terms of its inclusion of the NOS, to the best of the authors' knowledge. In addition, after years of work with different stakeholders and taking into consideration the developments in educational research and practice, Türkiye has recently introduced a new national educational model titled as the Maarif Model and substantially restructured and updated its entire K-12 curricula including the physics curriculum (Ministry of National Education [MoNE], 2024). However, it remains unclear to what extent and in what ways the new national physics curriculum in Türkiye incorporated the NOS aspects. In response to these significant gaps in the literature, this comparative study aimed to investigate the representations of the NOS in the Turkish national physics curriculum and the IB DP physics curriculum by employing the FRA as the analytical lens. Through systematic content analysis, the study aimed to quantify the coverage of the cognitive-epistemic and social-institutional aspects of science in each curriculum and to utilize epistemic network analysis (ENA) to visualize and compare the networked relationships and overall coherence among the NOS aspects delineated by the FRA categories. By doing so, this study provides a structured comparison of the national and international curriculum documents, contributing to the literature with the first FRA-based analysis of the NOS representations in the recent editions of the IB DP and Turkish physics curriculum. Examining the IB DP and Turkish contexts regarding the incorporation of the NOS aspects into the physics curriculum is timely and particularly relevant. The IB DP has a long history of being a transnational educational program implemented in diverse cultural settings and political contexts, and requires distinctive assessment strategies and contemporary pedagogical approaches (Dickson et al., 2018). On the other hand, the Turkish educational system has been strictly centralized with the K-12 curricula designed and enforced by the MoNE and public schools have little to no flexibility in adapting curricula based on their needs. In contrast to the IB DP, high-stakes assessments also play a very important role in the Turkish context where all students need to take a series of comprehensive exams covering multiple subject areas after graduating from high school to be qualified for university admission (Dickson et al., 2018). Therefore, comparing the IB DP and Turkish national physics curricula can illuminate whether and how NOS representations differ under contrasting governance structures (transnational vs. centralized) and assessment approaches (school-based/moderated vs. high-stakes external exams), and what these differences imply for pedagogical expectations and opportunities to learn about the NOS. Specifically, this study sought to address the following research questions:

1. To what extent do the Turkish national physics curriculum and the IB DP physics curriculum incorporate the categories belonging to the cognitive-epistemic and socio-institutional systems of the FRA?

2. How do the epistemic network structures compare between the cognitive-epistemic and social-institutional systems of the FRA in the Turkish national physics curriculum and the IB DP physics curriculum?

1.1 Significance of the Study

This study addresses a critical gap in science education literature by rigorously examining the representation of the NOS in two distinct curriculum frameworks. To the best of the authors' knowledge, this work represents a rare and methodologically rigorous attempt to combine the FRA with ENA for cross-cultural comparison of NOS representations in secondary science curricula. This comparison is essential for revealing whether and how different curriculum governance traditions (i.e., national policy-driven versus international inquiry-based) privilege particular aspects of the NOS, thereby offering vital insights for educational policy internationally. Furthermore, this study offers crucial, data-driven insights for future curriculum reform efforts in Türkiye by benchmarking the national curriculum's representation of the NOS against that of the internationally recognized IB Diploma Programme. The physics curriculum was selected as the disciplinary focus of this investigation for two reasons. First, a critical gap was identified in the existing literature: although curricular NOS analyses have been conducted for various science disciplines such as chemistry (e.g., Bytyqi-Damoni et al., 2025; Deng et al., 2025), biology (e.g., Cheung, 2020; Li et al., 2025) and physics (e.g., Caramaschi et al., 2022, Park et al., 2019), the authors were unable to find any systematic study examining the IB DP physics curriculum's explicit or implicit representations of NOS tenets. Focusing on physics enabled the researchers to address this unexamined area directly. Second, as a foundational discipline with a rich and well-documented history of scientific revolutions and paradigm shifts (Kuhn, 1970), physics offers particularly fertile ground for examining how NOS is represented in curricula. Its methodological diversity, spanning theoretical modeling, experimental inquiry, and mathematical abstraction, makes it a meaningful context for FRA-based analysis. Furthermore, given the widely acknowledged domain-specific nature of NOS (e.g., Erduran & Dagher, 2014), focusing the analysis on a single discipline was necessary to maintain analytical coherence and rigor.

2 Literature Review

2.1 NOS in K-12 Science Education: Historical and Contemporary Perspectives

Recognized as a fundamental component of scientific literacy, facilitating students' learning of the NOS has become an important goal of science education (Cheung, 2020; Ramnarain, 2024). Understanding the NOS is essential for students to grasp how scientific knowledge is produced and developed within the scientific community and how science interacts with the broader society (Gao et al., 2025). Science educators and standards documents worldwide agree that students should learn about the content of science (e.g., Newton's laws of motion) and the nature of scientific knowledge (e.g., theory-ladenness of observations in science) (Irzik & Nola, 2011).

Research on the NOS dates back to the 1970s (e.g., Billeh & Hasan, 1975; Herron, 1971). The developments of this research domain were closely linked to various perspectives and debates in the philosophy, history, and sociology of science. However, the

inability of these fields to reach a definitive agreement on the NOS has given rise to a fundamental difficulty referred to in the literature as the problem of definition or demarcation (Irzik & Nola, 2011). This theoretical uncertainty has led science education researchers to adopt a consensus view that focuses on teaching the NOS characteristics based on broad agreement rather than engaging in philosophical debates about the NOS (Lederman et al., 2002). This consensus has long guided NOS teaching in science education, presenting the *widely accepted* NOS characteristics among scientists, philosophers, and educators within a framework. These characteristics included portraying science as being empirical, involving creativity, not being entirely objective, and being theory- and culture-laden (Abd-El-Khalick, 2005). Initially, the consensus view was functional in terms of teacher training and the creation of assessment tools. Over time, however, it has faced significant criticisms. Specifically, it has been criticized for being too generalized and not differentiated enough. It has been said to fail to reflect the inherent variability of science across different disciplines, such as physics, biology, and chemistry (Fricke & Reinisch, 2023; Reinisch & Fricke, 2022). These criticisms have brought forth approaches that address the NOS through critical thinking and inquiry skills (Lederman et al., 2014) and models that focus on scientific practices beyond scientific knowledge (Erduran & Dagher, 2014; Kaya & Erduran, 2016).

Recent research emphasized instilling a more holistic and deeper understanding of the NOS among learners, focusing on not only its cognitive-epistemic aspects (e.g., tentativeness of scientific knowledge), but also its social-institutional dimensions (e.g., scientists work in certain institutional and political contexts, and require funding for their studies). This approach aligns with international reforms that highlighted the significance of the 21st-century skills, such as critical thinking and problem-solving, to attain scientific literacy objectives (Dickson et al., 2018). One of the most comprehensive theoretical conceptualizations in response to this need has been the FRA, which portrays science through interdisciplinary similarities and differences rather than uniform characteristics. In this vein, current NOS research has shifted toward utilizing more holistic frameworks, such as the FRA, that can address the applications, values, and social context of science in a coherent and integrated manner (e.g., Kaya et al., 2025; Mork et al., 2022).

One prominent theme in NOS-oriented literature has been examining students' understanding and alternative conceptions of the NOS aspects in formal and informal learning environments. These studies aimed to reveal students' perceptions and mental models related to the fundamental NOS dimensions, including the tentativeness of scientific knowledge, the diversity of scientific methodology, empirical nature of science, and the role of creativity and imagination in generating scientific knowledge (Khishfe & Abd-El-Khalick, 2002; Lederman et al., 2014). Recent scholarship, drawing on the FRA, has further expanded this research line to investigate how students construct multimodal representations of scientific practices and methods, offering novel analytical frameworks for comprehensive assessment (Cheung & Erduran, 2025). A second research theme focused on how the NOS can be taught more effectively. Research suggests that implicitly teaching about the NOS in science lessons is insufficient for facilitating a conceptual NOS understanding among learners (Abd-El-Khalick & Lederman, 2000; Khishfe & Abd-El-Khalick, 2002). Instead, explicit-reflective teaching approaches that address the NOS aspects as a standalone learning goal were found to be more effective (Deng et al., 2026; Park et al., 2020). Concurrently, studies examining the representation of the NOS in science textbooks and curriculum documents have emerged as another important research theme. Such studies have revealed that the NOS-related concepts were generally addressed in a very limited, superficial, or inconsistent manner (e.g., Yeh et al., 2023). Moreover, to ensure

a linguistically inclusive environment in diverse contexts, recent FRA-based research has explored the creation of translanguaging spaces in multilingual classrooms to facilitate students' explicit reflection and meaning-making of the NOS (Cheung et al., 2026).

2.2 The Conceptualization of Nature of Science (NOS) and the Shift to the Family Resemblance Approach (FRA)

For several decades, the inclusion of common NOS aspects in science curricula has been advocated worldwide, recognizing its critical role in fostering scientific literacy and enabling students to make informed decisions about socio-scientific issues (AAAS, 1990; Khishfe, 2023; NRC, 1996). However, reaching a consensus on a definition of the NOS for educational purposes has proven challenging. Traditionally, the field has adopted the "consensus view" (Lederman & Lederman, 2014), which focuses on a limited list of generalized aspects of the NOS that are considered essential for all students to learn (e.g., tentativeness of scientific knowledge, empirical nature of science, subjectivity, theory-ladenness).

Abd-El-Khalick (2012), Lederman et al. (2002), and McComas (1998) are among the key proponents of the consensus view, which holds that the nature of scientific knowledge is linked to seven epistemic aspects: the tentative nature of knowledge, the distinction between observation and inference, the theory-laden nature of scientific inquiry, the creative and imaginative dimensions of scientific work, the social and cultural embeddedness of science, the difference between scientific theories and laws, and the questioning of the myth of a universal scientific method. While these dimensions have been generally accepted in science education, they were criticized for failing to reflect the full complexity of scientific practice as a collective human enterprise (Allchin, 2011). Critics have argued that the consensus view oversimplifies science by reducing it to a list of principles, disregarding the epistemic, cognitive, and social dimensions of scientific work, and remaining insensitive to interdisciplinary differences (Allchin, 2011; Matthews, 2012). As a result, alternative frameworks have been developed in response to these limitations. Allchin (2011) proposed the Whole Science Approach, which better reflects the multidimensional nature of scientific practice, arguing that the consensus view leaves out important dimensions of science such as self-correcting mechanisms (e.g., peer review) and economic factors. However, this approach has also been criticized for lacking a systematic structure. Matthews (2012) proposed the Features of Science framework, offering a broader conceptualization that encompasses dimensions such as idealization, models, values, mathematization, worldviews, feminism, realism, and constructivism. However, as Erduran and Dagher (2014) point out, this framework also needs further development because it does not clearly state the rational basis on which it is based. All these accumulated criticisms have highlighted the need for a more systematic and comprehensive conceptualization of the NOS and paved the way for the development of the Family Resemblance Approach (FRA). In this context, although the FRA offers a thorough and systematic approach to analyzing a wide range of NOS representations in curriculum documents, it is crucial to recognize that other critical and philosophical viewpoints have also influenced the scholarly discourse on the NOS in science education. For example, feminist philosophers of science such as Haraway (1988) and Harding (1991) have challenged the notion of science as a value-neutral and universal enterprise. They argued that scientific knowledge is situated and influenced by gender, culture, and power relations. Bang and Marin (2015) have also emphasized the importance of considering diverse cultural and indigenous viewpoints in science education, raising the question of whether all forms of knowledge are equally

considered scientific. These perspectives draw attention to the socio-political dimensions of science that are often underrepresented in mainstream curriculum frameworks. While this study does not explicitly engage with these critical traditions, we recognize their significance for achieving a more comprehensive understanding of the NOS. We selected the FRA as the analytical framework for this study because it offers a structured, empirically applicable, and widely validated approach to examining the cognitive-epistemic and social-institutional dimensions of the NOS in curriculum documents (Erduran & Dagher, 2014).

2.3 Reconceptualizing the NOS: The Family Resemblance Approach (FRA)

The FRA is a robust theoretical framework developed in response to the limitations of traditional approaches to delineating the NOS and the challenges of defining science as a whole. First adapted to science education by Irzik and Nola (2011), the FRA conceptualizes science as a family with shared and variable characteristics, drawing inspiration from Ludwig Wittgenstein's philosophical concept rather than from a rigid definition. The FRA offers a more comprehensive model that can account for natural and expected differences among scientific disciplines (Irzik & Nola, 2011). Erduran and Dagher (2014) further developed this approach in the context of science education, synthesizing and extending Irzik and Nola's FRA to make it more applicable to teaching and learning contexts. Overall, the FRA is a significant theoretical framework because it portrays science more comprehensively and multidimensionally than most traditional NOS frameworks do. It provides a powerful tool for analyzing the NOS aspects of science curricula and textbooks by taking into account cognitive, epistemic, social, and institutional dimensions (Kurt & Kaya, 2025).

As shown in Fig. 1, the FRA framework defines the NOS through a broad range of categories grouped under two main systems (Erduran & Dagher, 2014):

Cognitive-epistemic system: It focuses on the internal workings of scientific knowledge production, structure, and validity. Essentially, it covers the characteristics and processes that science possesses as a field of knowledge and a cognitive endeavor. The cognitive-epistemic aspect consists of the following four categories:

1. Aims and values: The fundamental objectives of scientific research and the values that guide the achievement of these objectives.
2. Methods and methodological rules: The set of methods, approaches, and guidelines that scientists adhere to when conducting research. In other words, numerous methods exist in science, which vary across disciplines.
3. Scientific practices: The scientific enterprise includes a number of different cognitive, epistemic, and discursive practices.
4. Scientific knowledge: Scientific knowledge is a product of science that includes characteristics such as being empirically based, yet being open to revision based on new evidence.

Social-institutional system: This system ensures that science is understood as a collective human activity and a socially established institution that interacts with society. It addresses not only the production and validation of scientific knowledge but also how

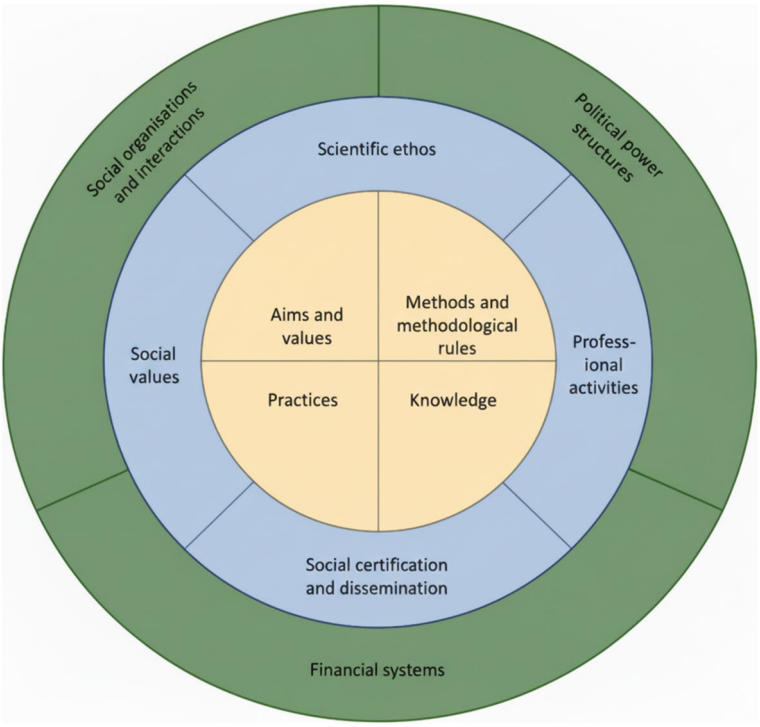


Fig. 1 The FRA wheel presents science as a cognitive-epistemic and social-institutional system (Erduran & Dagher, 2014)

scientists work as a community, how science is financed, and how society influences and accepts science. The social-institutional aspect of science consists of the following seven categories:

1. Professional activities: A scientist's work is diverse, and includes activities that facilitate the communication of their research. These activities include conference attendance and presentations, writing manuscripts for peer-reviewed journals, reviewing papers, and seeking funding.
2. Social certification and dissemination: The process by which the scientific community accepts scientific knowledge as valid and disseminates it to the general public.
3. Social values of science: The scientific enterprise encompasses various social values that influence and guide research, such as the impact of science on the environment and social responsibility.
4. Scientific ethos: Scientists are expected to adhere to the norms of the scientific community.
5. Social organizations and interactions: Institutions where scientists work and interact with each other (e.g., universities, research institutes, and laboratories).
6. Financial systems: The scientific enterprise is shaped by economic factors, particularly the provision and sources of research funding, which influence research priorities.

7. Political power structures: The scientific enterprise is shaped by the influence of governments and political authorities, particularly through science policy and the direction of research.

2.4 Analysis of NOS Representations through Content and Qualitative Approaches

A significant trend has emerged in studies using the FRA framework, which examined the integration of the NOS representations in science curricula and textbooks. These studies aimed to determine the extent to which educational materials reflected the cognitive, epistemic, social, and institutional aspects of the NOS. Examining the trends in curriculum analysis studies reveals a common pattern across different countries. Analyses of curricula in various contexts, including China (Gao et al., 2025; Xie et al., 2025), Brazil (Pimenta et al., 2026), Norway (Kostøl et al., 2023; Mork et al., 2022), and South Africa (Ramnarain, 2024), revealed that cognitive-epistemic aspects of the NOS were significantly more prevalent and detailed than the social-institutional aspects. This imbalance is particularly evident in the underrepresentation or sometimes complete omission of the social-institutional system categories, such as financial systems and political power structures, at the international level.

This trend is also consistent with findings from studies conducted in the Turkish context. Qualitative and content analyses of Turkish science education materials similarly point to a strong emphasis on the cognitive-epistemic aspects of science, often to the detriment of its social-institutional domain. For example, analyses of Turkish science curricula (Kaya & Erduran, 2016; Kurt & Kaya, 2025) and chemistry textbooks (Celik & Karatas, 2022) have consistently found a dominant focus on aspects like scientific practices and methods, while social dimensions such as political power structures and certification were scarce or completely absent. Specifically, a similar trend to that observed in other disciplines exists in the research findings of physics curriculum analysis studies. Xie et al. (2025) examined three different physics curriculum standards in China released over the past twenty years and found that the social-institutional system was consistently underrepresented. This system was particularly lacking in the categories of professional activities, social organizations and interactions, and financial systems. The analysis also revealed that connections within the cognitive-epistemic system were more prevalent and extensive than those within the social-institutional system (Xie et al., 2025). These results suggest that the NOS was primarily addressed in terms of the production and verification of knowledge in Chinese physics curricula, while the social and institutional context of science remained secondary. This trend has been similarly observed in studies conducted in different national and cultural contexts. For example, a study of the general relativity theory section in South Korean high school physics textbooks found that the NOS coverage focused on scientific knowledge and practices and the professional activities of scientists but underrepresented the social-institutional aspects of science (Park et al., 2019). This situation has been consistently reported in studies conducted in China, Kosovo, and Türkiye (Bytyqi-Damoni et al., 2025; Celik & Karatas, 2022; Xie et al., 2025).

Kaya et al. (2025) have previously conducted comprehensive comparative analyses, applying the FRA framework to the 2018 Turkish physics, chemistry, and biology curricula across grade levels; these curricula were later replaced by the current versions released in 2024. Consistent with the present findings, these prior studies established the consistent predominance of cognitive-epistemic categories over social-institutional aspects within the Turkish educational context. Our work builds upon this established

literature by offering the first application of ENA to the IB DP and Turkish physics curricula. Building on this line of research, the present study extends the application of the FRA framework to a new comparative context by examining the latest versions of the Turkish national physics curriculum and the internationally recognized IB DP physics curriculum. Through the use of ENA, this study moves beyond the valuable, yet limited, scope of analyses based on category frequencies, which were employed in earlier analyses of the Turkish context. In doing so, it enables a more nuanced examination of the interconnectedness and structural dynamics of NOS representations.

2.5 Modeling Relational Structure: The Use of Epistemic Network Analysis (ENA) in NOS Research

Studies using ENA demonstrated that the connections between the NOS categories primarily existed within the cognitive-epistemic system. These studies also showed that the social-institutional dimensions were not sufficiently integrated with other NOS elements (Cheung, 2020; Pimenta et al., 2026; Yeh et al., 2023). Overall, these findings suggest that the current approach to science education emphasizes the processes of knowledge production and verification while treating the social, political, and economic contexts of science as secondary. As a methodological approach introduced by Shaffer et al. (2016), ENA provides a critical advancement that complements traditional qualitative and content analysis methods by allowing researchers to model and quantify the relational structure and strength of connections among NOS categories, thereby moving beyond simple frequency counts.

Recent publications using ENA further illustrate its critical utility in revealing patterns of consistency and integration across different science curricula: Pimenta et al. (2026) used ENA to analyze the Brazilian Common Core Curriculum and found stronger network centrality for cognitive-epistemic categories. Xie et al. (2025) applied ENA to Chinese physics curriculum standards from 2001 to 2022, showing a steady increase in connections over time, but one that remained primarily within the cognitive-epistemic system. In chemistry education, Deng et al. (2025) used ENA to examine the Chinese General High School Chemistry Curriculum Standard, identifying inconsistencies and a lack of full coverage in the social-institutional system. Similarly, Gao et al. (2025) used ENA to examine the reformed Chinese biology curriculum and noted minimal focus on the social-institutional system. These ENA-based studies provide a strong methodological justification for the use of ENA in the present study, as this technique has the capacity to identify not only the presence of NOS dimensions but also their structural integration and consistency.

Building upon this existing literature, the current study addresses the critical gap identified by previous content-based analyses in Türkiye. While studies like Celik and Karatas (2022) have pointed out the dominance of the cognitive-epistemic system in Turkish science education, the structural coherence and relational strength among the NOS categories in the context of secondary science curricula have not been rigorously explored using advanced network modeling. Therefore, the present study provides the first ENA-based comparison between Turkish and IB DP physics curricula, offering a new, evidence-based understanding of the interconnectedness and holistic representation of the NOS aspects across national and international curricular contexts.

2.6 The IB Diploma Programme and the Turkish Context

This study aimed to examine the representation of the concepts relevant to the NOS, a fundamental component of scientific literacy, in two distinct educational programs: the IB DP physics curriculum and the Turkish national physics curriculum. These two programs provide a meaningful basis for a comparative analysis of how the NOS is conceptualized and reflected in the curriculum, given their different educational philosophies and institutional structures. To clarify the context of this comparison, it is essential to first present the general framework of both programs.

The IB is a global, non-profit organization that offers four challenging educational programs to schools worldwide including Primary Years Programme (PYP), Middle Years Programme (MYP), Diploma Programme (DP), and Career-related Programme (CP). The IB DP targets students aged 16–19 (i.e., upper elementary) and is positioned as a high school graduation qualification program, which has been recognized by many higher education institutions worldwide (Dickson et al., 2018; Kidson et al., 2019). The IB DP encompasses core subjects (e.g., theory of knowledge) and six subject groups (e.g., mathematics, sciences) (IBO, 2025b). The sciences subject group includes courses such as physics, biology, and computer science. Along with offering various courses rigorously developed for high school students, the IB DP also aims to develop students' twenty-first-century skills such as critical thinking and research skills. Past studies have examined the critical thinking skills of IB students compared to those of peers in national programs (e.g., Double et al., 2023). The IB DP uses a concept-driven, inquiry-based teaching approach that encourages interdisciplinary thinking (Dickson et al., 2018). The IB DP physics course typically spans a 2-year teaching period and is assessed through centralized examinations at the end of the program (IBO, 2023). Students take the course through either the Standard Level (SL) or the Higher Level (HL) options, which differ in terms of content depth and learning expectations. The HL level is distinguished by its more comprehensive subject content and higher cognitive demands. The IB DP physics curriculum guide examined in this study is the current version taught in schools today, which was assessed for the first time in 2025 (IBO, 2023).

In Turkey, science education has long been at the center of curriculum reforms aimed at increasing scientific literacy (Celik & Karatas, 2022; Wilkinson, 1999). Compulsory education in Turkey is structured as a 12-year system under the 4+4+4 model, with high school comprising the final 4 years designated as high school education. At this level, physics is taught as a standalone subject from grades 9 to 12. The secondary education physics curriculum analyzed in this study was prepared and published within the framework of the Maarif Model 2024 (MoNE, 2024). This new model aims to restructure curricula based not only on content transfer, but also on values, skills, and learning processes. In line with this model, the new national physics curriculum published in 2024 aims to facilitate experiential, contextual, and discovery-based learning. The curriculum clearly defines total hours through unit structures, learning outcomes, and timetables from 9 to 12th grade. This comparative analysis of two programs aims to reveal the extent to which the cognitive-epistemic and social-institutional system dimensions of NOS were represented in science education curriculum documents. The study contributes to the literature by revealing the similarities and differences in how a national and international curriculum incorporated the aspect of the NOS as framed in the FRA.

The curricular documents analyzed in this study are implemented in distinct educational settings in Türkiye. The IB DP is typically offered by private, foundation, or

specific high-profile public schools mostly serving students from higher socio-economic backgrounds, whereas the Turkish national curricula are implemented across all public high schools in Türkiye. These structural differences are further shaped by broader political and socio-cultural factors, including centralized curriculum governance in Türkiye and the national priorities that have historically influenced science education policy (MoNE, 2024). Structurally, the national curricula are characterized by detailed, content-heavy subject-matter coverage and are predominantly taught in Turkish. In contrast, the IB DP emphasizes conceptual understanding, inquiry-based learning, critical thinking, and Theory of Knowledge (TOK) integration, often using English as the primary language of instruction (Dickson et al., 2018). Regarding the prevalence of the IB DP in Türkiye, while its implementation remains limited, it is a popular international program among Turkish schools and offers a relevant international point of comparison for examining curriculum quality and NOS integration. Comparing it with the Turkish national curriculum therefore offers a productive analytical lens for identifying strengths and areas for improvement regarding meaningful NOS integration in both curricular contexts, with direct implications for curriculum reform efforts in Turkey (MoNE, 2024).

3 Methods

3.1 Research Design

This study employed a comparative, deductive content analysis design to examine the representations of the NOS aspects according to the FRA. Deductive content analysis is recommended when a predefined theoretical framework guides the analysis process (Elo & Kyngäs, 2008). Given the multidimensional and complex structure of the NOS, this study utilized the FRA as an analytical lens. This approach conceptualizes scientific knowledge, practices, and institutional structures as interrelated systems rather than treating science as merely a list of isolated characteristics (Erduran & Dagher, 2014). The present study adopted a mixed-methods approach integrating quantitative content analysis and quantitative epistemic network analysis (ENA) to reveal the representation frequencies of the NOS aspects and the structural relationships between them. ENA is a widely used analysis technique in the literature that enables the comparison of complex epistemic patterns by examining relational structures between codes (Shaffer et al., 2016).

3.2 Data Sources

The data sources in this study consisted of the curricula of two official physics teaching programs: one has been implemented internationally in many countries worldwide and the other nationally in Türkiye. Included in the scope of analysis were the IB DP physics curriculum, representing the international context (IBO, 2023), and the Turkish national physics curriculum (MoNE, (Ministry 2024), representing the national context. The entirety of both curriculum documents was analyzed in this study. Sentences constituted the unit of analysis. The aim was thus to examine both explicit and implicit representations of the NOS holistically across the entire curriculum.

The Turkish national curriculum covers the secondary education level from 9th to 12th grade and aims to help students construct their knowledge of physics experientially and through discovery, based on the fundamental approaches of the Turkey Century Education

Model. This program emphasizes values such as justice and altruism, as well as skills such as sustainability literacy, in addition to subject-specific content. In contrast, the IB DP Physics is a 2-year, globally recognized program for students aged 16–19. At the heart of the program are interdisciplinary components such as Theory of Knowledge (TOK) and Extended Essay (EE), and the subject is approached in a concept-based and research-based manner. The fact that both documents examined in this study are current editions ensures that the comparison is made in the context of contemporary educational policies. As seen in Table 1, the two curricula represent differing educational governance structures and pedagogical philosophies. While the Turkish national curriculum operates under a centralized system with a focus on delivering experiential, contextual, and discovery-based learning across grades 9 through 12, the IB DP is a global, concept-driven program for the 16–19 age group, strongly integrating with core components such as TOK and emphasizing an inquiry-based approach. The difference in the scope of content is also reflected in the teaching hours, with the IB DP's Higher Level (HL) option recommending 240 h (IBO, 2025b), which is higher than the Turkish curriculum's 144 h for the final two years (MoNE, 2024). This comparative study utilizes the distinctive philosophical and structural features of these two contemporary curricula to examine.

3.3 Data Analysis

Data analysis was conducted in a two-stage complementary process: deductive content analysis and ENA. First, the curriculum texts underwent a cognitive content analysis based on the FRA framework (Erduran & Dagher, 2014). All statements were coded by using the MAXQDA software. The FRA framework addresses the NOS through eleven distinct categories organized under two main systems: the cognitive-epistemic system and the social-institutional system. The cognitive-epistemic system includes categories such as the aims and values of science, methods and methodological rules, scientific practices, and scientific knowledge. The social-institutional system includes categories such as professional activities, social certification and dissemination, social values of science, scientific ethos, social organizations and interactions, financial systems, political power structures.

Two coders, the first and second author, independently coded the curriculum texts, and agreement statistics were calculated to determine inter-coder reliability. The analysis revealed a Cohen's Kappa reliability coefficient of.80 between coders, indicating a high level of agreement (Landis & Koch, 1977). The analysis followed a deductive approach in which all curricular statements were systematically examined against the predefined FRA categories. Each statement was read in its full context and evaluated for alignment with one or more FRA categories based on its underlying epistemological meaning rather than the presence of specific keywords. To illustrate, the IB DP statement "Classifying such observations and underlying patterns in the natural world is the essence of what scientists do, underpinned by the assumption that the universe exists as an external reality accessible to the human experience" (IBO, 2023, p. 6) was coded under both *Aims and Values of Science* and *Scientific Practices*, as it simultaneously reflects a normative orientation toward scientific activity and describes a core scientific practice. This example demonstrates the non-mutually exclusive nature of the coding process, whereby a single statement could be assigned to multiple categories where epistemologically warranted. No additional themes or categories emerged during the analysis; all coding decisions were anchored exclusively within the original

Table 1 Structural and contextual features of the analyzed curriculum documents

Feature	Turkish Physics Curriculum (2024)	IB DP Physics Guide (2023)
Publisher/Institution	Turkish Ministry of National Education (MoNE)	International Baccalaureate Organization (IBO)
Scope (Grade/Age Level)	Grades 9–12/Ages 15–18 (High School)	Grades 10–12/Ages 16–19 (High School)
Duration (Recommended Hours of Instruction)	Gr. 9–10: 144 Hours; Gr. 11–12: 288 Hours	Standard Level (SL): 150 Hours; Higher Level (HL): 240 Hours
Core Pedagogical Approach	Experiential, Contextual, and Discovery-Based Learning	Concept-Driven and Inquiry-Based Learning
Philosophical/Structural Focus	Values (e.g., justice, altruism), Skills, and Dispositions; Social-Emotional Learning Skills (e.g., self-regulation); Literacy Skills (e.g., data literacy)	Nature of Science (NOS), Core (Theory of Knowledge; Creativity, Activity, Service; Extended Essay)
Document Page Count	106	78

FRA framework as operationalized by Irzik and Nola (2011) and Erduran and Dagher (2014).

In the second stage, the coding data obtained from the content analysis was used as input for ENA. ENA was selected as the analytical approach for this study because it models the relational structure among co-occurring NOS categories within a given unit of analysis, moving beyond frequency counts. This capability aligns with the FRA's theoretical assumptions, which conceptualize NOS as an interconnected cognitive-epistemic and social-institutional system rather than as a collection of discrete elements (Erduran & Dagher, 2014). Previous studies combining FRA-based content analysis with ENA have also shown its effectiveness for this purpose (Caramaschi et al., 2022; Cheung, 2020; Xie et al., 2025). ENA, developed by Shaffer et al. (2016), was used in the related studies to examine the structural relationships and connection densities between the NOS categories that occur within the same text unit. In this study, ENA was utilized to compare the extent to which the NOS categories were interrelated within each curriculum, as well as the strength of connections between the cognitive-epistemic and social-institutional systems. The two analytical approaches, the FRA-based content analysis and ENA, served complementary functions in this study. The deductive content analysis based on the FRA determined which NOS categories were present in each curriculum and how frequently they were emphasized. This analysis yielded foundational descriptive data. Then, ENA used the coded data to model co-occurrence patterns among the categories. This quantified the strength of the connections between the NOS elements and revealed structural findings that frequency analysis alone could not capture. The network structures generated by the analysis were presented as models showing how well the curricula addressed different dimensions of the NOS holistically. This approach permitted the quantification not only of NOS category frequencies, but also of centrality and the strength of inter-system connections. The ENA analysis was conducted using the ENA web-based platform (https://www.epistemicnetwork.org), where network graphs were generated and interpreted. Prior to the ENA procedure, qualitative coding was carried out in MAXQDA. The coded text segments, along with their associated NOS codes, were exported and organized in an Excel spreadsheet, which served as the input for the ENA. The unit of analysis was defined as individual sentences to determine the textual scope within which code co-occurrences were recorded. A co-occurrence matrix was constructed from the coded data for each unit of analysis, quantifying how frequently any two NOS categories appeared together in the same sentence. The ENA algorithm was then used to aggregate and project these matrices into a two-dimensional space. This produced visual network models that allowed for direct comparison of the epistemic structures of the two curricula. Finally, we subjected the network centroids and connection weights to statistical comparison to identify significant structural differences between the IB DP and Turkish national physics curricula. In this process, the coded segments were treated as units of analysis, enabling an examination of the co-occurrence of NOS categories and the resulting connections between the cognitive-epistemic and social-institutional systems.

After coding the curriculum statements according to the predefined categories, the frequency of each category was calculated for both curricula. To examine whether the distribution of categories differed significantly between the IB DP Physics curriculum and the Turkish national physics curriculum, a chi-square test of independence was conducted.

4 Findings

The findings are presented in two sections corresponding to the research questions of the study. The first section addresses the extent to which categories belonging to the cognitive-epistemic and socio-institutional systems of the FRA were incorporated in the Turkish national physics curriculum and the IB DP physics curriculum. The second section focuses on a comparative analysis of the epistemic network structures of these two systems within and across the two curricula.

4.1 To what extent do the Turkish national physics curriculum and the IB DP physics curriculum incorporate the categories belonging to the cognitive-epistemic and socio-institutional systems of the FRA?

This study examined the representation of the NOS elements in the IB DP physics curriculum and the Turkish national physics curriculum using the FRA framework. An analysis of the total number of occurrences indicates that the Turkish national physics curriculum placed substantially more emphasis on the NOS aspects compared to the IB DP physics curriculum. Specifically, the Turkish national physics curriculum had a total of 1,558 coded instances related to the NOS, whereas the IB DP physics curriculum contained 868.

An examination of the general representation of the two main systems within the FRA reveals that cognitive-epistemic categories of science were dominant in both curricula. Specifically, 630 occurrences (73%) in the IB DP physics curriculum belonged to the cognitive-epistemic categories of science, while 238 occurrences (27%) belonged to the social-institutional categories of science. Similarly, the Turkish national physics curriculum demonstrated 1,076 occurrences (69%) in the cognitive-epistemic categories of science and 482 occurrences (31%) in the social-institutional categories of science (see Fig. 2). Figure 3 illustrates the comparative frequencies of the individual FRA categories across both curricula. The following sections detail the distribution of the eleven aspects across these two main categories.

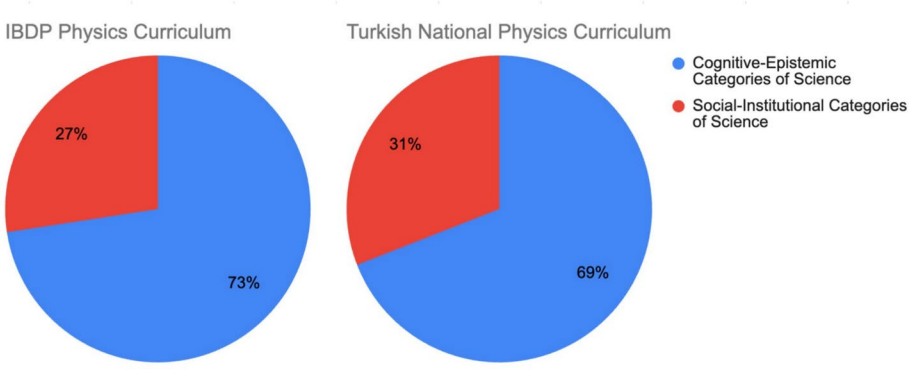


Fig. 2 Distribution of cognitive-epistemic and social-institutional NOS categories in the IB DP and Turkish national physics curricula

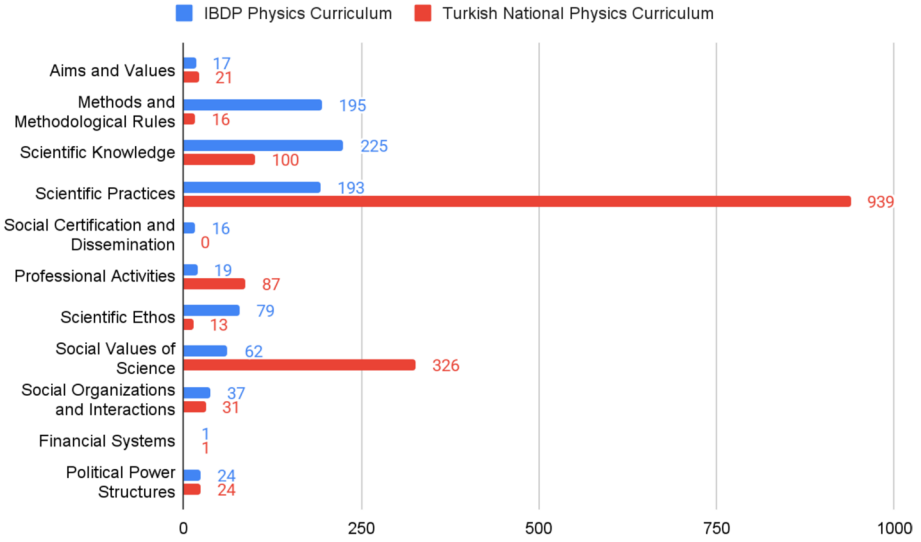


Fig. 3 Comparative frequencies of the FRA categories across the Turkish national physics curriculum and the IB DP physics curriculum

4.1.1 Distribution of the Cognitive-Epistemic Categories

The distribution across the cognitive-epistemic categories highlights distinct focus areas between the two curricula. This system comprises four categories: aims and values, methods and methodological rules, scientific knowledge, and scientific practices.

The Turkish national physics curriculum appeared to devote a significant portion of its cognitive-epistemic references to the scientific practices. This category was the most dominant, comprising 939 occurrences (60% of the total curriculum), which indicates a strong emphasis on scientific process skills and application-based learning. The other cognitive-epistemic categories were represented at much lower frequencies, followed by scientific knowledge ($n = 100$, 6%), aims and values ($n = 21$, 1%), and methods and methodological rules ($n = 16$, 1%).

In contrast, the IB DP physics curriculum demonstrated a more balanced representation across the cognitive-epistemic categories. The highest representation was found in the scientific knowledge category, with 225 occurrences (26%). This category was closely followed by the methods and methodological rules category, with 195 occurrences (22%), and the scientific practices category, with 193 occurrences (22%). The 195 occurrences in the methods and methodological rules category were notably higher than the 16 occurrences in the Turkish national physics curriculum, suggesting that the IB DP physics curriculum placed a stronger emphasis on the rules, logic, and stages of the scientific methodologies. The aims and values category had the fewest occurrences in both curricula ($n = 17$, 2% for the IB DP curriculum, and $n = 21$ (1%) for the Turkish curriculum).

4.1.2 Distribution of the Social-Institutional Categories

The social-institutional categories involved the social aspects of science, including social values of science, professional activities, scientific ethos, social organizations and interactions, and social certification and dissemination, political power structures, and financial systems.

The strength of the social-institutional system in the Turkish national physics curriculum was largely driven by the social values of the science category. With 326 occurrences (21% of the total curriculum), this category constituted the dominant share of social-institutional occurrences. This suggests that the Turkish national physics curriculum placed a notably higher emphasis on external scientific values, such as ethics, social responsibility, and sustainability, than the IB DP physics curriculum does. The professional activities category is also higher in the Turkish national physics curriculum ($n = 87$, 6%) than in the IB DP physics curriculum ($n = 19$, 2%).

The IB DP physics curriculum had the highest social-institutional representation in the scientific ethos category, with 79 occurrences (9%). This indicates that the IB DP physics curriculum focused approximately six times more on the internal norms and conduct of the scientific community than the Turkish national physics curriculum ($n = 13$; 1%). The social organizations and interactions category was represented at a relatively low level in both curricula with 37 occurrences (4%) in the IB DP physics curriculum and 31 occurrences (2%) in the Turkish national physics curriculum. The political power structures category was represented at a low frequency (24 occurrences for each; 3% and 2%, respectively) in both curricula. In both curricula, financial systems received only one occurrence, making it the category with the weakest representation overall. One particularly striking finding concerns the social certification and dissemination category. The Turkish national physics curriculum demonstrated no occurrences to this category, suggesting a complete omission of critical processes such as peer review, publication, and formal institutional mechanisms for validating scientific knowledge. In contrast, the IB DP physics curriculum includes 16 occurrences (2%) for this category, which is still quite low. Table 2 shows sample excerpts from the IB DP physics curriculum and the Turkish national physics curriculum illustrating these FRA categories. During the coding process, a single statement may be assigned to multiple categories if it reflects several categories of the FRA. For instance, the statement, "The aim of physics is to understand the relationship between space-time, matter, and energy based on observation and experimentation" (MoNE, 2024, p. 4), could be coded under the categories of aims and values, scientific practices, and scientific knowledge simultaneously. This is because the statement refers to the purpose of physics (i.e., aims and values), emphasizes the role of observation and experimentation in producing scientific knowledge (i.e., scientific practices), and emphasizes the conceptual understanding of the relationship between space–time, matter, and energy (i.e., scientific knowledge). Therefore, overlapping coding was permitted when a statement meaningfully addressed more than one category.

4.2 How do the epistemic network structures compare between the cognitive-epistemic and social-institutional systems of the FRA in the Turkish national physics curriculum and the IB DP physics curriculum?

To examine whether the distribution of FRA categories differed between the IB DP Physics curriculum and the Turkish national physics curriculum, a chi-square test of independence was conducted. The results indicated a statistically significant difference in the distribution of categories between the two curricula, $\chi^2(10) = 851.75$, $p < .001$. The effect size was large

Table 2 Comparative excerpts from the IB DP and Turkish physics curricula

FRA categories	IB DP Physics Curriculum Excerpts (IBO, 2023)	Turkish National Physics Curriculum Excerpts (MoNE, (2024)
Aims and values	- Classifying such observations and underlying patterns in the natural world is the essence of what scientists do, underpinned by the assumption that the universe exists as an external reality accessible to the human experience (p. 6) - From the beginnings of seismology in China, through material science in Mesopotamia to astronomy in the Islamic Golden Age, the search for an objective understanding of the natural world transcends the limitations imposed by national boundaries (p. 12)	- The aim of physics is to help understand the relationship between space–time, matter, and energy based on observation and experimentation (p. 4) - It is aimed that students develop an interest in physics and become willing to explore scientific knowledge related to physics (p. 5)
Methods	- The course also encourages students to make comparisons between different areas of knowledge and reflect on how knowledge is arrived at in the various disciplines, what the disciplines have in common, and the differences between them (p. 3) - It is in this manner that objective experiments are subjectively experienced by scientists who repeat them to confirm the value of what is transmitted, constituting the essence of the scientific experience (p. 9)	- The ability to reason inductively regarding the definition of physics (p. 15) - Selects strategies, methods, or techniques appropriate to the research objective (p. 51)
Scientific practices	- Encourage students to analyse knowledge claims and explore questions about the construction of knowledge (p. 3) - Experimentation through a variety of forms can be used to introduce a topic, address a phenomenon or allow students to consider and examine authentic questions and curiosities (p. 16)	- The Physics Course Curriculum aims to develop discipline-specific skills in students by enabling them to acquire scientific knowledge, skills, and attitudes; apply physics-specific knowledge in their daily lives; distinguish accurate information; analyze and evaluate information; and produce scientific knowledge (p. 4) - Students are asked to design an experiment in which they can explain the rationale for connecting generators in series or parallel (p. 50)
Scientific knowledge	- The TOK course examines the nature of knowledge and how we know what we claim to know (p. 3) - Conceptual understanding is therefore an outcome of a non-linear, ongoing process of evolving understandings, adapting previous understandings, and identifying and dispelling misconceptions (p. 17)	- The aim is for students to express their thoughts using field-specific terms, scientific rules, theories, and laws, taking into account different disciplines when necessary (p. 5) - Evaluates the accuracy of the information collected regarding the structure, operating principles, and applications of fiber optic materials (p. 78)

Table 2 (continued)

FRA categories	IB DP Physics Curriculum Excerpts (IBO, 2023)	Turkish National Physics Curriculum Excerpts (MoNE, (2024)
Social certification and dissemination	- Peer review is essential to verify the research methods of knowledge claims prior to their publication in journals (p. 8) - These are scrutinized by the scientific community and, if accepted, become knowledge (p. 9)	- *(not available)*
Scientific ethos	- The IB respects the principles of intellectual property and makes strenuous efforts to identify and obtain permission before publication from rights holders of all copyright material used (p. Preface) - Creativity is essential to particle physics, cosmology, and to mathematics, and to other fields of science, just as it is to its more widely acknowledged beneficiaries—the arts and humanities (p. 9)	- The aim is for students to evaluate the world from a scientific, ethical, and social perspective and to develop a sense of responsibility regarding the impact of their activities on themselves, their environment, Türkiye, and the world (p. 5)
Social values	- While discussing the depletion of energy sources and the constant need for new energy resources to meet energy demands, students can explore the concepts of responsibility, power and justification (p. 11) - It is an everyday, grounded science encompassing advances in communication, medical technology and renewable energy (p. 9)	- The aim is for students to recognize the contributions that knowledge and the technologies produced make to the development of societies (p. 5) - The contributions of technologies emerging from scientific studies to the development of societies, as well as the factors underlying progress and advancement, reveal the importance of physics (p. 4)
Professional activities	- How are scientific knowledge claims generated, tested, communicated, evaluated and used? (p. 7) - Organizing or participating in a social media outreach or advocacy campaign, for example, on an environmental or health concern (p. 12)	- Groups present their findings using materials such as infographics, posters, or flyers that relate to physics and careers, or they can draw up a career-focused roadmap for a profession working in the field of physics (p. 17) - Students analyze the conclusions they reach from their drawings and share them with their classmates (p. 97)

Table 2 (continued)

FRA categories	IB DP Physics Curriculum Excerpts (IBO, 2023)	Turkish National Physics Curriculum Excerpts (MoNE, (2024)
Social organizations and interactions	- Given the global nature of many scientific issues, international organizations often have a focus on the engagement of science with the public domain (p. 12) - This collective work by the scientific community is one of the features of "doing" physics (p. 9)	- The ability to inquire about career opportunities related to physics at institutions or organizations operating in the field of science and technology (p. 15) - General information can be provided about experiments conducted at research centers such as CERN, which focus on gaining knowledge about the fundamental particles that constitute the universe (p. 103)
Financial systems	- Advancements in technology, along with the cost of modern research facilities, continues to reinforce the role of international collaborative work (p. 12)	- Students draw conclusions by relating the device they researched to issues such as human and environmental health, personal privacy, and Türkiye's independence and protection in the military sphere, and include these conclusions in their presentations (p. 98)
Political power structures	- Students explore the means of producing knowledge within the core theme of "knowledge and the knower" as well as within various optional themes (knowledge and technology, knowledge and politics, knowledge and language, knowledge and religion, and knowledge and indigenous societies) and areas of knowledge (the arts, natural sciences, human sciences, history and mathematics) (p. 3) - For example, while discussing the depletion of energy sources and the constant need for new energy resources to meet energy demands, students can explore the concepts of responsibility, power and justification (p. 11)	- The contributions that technologies resulting from scientific research in physics make to the development of societies highlight the importance of physics as a fundamental element underlying development and progress (p. 4) - The aim is for them to take Türkiye's development plans into account in their career planning (p. 5)

(Cramer's V = .59), indicating a strong association between curriculum type and the distribution of FRA categories (Moraine et al., 2021). Examination of standardized residuals showed that the IB DP curriculum emphasized categories such as methods and methodological rules, scientific knowledge, and scientific ethos, whereas the Turkish curriculum showed a stronger emphasis on scientific practices and social values of science.

To further examine how FRA categories are structurally connected within each curriculum, ENA was conducted. The representation of the NOS in the Turkish national physics curriculum and the IB DP physics curriculum was examined using ENA within the framework of the FRA. Each network visualized in ENA graphs represents the frequency with which concepts appear in curriculum texts and the relationships between these concepts. The nodes in the graph correspond to the NOS categories defined within the FRA framework. The nodes' positions in two-dimensional space reflect the proximity of the relationships between the categories, as calculated statistically (Shaffer et al., 2016). The connections (edges) between nodes are the core analytical component of ENA and indicate that two NOS categories were addressed together in the same context (stanza) of the curriculum texts. The thickness of these connections indicates the frequency and strength of the association. As the line thickens, the curriculum presents the relevant NOS dimensions in a more integrated manner. The centroid (center of gravity) at the center of the graph provides a statistical summary of the overall NOS orientation of each curriculum. Thus, the ENA visuals revealed which of the NOS dimensions the curricula focused on, how they related to other dimensions, and how extensively they addressed the NOS within a holistic epistemic structure, all through a single relational map (Shaffer et al., 2016).

Findings were presented focusing on the patterns of interconnectedness between the cognitive-epistemic and socio-institutional systems. The epistemic network connections among all FRA categories in the IB DP physics curriculum are shown in Fig. 4, while the epistemic network connections for the Turkish national physics curriculum are shown in Fig. 5.

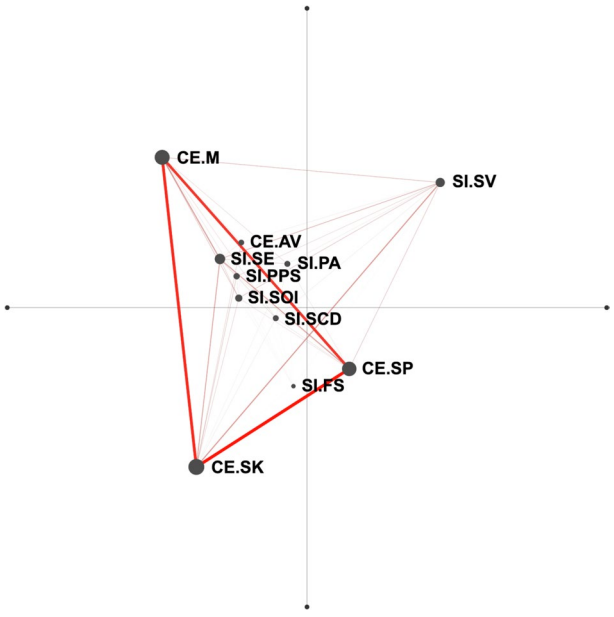


Fig. 4 Overview of epistemic network connections across FRA categories in the IB DP physics curriculum. *Notes.* The cognitive-epistemic system elements are marked with prefix "CE": aims and values (CE.AV), scientific practices (CE.SP), methods and methodological rules (CE.M), and scientific knowledge (CE.SK). The social-institutional system elements are marked with the prefix "SI": scientific ethos (SI.SE), social certification and dissemination (SI.SCD), social values of science (SI.SV), and political power structures (SI.PPS)

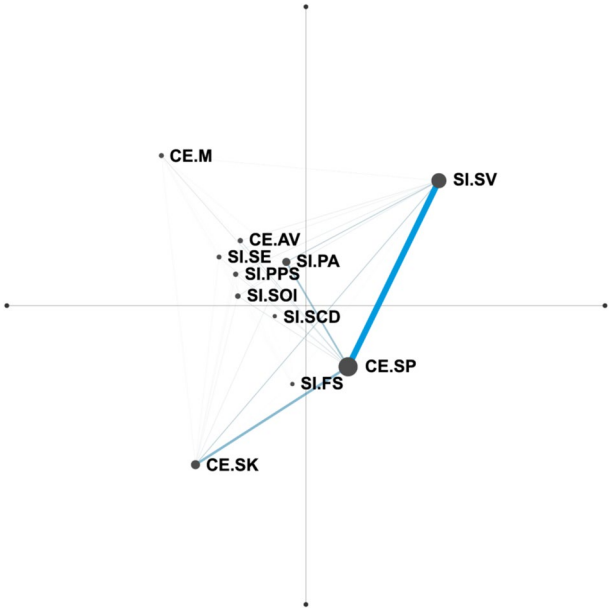


Fig. 5 Overview of epistemic network connections across FRA categories in the Turkish national physics curriculum. *Notes.* The cognitive-epistemic system elements are marked with prefix "CE": aims and values (CE.AV), scientific practices (CE.SP), methods and methodological rules (CE.M), and scientific knowledge (CE.SK). The social-institutional system elements are marked with the prefix "SI": scientific ethos (SI.SE), social certification and dissemination (SI.SCD), social values of science (SI.SV), and political power structures (SI.PPS)

The ENA results showed that both curricula primarily structured the coverage of the NOS through a cognitive-epistemic system. The epistemic network structure of the IB DP physics curriculum (Fig. 4) shows that the cognitive-epistemic system was at the center, but the connection patterns exhibited a more balanced distribution. Notably, the connections between the methods and methodological rules and aims and values nodes appeared to be stronger than in the Turkish national physics curriculum. Consequently, the epistemic network corresponding to the NOS occurrences in the IB DP physics curriculum established a more holistic relationship between scientific knowledge production, methods, and epistemic values.

Examining the network structure of the Turkish national physics curriculum (Fig. 5) showed that the most intense and dominant connections were between the scientific knowledge and the methods and methodological rules nodes. This structure, supported by the frequency data, demonstrated that science was primarily represented by the characteristics and production of scientific knowledge and the processes used to obtain that knowledge. In contrast, the categories representing epistemic goals, such as the aims and values, occupied a less central position within the network and lacked strong connections with the central nodes. These patterns suggested that the Turkish curriculum foregrounded the cognitive aspects related to scientific knowledge and methodology while under-integrating epistemic aspects of science such as why scientific knowledge is pursued, what counts as warranted knowledge, and the values that shape these judgments.

The analysis results also revealed that the socio-institutional system was relatively underrepresented within the network structure in both curricula. Categories such as social certification and dissemination, social organizations and interactions, and financial systems in the Turkish national physics curriculum were located on the periphery of the network in Fig. 3 and had almost no connection with other FRA categories. This result was consistent with the frequency data, where these categories had low counts, and it showed that science

was presented as largely disconnected from its social, economic, and institutional contexts in both curricula.

In summary, when evaluated overall, the epistemic network structures presented in Figs. 4 and 5 revealed that both curricula addressed the NOS primarily through cognitive-epistemic dimensions, while the social, institutional, and economic aspects of science were represented in a very limited and fragmented manner. However, while the IB DP curriculum presented a relatively more holistic epistemic network structure by establishing more meaningful connections between epistemic values and scientific methods, the Turkish curriculum positioned scientific knowledge within a product- and method-oriented structure and largely neglected the associated socio-institutional aspects that complement this structure.

To evaluate whether the two-dimensional ENA projection adequately represents the underlying high-dimensional data used in the comparison of the IB DP and Turkish curricula networks, goodness-of-fit statistics were examined. The ENA model demonstrated excellent goodness of fit, with Pearson correlations of.93 and.90 for the x and y axes respectively, indicating that the two-dimensional representation accurately reflects the high-dimensional data structure. The model accounted for 21% of the variance on the x axis (MR1) and 18% on the y axis (SVD2). An independent-samples t-test assuming unequal variance revealed that the IB DP and Turkish curricula were statistically significantly different along the x axis (MR1), with IB DP ($M = -0.30$, $SD = 0.22$, $N = 702$) positioned significantly to the left of Turkish curriculum ($M = 0.16$, $SD = 0.32$, $N = 1337$; $t\ (1906.37) = -37.87$, $p < .001$, Cohen's $d = 1.57$), indicating a large effect size. Along the y axis (SVD2), no statistically significant difference was found between the two curricula (IB DP: $M = 0.00$, $SD = 0.33$; MoNE: $M = 0.00$, $SD = 0.33$; $t\ (1431.04) = 0.00$, $p = 1.00$, Cohen's $d = 0$), suggesting that the primary structural difference between the two epistemic networks lies along the horizontal dimension. As illustrated in Fig. 6, the comparison plot reveals that the IB DP units (red) cluster to the left along the MR1 axis, gravitating toward CE.M (Methods and Methodological Rules) and CE.AV (Aims and Values of Science), while the Turkish curriculum units (blue) cluster to the right, pulled strongly toward SI.SV (Social Values of Science) and CE.SP (Scientific Practices). The centroid of the IB DP is positioned to the left ($M = -0.30$) whereas the centroid of the Turkish curriculum is positioned to the right ($M = 0.16$), reflecting the fundamentally different epistemic orientations of the two curricula. The individual network plots (Figs. 5 and 6) further confirm this distinction: the IB DP network shows stronger connections among CE.M, CE.SK, CE.AV, and CE.SP, forming a more densely interconnected cognitive-epistemic structure, whereas the Turkish curriculum network is characterized by a dominant CE.SP–SI.SV connection with a notably strong link extending toward SI.SV, indicating a predominance of scientific practices coupled with social values rather than a balanced epistemic network.

5 Discussion

This study utilized a content analysis approach in addition to ENA to examine the official texts of the recent editions of the IB DP physics curriculum and the Turkish national physics curriculum utilizing the FRA as an analytical lens. Frequency analyses revealed the quantitative distribution of the NOS aspects identified in the curricula, while ENA made visible how these components formed an epistemic coherence or fragmentation within the curriculum documents. The results revealed fundamental differences in the way both

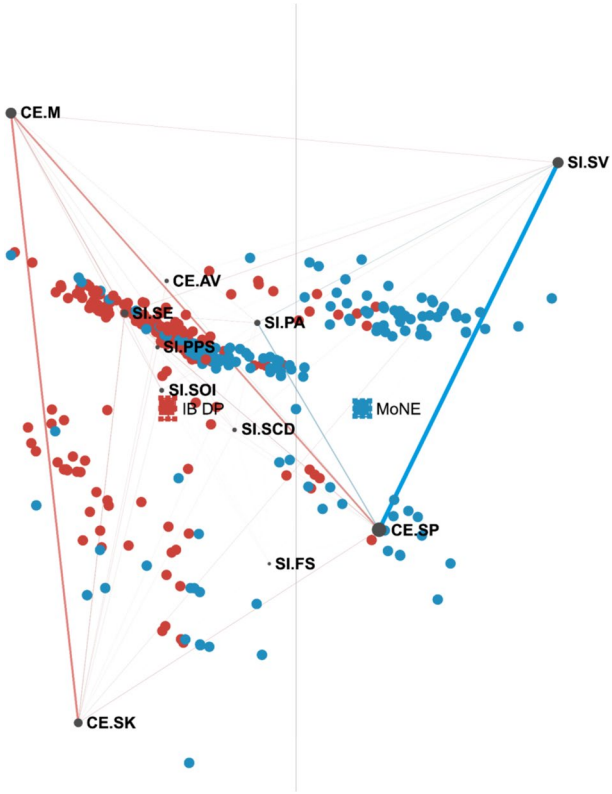


Fig. 6 ENA comparison plot of the IB DP and Turkish physics curricula. *Notes.* The cognitive-epistemic system elements are marked with prefix "CE": aims and values (CE.AV), scientific practices (CE.SP), methods and methodological rules (CE.M), and scientific knowledge (CE.SK). The social-institutional system elements are marked with the prefix "SI": scientific ethos (SI.SE), social certification and dissemination (SI.SCD), social values of science (SI.SV), and political power structures (SI.PPS)

curricula approached the NOS, while also pointing to the structural limitations that parallel FRA-based international curriculum analyses (e.g., Cheung, 2020; Gao et al., 2025; Xie et al., 2025).

The quantitative findings obtained from the distribution of the FRA categories and their comparative frequencies provide critical information for both policy and practice. The most important finding is the confirmation of a global trend. The findings showed that the vast majority of the NOS coverage identified in the IB DP physics curriculum and Turkish national physics curriculum were grouped under the cognitive-epistemic categories (72% and 69%, respectively). This suggests that the cognitive-epistemic categories still maintain clear dominance over the social-institutional categories. This imbalance carries a potential risk of presenting physics as an idealized discipline, disconnected from the vital human, ethical, economic, and political contexts that shape scientific knowledge production. Moreover, this systemic imbalance aligns with a structural trend reported in numerous national curriculum analyses conducted using the FRA framework. For example, Kaya and Erduran (2016) and Kurt and Kaya (2025) examined different subject curricula in the Turkish context and found that the NOS coverage predominantly focused on cognitive aspects, such as the nature, methods, and applications of scientific knowledge. Meanwhile, the social-institutional categories were found to be mostly neglected. Similarly, studies on the secondary science curricula of Norway (Kostøl et al., 2023) and Kosovo (Bytyqi-Damoni et al., 2025) reported underrepresentation of the social-institutional elements of the NOS. Taken together, these findings suggest a cross-cultural pattern in which NOS was framed largely around individuals' reasoning

and methods, with comparatively limited emphasis on community-level processes such as social certification, dissemination, and institutional structures.

Frequency data showed that the Turkish national physics curriculum placed a quite strong emphasis on the scientific practices category within its cognitive-epistemic system (60%). However, when considered alongside the ENA findings, this quantitative concentration suggests a structural limitation. The Turkish national physics curriculum's epistemic network structure appeared to establish connections predominantly between the scientific knowledge and the methods and methodological rules nodes (Fig. 5). In contrast, it exhibited weak relationships with epistemic aspects, such as the aims and values of science. This suggests that science in the most recently released physics curriculum in Türkiye was represented in a structure that is more product- and process-oriented without sufficiently highlighting the underlying epistemic aims and values. Although scientific practices such as conducting experiments, collecting data, and taking measurements were commonplace in the Turkish curriculum, it was not clearly stated within which scientific methods these practices are carried out or what epistemic purposes they serve for.

In contrast, the ENA structure of the IB DP physics curriculum revealed relatively strong connections between the methods and methodological rules and the aims and values. This network structure underlines a more comprehensive conceptualization of science by presenting scientific methods as tools used to achieve specific epistemic goals and values, rather than merely as technical applications. This distinction is particularly important in physics education. Physics is defined by its attempt to understand nature through abstraction, idealization, and mathematical modeling. However, the Turkish national physics curriculum's focus on scientific practices and its underemphasis of the epistemological foundations of the methods employed in science suggests that Turkish students may experience difficulty grasping the differences in hierarchy and epistemology between types of knowledge in physics, such as laws, principles, and models. There is also a risk that physics will move away from its nature as a foundational science and focus primarily on laboratory skills. In contrast, the IB DP demonstrated a relatively balanced representation, which indicated that the interrelationship between the experimental and theoretical dimensions of physics was addressed in a more holistic manner.

Examining the distribution of the social-institutional system revealed that representation in this area of Turkish physics curriculum was largely shaped by the social values of science category (326 counts; 21%). This suggests that institutional mechanisms and structural processes involved in producing scientific knowledge remained largely in the background. The most striking indicator of this neglect was the complete absence of NOS coverage related to the social certification and dissemination category in the Turkish curriculum. Past studies of the Chinese physics curriculum (Xie et al., 2025) and the Hong Kong biology curriculum (Cheung, 2020) showed that the peer review mechanism and formal validation processes all scientists employ to generate scientific knowledge were generally underrepresented in curricula. Compared with these curricula, the Turkish physics curriculum presents an even starker finding, as social certification and dissemination processes were entirely missing.

The ENA results for the Turkish physics curriculum show the social-institutional nodes in peripheral positions with limited connections, which mirrors the fragmented network structure reported by Cheung (2020). This kind of structure may reinforce the idea in the curriculum that science is mostly an individual activity, separated from its social, institutional, and political/financial contexts. This deficiency is particularly critical in the context of physics. Current research and development (R&D) activities in certain fields of physics require large-scale institutional structures, international collaborations, and comprehensive funding mechanisms. For example, the CERN experiments in Geneva, Switzerland

are carried out through a multinational collaboration in which participating countries contribute both personnel and budget, which highlights the institutional, political, and financial dimensions of contemporary research in physics. Regarding the financial systems category, only one instance of coverage was identified in both curricula, while the political power structures category had relatively limited coverage. This suggests that a significant opportunity to show students how political and economic decisions at micro (e.g., university budget allocation) or macro-level (e.g., limiting national budget for research to certain areas to serve political agenda) shape scientists' work and generation of scientific knowledge has been missed. Notably, the absence of coverage regarding the social certification and dissemination category in the Turkish curriculum hinders conveying the idea to students that specialized claims in physics or science in general only gain validity by the scientific community through extensive peer review and validation processes such as replications of empirical investigations.

Comparative frequencies reveal distinctly divergent curriculum philosophies. Despite having a significantly higher total number of coded examples, the Turkish curriculum exhibits an extremely skewed distribution. The dominant emphasis on scientific practices (60%) and social values of science (21%) points to a clear policy goal of encouraging active participation in science and promoting social responsibility and values, reflecting a possible alignment with the Maarif Model 2024's goals of experiential learning and sustainability literacy. In contrast, the near-total neglect of the social certification and dissemination category stands out as a critical finding; it suggests that students may not sufficiently encounter fundamental institutional processes such as peer review and formal verification of information, potentially leading to an incomplete understanding of how scientific claims gain legitimacy within the broader international community. The IB DP curriculum, on the other hand, exhibits a more balanced distribution among cognitive-epistemic categories; scientific knowledge, methods, and practices are strongly represented, while scientific ethos is given greater emphasis, and the social certification and dissemination category is also incorporated into the curriculum. This structure aligns with the transnational, inquiry-based, and Theory of Knowledge-integrated philosophy of the curriculum. This approach provides a more conducive ground for developing a holistic understanding of science that establishes the connection between what is known, how it is known, and the norms within which it is validated.

The findings also carry important implications for education stakeholders. For teacher educators, the data reveals a clear need for instruction on underrepresented social-institutional categories such as funding systems and political power structures. In the Turkish context, the integration of the concept of social certification and dissemination into the curriculum can be considered a priority area in terms of closing the gap between knowledge production and its validation. For curriculum researchers, this study concretely demonstrates how opposing educational management structures—the centralized and policy-oriented Turkish system and the globally benchmarked IB DP—shape NOS integration strategies in different ways. While the Turkish model primarily emphasizes exposure volume and social-applied dimensions, the IB DP highlights structural consistency and epistemological balance. Future research could comparatively examine the pedagogical effectiveness of these two different approaches in developing scientific literacy.

To explain the observed similarities and differences, the general similarity of the cognitive-epistemic system is most likely a legacy of the historical consensus view regarding the NOS (Lederman et al., 2002); this view tends to emphasize epistemological aspects that are easier to define and evaluate compared to the social-institutional dimensions that shape the formation of scientific knowledge. The differences, on the other hand, may be explained

more consistently in terms of curricular contexts: the high frequency and skewed distribution in the Turkish curriculum may be linked to a centralized management approach and a national priorities perspective; this suggests that locally defined values and practical skills are prioritized, pushing global institutional self-governance processes into the background. The relative balance in the IB DP can be explained by the curriculum's global mission, which necessitates a focus on the universal philosophical and methodological structures of scientific knowledge, the scientific ethos, and global knowledge verification systems.

6 Conclusion

This study utilized content analysis and ENA approaches through the lens of the FRA to examine the representations of the IB DP physics curriculum and the Turkish national physics curriculum. The findings revealed that both curricula primarily incorporated the NOS aspects through the cognitive-epistemic categories and only partially represented the associated social-institutional dimensions of science. This finding aligns with a global trend frequently reported in the FRA-based studies of secondary science curricula.

The present study findings have important implications for NOS-related research and the development of physics curricula for national or international context. First, the results revealed that evaluating the NOS coverage solely based on counting the occurrences of the NOS aspects embedded in the curriculum may provide an incomplete picture by missing the epistemic structure (i.e., coherence and interconnectedness) of the targeted NOS categories. Consideration must also be given to how these categories form epistemic coherence within the entire curriculum. The weak connections observed in the ENA findings in the Turkish context, despite identifying the high frequencies of some FRA categories, clearly demonstrated that quantitative density does not necessarily translate into a coherent and integrated representation of the NOS. Furthermore, the underrepresentation of the social-institutional system categories identified in the curriculum documents of our study points to a new line of research in the literature. A critical gap exists regarding how the NOS elements are represented in textbooks within multilingual contexts. In this context, the work of Cheung et al. (2026), which demonstrates the contribution of *translanguaging spaces* and *multimodal representations* to NOS learning in multilingual classrooms, can shed light on the curriculum-to-textbook translation process. Future studies should address this important gap by examining the extent to which textbooks incorporate students' multilingual and cultural resources when presenting the social dimensions of NOS, and whether these approaches increase the accessibility of NOS.

The findings of our study indicate that the underrepresentation of the NOS dimensions observed in the Turkish national physics curriculum has important implications for various stakeholders in secondary science education. From the perspective of policymakers and curriculum designers, the current curriculum needs to be revised to make vital NOS elements such as the social certification and dissemination of science, financial systems, and political power structures more visible. This will pave the way for presenting physics not only as a body of knowledge and methods but also as an ethical, institutional, and social endeavor. In addition, teacher educators and practicing teachers should integrate clear and reflective pedagogical approaches that address the social dimensions of NOS (e.g., scientific ethics and responsibility) into their lessons to address these gaps in the national curriculum. In particular, the strong integration between the aims and values of science and methodology observed in the IB DP curriculum could serve as a model for fostering

a more holistic understanding of the NOS. For the academic community, combining the FRA with ENA offers a robust and rigorous methodological roadmap for examining the structural relationships of NOS in curricula both quantitatively and qualitatively. Future research should deepen international curriculum comparisons by applying this method to different disciplines and cultural contexts.

In the context of physics education, an excessive focus on scientific practices and an epistemically weak treatment of the methods and methodological rules category can lead students to perceive physics as a collection of experimental techniques and applications rather than as a theory-driven science grounded in laws, models, and principles. However, scientific methods are not merely technical procedures. In physics, they are selected and justified in relation to epistemic aims such as reliability, precision, and explanatory power. From a social-institutional perspective and considering the large-scale, high-cost nature of contemporary physics research, which is based on international collaborations, the limited or negligible representation of the categories of social certification and dissemination, financial systems, and political power structures was particularly noteworthy. This may lead students to view physics as a discipline isolated from social, cultural, economic, and political contexts. This perception conflicts with the goals of science literacy.

The findings of this study suggest various directions for multi-layered research on the structure of NOS in physics curricula and its reflection in the teaching process. First, analyzing the textbooks and teacher guides used in the Turkish and the IB DP physics curricula with FRA and ENA in future studies may reveal how the NOS representations defined in the written curriculum are implemented in the classroom. These studies have potential to highlight any discrepancies between the intended and implemented NOS teaching in K-12 science education. As revealed in the findings, whether the apparent neglect in the social certification and dissemination category is also observed in other science disciplines such as biology and chemistry, and in different national contexts, should be investigated through interdisciplinary and multi-country comparative studies. Such studies have the potential to reveal whether this neglect is discipline-specific or reflects a more general trend in curriculum design.

Although this study presents important findings, they should be evaluated within certain limitations. First, the analysis was limited only to the official curriculum documents. Since teacher guides, textbooks, classroom practices, and assessment processes were not examined, there may be differences between the intended NOS representation in the curriculum and the implemented or actual NOS coverage in the classroom. Furthermore, the study focused solely on the physics discipline of two curricula. Examining more curricula from different countries and other science disciplines within the same countries would increase the generalizability of the findings. Future research could productively integrate these critical perspectives with FRA-based analyses to provide a more nuanced account of how NOS is represented in diverse cultural and political contexts.

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Ulku Seher Budak: investigation, formal analysis, data curation, visualization, writing—review and editing.

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Declarations

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