Science & Education (2025) 35:127–164
https://doi.org/10.1007/s11191-025-00643-2

ARTICLE

Rethinking Nature of STEM: Theoretical Insights and the Development of EPISTEMIK-Fire as an Assessment Tool

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Accepted: 22 March 2025 / Published online: 11 April 2025

Abstract
Nature of STEM (NoSTEM) encompasses epistemological, social, and ethical dimensions underlying STEM disciplines, emphasizing their interdependence rather than treating them as isolated domains. This perspective challenges reductionist and technocentric views, fostering a holistic understanding of science and technology in society. Nevertheless, currently, no validated instruments specifically evaluate NoSTEM, making the development of such instruments essential for advancing interdisciplinary STEM education. Thus, we present Evaluating Performance in STEM Integrated Knowledge (EPISTEMIK), a roadmap for developing instruments to assess NoSTEM in educational contexts grounded in a solid theoretical-philosophical framework. Based on this, we introduce a mixed-method instrument, combining statistical validation with qualitative analysis to ensure instrument robustness, focused on fire ecology (EPISTEMIK-Fire), consisting of 11 closed-ended and 2 open-ended items. EPISTEMIK-Fire uses fire ecology to explore interdisciplinary integration and critical reflection. However, while we introduce both EPISTEMIK and EPISTEMIK-Fire, the results primarily focus on validating the latter. Findings highlight EPISTEMIK-Fire's potential to provide a comprehensive understanding of NoSTEM, addressing gaps in existing evaluation tools by capturing interdisciplinary knowledge and socio-ethical implications. Beyond this application, our study contributes to STEM education by offering a rigorous framework for assessing interdisciplinary integration. Future applications aim to extend this instrument to diverse STEM fields and educational levels, fostering critical scientific literacy.

1 Introduction

STEM disciplines (science, technology, engineering, and mathematics) have allowed humanity to understand the universe's workings and design new devices and profoundly influenced social relations (Latour, 1987; Miller, 2022; Solomon, 1988). However, a crisis in public perception of science and technology is currently observed, characterized by

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declining trust in scientific institutions, fueled by concerns about corporate influence, ethical controversies, and perceived inconsistencies in scientific communication (Bos et al., 2023; Lupia et al., 2024). Additionally, the widespread dissemination of misinformation—often amplified by social media and politicized debates—has led to confusion regarding scientific consensus on critical issues such as climate change, vaccines, and genetic engineering (Kiratli, 2023). This environment of uncertainty has contributed to increasing skepticism toward technological advancements, with some segments of the population viewing emerging technologies not as progress but as potential threats to privacy, employment, and societal well-being (Fuertes-Prieto et al., 2020; Mugaloglu, 2014). This crisis can have various causes (socioeconomic conditions, access to culture, and gender gaps, among others); one of the key contributing factors is the lack of adequate scientific literacy, which limits individuals' ability to critically evaluate scientific information and engage in informed decision-making (Rupérez et al., 2019). If we aspire to a more democratic society where citizens can make informed and critical decisions, it is essential to rethink STEM education, ensuring that it fosters critical thinking, contextual understanding, and interdisciplinary connections, rather than relying on reductionist and decontextualized approaches (Fernández et al., 2002; Manassero-Mas & Vázquez-Alonso, 2022).

In response to this situation, there is a consensus on renewing science and technological education through more integrated and critical approaches. Among these, integrated STEM education (Frodeman, 2017; Le et al., 2023), the Nature of Science (NoS) (Adúriz-Bravo, 2014; Lederman & Lederman, 2015), and Science-Technology-Society (STS) (York, 2018) stand out, incorporating concepts from the history, philosophy, and sociology of science to provide a more contextualized education. More recently, these perspectives have been combined into what some authors call Nature of STEM (NoSTEM), an emerging approach that emphasizes the interconnections between science, technology, engineering, and mathematics and incorporates epistemological, ethical, and sociopolitical dimensions into STEM education (Ortiz-Revilla et al., 2022; Chesky & Wolfmeyer, 2015). NoSTEM challenges traditional technocentric and reductionist views by promoting an understanding of STEM disciplines as socially and culturally embedded fields. This approach seeks to develop a critical and humanistic vision by fostering students' ability to critically analyze the implications of scientific and technological advancements, recognize the ethical dilemmas they may pose, and understand their role in shaping a more fair and sustainable society (Faulconer et al., 2020).

NoSTEM proposes a deep and critical integration of STEM disciplines, overcoming fragmentation and the usual technocentric perspective. It draws on theoretical models such as Hughes' seamless web concept (Bijker et al., 1987), which emphasizes the interdependence of disciplines without epistemological hierarchies (Roehrig et al., 2021). It also adopts the Family Resemblance Approach (FRA) (Irzik & Nola, 2011), which addresses the complexity of STEM disciplines by recognizing similarities and differences in their epistemic and social dimensions. This approach not only facilitates knowledge contextualization but also promotes citizen participation in critical decisions about the environment and technology (Araya et al., 2023).

The field of fire ecology is an appropriate framework for exploring NoSTEM, as it combines scientific and social elements, allowing citizens to make informed decisions in emergency situations, which is crucial in the context of the current climate crisis (Böcher, 2020; Park et al., 2023). However, while there are instruments in the literature for evaluating attitudes and perceptions toward STEM, there are no widely available tools for assessing NoSTEM aspects in these areas. Therefore, the objective of this work is, not only to contribute to the NoSTEM debate, but to develop and validate a specific assessment instrument for

NoSTEM, addressing this need and contributing to a better understanding and teaching of this approach in contemporary education.

2 Theoretical Framework

2.1 Relevance and Limitations of the STEM Education

STEM approach has gained increasing relevance in the educational field. It is seen as a key strategy for preparing students to face the challenges of an increasingly complex world (Bybee, 2013; Habig et al., 2020). This approach should not be understood as a mere sum of disciplines, but rather as an integration that enables the application of knowledge from various fields in interconnected contexts (Breiner et al., 2012; Dare et al., 2018). Governmental institutions and international organizations, such as the OECD, have promoted its presence, which emphasizes the importance of strengthening STEM skills for economic and social development in an increasingly automated labor market (OECD, 2019). Policies such as the "Every Student Succeeds Act" in the USA (ESSA, 2015) and the LOMLOE in Spain (2020) reflect the intention to integrate this approach in early educational stages, aiming to foster technoscientific skills and reduce gender gaps in traditionally male-dominated fields (Wang & Degol, 2017; Zhan et al., 2022).

Despite its global expansion, the implementation of STEM is not without limitations (Toma & García-Carmona, 2021). One of the most frequently mentioned challenges is the lack of consensus on its conceptualization and application (Portillo-Blanco et al., 2024), which has led to pedagogical practices that sometimes appear innovative but adapt existing approaches (Thibaut et al., 2018). Furthermore, the adoption of STEM has often been constrained by the traditional structure of educational systems, which hinders transdisciplinary integration, especially when teachers lack adequate interdisciplinary training (Chen & So, 2022; Lederman & Lederman, 2015). This shortfall can generate resistance and result in superficial implementation, where activities fail to achieve genuine integration of the disciplines (Gardner & Tillotson, 2019; Nadelson & Seifert, 2017).

Although there is growing evidence of the attitudinal benefits of the approach, such as increased motivation toward science, improvements in deep content understanding remain a topic of debate (Dominguez et al., 2024). The literature also warns of STEM's tendency to prioritize the technical sciences at the expense of social sciences and humanities, which could limit a holistic understanding of complex problems. Furthermore, STEM has been criticized for being excessively professionalizing and overly aligned with the productivist interests of capitalism, focusing heavily on market-driven technical skills rather than fostering a comprehensive education (Zouda, 2018). This raises the risk of shaping students with an excessively technical focus and less critical awareness of the social and ethical impacts of science and technology (Burks et al., 2019; Diekman & Steinberg, 2013; Winberg et al., 2019). In response to these criticisms, complementary educational currents have been proposed, highlighting the need to contextualize science and technology within their social, political, and cultural dimensions, thereby promoting a deeper and more conscious scientific literacy (Brocos & Jiménez-Aleixandre, 2020; Casler-Failing et al., 2021; Lederman, 2007).

While STEM education has promoted interdisciplinarity, its predominant focus on technical knowledge has often overlooked the broader social and epistemological dimensions of scientific inquiry. In response to these limitations, educational currents such as

Science-Technology-Society (STS) and the Nature of Science (NoS) have to be considered since they offer complementary perspectives that integrate ethical, historical, and sociocultural dimensions into science education.

2.2 Complementary Views: STS and NoS in Science Education

Following the criticisms and limitations pointed out in the STEM approach, it is relevant to consider educational currents such as STS and NoS, which both offer complementary perspectives enriching science education by adding social and epistemological dimensions.

Emerging in the 1960s and 1970s, the STS movement originated in philosophy faculties as a critical response to the traditional view of science. Initially developed within the fields of philosophy, history, and sociology of science, STS later influenced science education by promoting the integration of technological and social dimensions into scientific teaching (Taylor & Patzke, 2021). Rather than merely focusing on the transmission of concepts, this educational current emphasizes how scientific knowledge interacts with social, cultural, economic, and ethical structures. By highlighting that scientific and technological decisions are not neutral, STS fosters a more active and reflective citizenship, empowering students to engage in informed debates about technoscientific advances and their social implications (Tenreiro-Vieira & Vieira, 2016; Zandvliet, 2023).

The concept of NoS has become increasingly relevant in science education as a key tool for fostering critical thinking about socially significant issues. Although several authors (Dewey, 1916; Schwab et al., 1982, among others) emphasized that science should be taught not merely as a body of knowledge but as a process of inquiry and critical thinking, a significant milestone occurred in 1960 when the National Society for the Study of Education in the United States published its yearbook Rethinking Science Education, highlighting the importance of students developing a solid understanding of NoS (Patricio Pujalte et al., 2014). From an interdisciplinary perspective, NoS can be understood as meta-knowledge about science, emerging from philosophical, historical, and sociological reflections, as well as contributions from scientists and science educators (Acevedo-Díaz & García-Carmona, 2016).

Although STS and NoS address different aspects of science education—one focused on the social dimension and the other on the epistemological—they share the goal of transcending mere content transmission by promoting critical thinking about how science works and influences our lives (Erduran & Dagher, 2014).

Recognizing the strengths and limitations of these educational currents (see Table 1), our research group aims to holistically integrate the visions of STS, NoS, and STEM. While STEM education fosters interdisciplinary scientific and technological knowledge (Wang et al., 2020), STS contributes a sociocultural and ethical dimension (Halwany et al., 2021), and NoS strengthens the epistemological and methodological understanding of science as an activity and a job (Mohan & Kelly, 2020). Integrating these perspectives allows for a more comprehensive educational approach that moves beyond the compartmentalization of scientific disciplines, fostering critical thinking and contextualized learning (Park et al., 2020). Given the increasing complexity of contemporary technoscientific challenges, this integration provides a necessary framework to equip students with tools to assess and engage with science and technology in society critically.

Although STS and NoS have contributed significantly to broadening the scope of science education, their implementation often remains fragmented or secondary to content-based instruction (Vázquez-Alonso et al., 2014). To address this challenge, the NoSTEM

Table 1 Advantages and limitations of the mentioned educational currents

Educational currents	Advantages	Limitations
STEM	- Promotes technical and scientific skills - Encourages innovation and preparation for careers in science and technology - Drives practical and project-based learning - Fosters logical thinking and problem-solving	- Technocentric approach, emphasizing technique over critical reflection - Often lacks adequate integration of social and ethical implications - May prioritize workforce skills over holistic education - If not properly focused, it can treat STEM disciplines in isolation, limiting interdisciplinarity
STS	- Encourages critical reflection on the social and ethical impact of science and technology - Connects science with real socio-scientific issues - Helps students develop an understanding of social and ethical responsibility - Focuses science on contexts that are relevant to society	- Primarily focused on social implications, sometimes at the expense of STEM technical skills - Application centered on specific disciplines, especially in the natural sciences, which limits the integration of other STEM areas - Lack of technical depth in solving practical problems - Greater emphasis on social critique than on scientific innovation
NoS	- Develops an epistemological understanding of science - Highlights the dynamic and tentative nature of scientific knowledge - Promotes critical thinking about scientific methods - Helps to understand how science connects with other fields of knowledge	- Tends to focus on the epistemology of the natural sciences, neglecting technology and engineering - Lacks an interdisciplinary approach that integrates other STEM areas - Does not adequately address the social impact of technological decisions - May remain theoretical without connecting to real practical applications

approach seeks to holistically integrate these perspectives, ensuring that STEM education not only conveys disciplinary knowledge but also fosters critical thinking, ethical awareness, and contextual understanding.

2.3 Nature of STEM: An Integrative Proposal

In response to the limitations of the STEM approach and the debate proposed by authors such as Peters-Burton (2014) and Erduran (2020), we build upon and deepen the concept of the Nature of STEM (NoSTEM), an integrative and critical perspective of science, technology, engineering, and mathematics disciplines. While we are not the first to use this term, our contribution seeks to advance its conceptualization and application through the systematic development of well-founded educational proposals and empirical studies (Fig. 1). While previous discussions of NoSTEM have often remained at a theoretical level, our research incorporates a range of methodological approaches and empirical data to explore its potential in STEM education. By grounding NoSTEM in already established educational research methodologies, we aim to provide a framework that supports its practical implementation and further investigations in this field (Kahn & Zeidler, 2016).

Inspired by Mejias et al. (2021), we recognize Science inside STEM as a unique set of practices that do not completely overlap with traditional science but encompass multiple intersections with the social and natural sciences, revealing the emergence of diverse epistemic cultures (Knorr-Cetina, 2009). Rather than viewing STEM disciplines as ends in themselves, NoSTEM understands them as means to improve human life and social well-being. In line with this epistemological openness, NoSTEM also challenges conventional disciplinary boundaries by arguing that the concept of "Science" should include both natural and social sciences, acknowledging their intertwined contributions to knowledge. Similarly, it considers that disciplines such as linguistics and logic, often marginalized or excluded, should be understood as essential components of mathematics, especially when

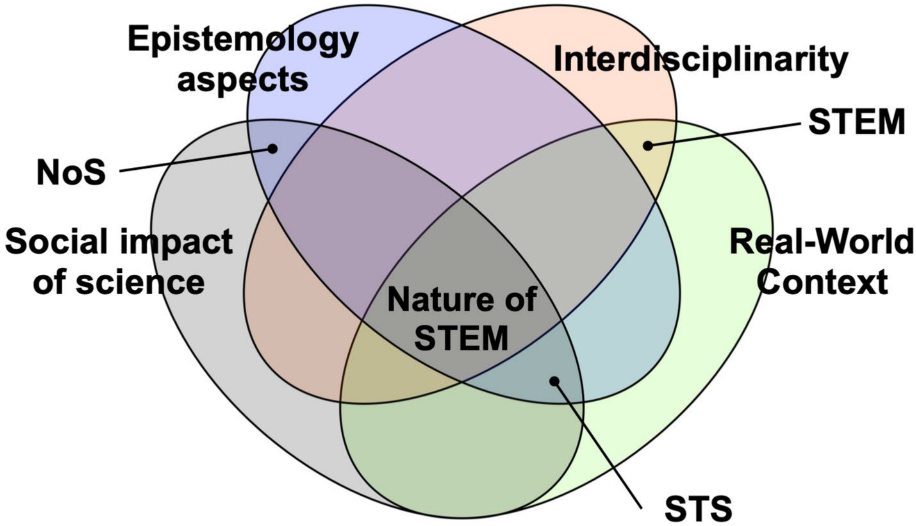


Fig. 1 Diagram of our conception of Nature of STEM

addressing meaning-making, reasoning, and symbolic representation in interdisciplinary contexts. This approach highlights that technoscientific knowledge is not neutral, but is shaped by social, cultural, and ethical factors (Fig. 1).

Unlike conventional STEM approaches, which present science and technology as objective tools for solving technical problems, NoSTEM emphasizes that technoscientific advances are conditioned by political power, cultural values, and economics (Edwards, 2018; Latour, 1987). Additionally, by incorporating principles of post-normal science, NoSTEM addresses contemporary challenges that traditional science cannot always effectively tackle, such as climate change or health crises In these cases, where risks are high and values are disputed, NoSTEM promotes an inclusive scientific practice that integrates multiple perspectives (Funtowicz & Ravetz, 1993; Zapp, 2018). Another fundamental aspect of NoSTEM is its emphasis on the social and ethical dimensions of technoscientific decisions. In response to one of the main criticisms of the conventional STEM approach—its disconnection from social and ethical dimensions—NoSTEM encourages critical reflection on the impact of technological decisions, urging students to consider sustainability, equity, and social justice in their projects (Hancock & Turner, 2023; Nguyen et al., 2020). This implies that technoscientific decisions must align with ethical values that consider social and environmental well-being (Bazzul, 2015; Reyes, 2019).

NoSTEM is characterized by its genuine interdisciplinarity. Unlike many STEM proposals, which tend to fragment disciplines, NoSTEM facilitates true epistemological and methodological integration, enabling students to understand the deep connections between science, technology, engineering, and mathematics, addressing complex problems from multiple perspectives (Ortiz-Revilla et al., 2020; Martín-Páez, 2019). This approach is based on the concept of the "seamless web" (Hughes, 1986) where barriers between STEM disciplines are considered artificial constructs, and knowledge flows continuously among them. This concept reinforces a key principle of NoSTEM: the absence of epistemic hierarchies among disciplines (González de Prado Salas et al., 2021; Reynante et al., 2020). In science education, certain areas are often prioritized over others, valuing, for instance, science over engineering or technology, or relegating mathematics to a mere tool. However, this hierarchy is artificial and based on a limited view of knowledge (Gontier, 2021; Osbeck & Nersessian, 2017). If we observe the daily work of chemists, engineers, or researchers, among others, the boundaries between disciplines become blurred. Don't medical doctors, the paradigm of technologists, apply scientific reasoning in their diagnoses and treatments? Don't scientists in laboratories use optimization methods typical of engineering, such as improving experimental processes to increase their efficiency? Similarly, logical and mathematical reasoning is transversal and underlies all scientific and technological activities (Boon & Van Baalen, 2018). Nature does not operate under strict disciplinary divisions; we have segmented knowledge to manage it better. Therefore, it is essential to overcome these divisions in education, as proposed by NoSTEM, to more accurately reflect how knowledge is generated and applied.

Another key aspect of NoSTEM is its emphasis on the epistemic dimension of disciplines. It is not only about teaching concepts and technical skills but also about fostering a deep understanding of how knowledge is constructed and validated in each field. This involves critical reflection on the methodologies, limitations, and uncertainties inherent in technoscientific knowledge. Instead of transmitting static, closed knowledge, NoSTEM promotes a reflective attitude, where students understand that science is a dynamic process and that technological solutions are constantly being revised. This methodological plurality is reflected in the NoSTEM proposal, which recognizes that each discipline offers unique approaches, from empirical inquiry in natural sciences to design and optimization in engineering, and formalization in logic (Feyerabend, 1988; Lohse & Bschir, 2020). This would allow students to approach problems from multiple perspectives, fostering more comprehensive and effective learning.

Pedagogically, NoSTEM aims to adopt a practical and competence-based approach. Learning is project-based and involves investigations that require the application of scientific and technological tools in real contexts (Ortiz-Revilla et al. 2019). This is particularly suitable for higher educational levels, such as secondary and university education, where students already possess the cognitive maturity needed to integrate interdisciplinary knowledge and reflect on its social and ethical implications.

In secondary education, NoSTEM can help students connect different STEM disciplines in solving practical problems, while in higher education, the approach becomes more relevant by enabling students to address more complex problems, deepening the critical and social dimensions of their technoscientific decisions (Davis et al., 2019; Eugenio-Gozalbo & Estrada-Vidal, 2023). At this level, NoSTEM is more useful, not only helping students master technical and methodological skills but also enabling them to apply their knowledge in an informed and responsible manner in professional and research contexts (Lin et al., 2022). Although NoSTEM can be adapted to other educational levels, we believe that its potential is maximized at the secondary and higher education levels, where students' cognitive maturity would allow them to fully benefit from interdisciplinary integration and critical reflection on the social impact of science and technology.

This educational potential is best realized through carefully designed instructional strategies that operationalize NoSTEM principles in the classroom. One such approach is the development of transdisciplinary didactic sequences, which provide structured yet flexible frameworks for integrating scientific and technological concepts with their broader social and ethical dimensions.

2.4 NoSTEM as a Tool for Designing Transdisciplinary Didactic Sequence

The NoSTEM perspective offers a promising tool for designing and developing teaching sequences that aim for a more meaningful integration of scientific, technological, engineering, and mathematical disciplines, approached from a more humanistic perspective than traditional approaches (Millar, 2020), recognizing science and technology as deeply interconnected with ethical, social, and cultural dimensions. Rather than presenting STEM as a purely technical or neutral domain, this perspective encourages students to critically analyze how scientific and technological developments influence and are influenced by societal values, power structures, and historical contexts. By fostering ethical reflection and social responsibility, NoSTEM aims to equip students with the ability to engage with STEM knowledge in ways that contribute to more equitable and sustainable futures (Cobian et al., 2024; Pleasants, 2020). By incorporating real-world problems that require a transdisciplinary approach, NoSTEM has the potential to connect academic content with situations relevant to students, making learning more meaningful and applicable (Lage-Gómez & Ros, 2023). This contextual link not only motivates students but also helps them visualize how knowledge from different fields intertwines to offer more elaborate solutions (Lesseig et al., 2023).

One of the main advantages of NoSTEM in developing teaching sequences is its methodological flexibility, facilitating the integration of diverse teaching methods such as scientific inquiry, engineering design, and computer simulation (Greca et al., 2014; Jimenez-Liso et al., 2022; Simarro & Couso, 2021). This allows the creation of sequences that explore different paths to solutions, adapting to both the nature of the problem and the interests of the students.

NoSTEM serves as a tool for designing integrated didactic sequences that incorporate scientific, technological, and social dimensions in meaningful learning contexts. One example is a didactic sequence on fire ecology, designed and developed in other works from this research group (Martínez-Martínez & Greca, 2024). This sequence begins with exploring the physical and chemical principles of fire, helping students understand its natural role in ecosystems. It then incorporates historical and anthropological perspectives by analyzing how different societies have managed fire across time, from indigenous fire management practices to contemporary wildfire policies. To deepen engagement, students work with real-world data on fire regimes and climate change, examining the increasing frequency of wildfires and their socio-environmental consequences. Ethical and political discussions are integrated through debates on land management, urban planning, and the role of science in decision-making. The sequence concludes with a communication and social awareness project, where students design outreach materials—such as infographics, videos, or community talks—to educate the public about wildfire prevention, sustainable fire management, and the broader implications of climate change. This experience has demonstrated that NoSTEM-based sequences can foster a deeper understanding of the interconnectedness between science, technology, and society while enhancing students' ability to critically analyze real-world problems and actively engage in science communication and public awareness efforts.

Beyond these practical applications, the NoSTEM perspective also emphasizes the development of epistemological competencies. Teaching sequences designed under this framework focus on the transmission of technical content and invite students to reflect on how knowledge is constructed in each discipline, its limitations, and how different methodological approaches can influence the solutions generated. This critical dimension fosters the application of knowledge and the evaluation of the reliability and relevance of the methods used, promoting scientific literacy among citizens (Drumond Vieira et al., 2017; Williams & Rudge, 2016).

Regarding curriculum design, NoSTEM enables the creation of progressive sequences that gradually develop skills and knowledge but with a holistic and integrated vision. The sequences could be organized around significant problems or projects, facilitating the cumulative construction of knowledge. Each stage would address an aspect of the situation from a different disciplinary perspective, demonstrating how the disciplines interact and complement each other (Leung, 2020). Additionally, the collaborative approach fostered by NoSTEM promotes the development of technical, social, and emotional skills, as the interdisciplinarity nature of the problems requires teamwork, effective communication, and joint decision-making (Cobo et al., 2022).

In the context of NoSTEM, evaluation tools must go beyond assessing traditional STEM concepts to also measure interdisciplinarity, social, and epistemological competencies. (Gess et al., 2019; Żyluk et al., 2018).

The effectiveness of these instruments is understood in terms of their ability to capture complex aspects of STEM education that are often overlooked in traditional assessments. Rather than focusing solely on factual recall or procedural knowledge, an effective NoSTEM assessment tool should provide insights into students' capacity to engage with science critically, reflect on its ethical and social dimensions, and make informed decisions as future citizens (McArthur et al., 2022; Reynders et al., 2020).

Traditional assessment approaches in STEM education have often prioritized memorization and the resolution of technical problems, which, while essential, do not fully capture the broader competencies emphasized in NoSTEM, such as epistemological reflection, interdisciplinary integration, and ethical reasoning (Lederman, 2007; Osborne & Dillon, 2008). Research in science education has highlighted the need for assessment tools that go beyond factual recall to evaluate students' ability to contextualize scientific knowledge and critically engage with its societal implications (Roberts & Bybee, 2014; Zandvliet, 2023). By incorporating both quantitative and qualitative elements, the instrument that we present in this paper, called EPISTEMIK-Fire, seeks to address these limitations and provide a more comprehensive evaluation of how students engage with science and technology in meaningful ways (Urrutia & Araya, 2022). It has been specifically designed for students in the final years of secondary education, recognizing that this stage often represents the last formal engagement with scientific education for a significant portion of the population (Ranellucci & Rosenberg, 2024).

2.5 The Need for a Specific Assessment Instrument for NoSTEM

As of November 1, 2024, a search conducted in WOS and SCOPUS did not reveal any instruments specifically designed to evaluate the Nature of STEM. This finding highlights a significant gap in this emerging approach's research and educational assessment. The lack of appropriate tools for comprehensively measuring NoSTEM knowledge and competencies restricts our ability to understand and enhance scientific literacy from an interdisciplinary and critical perspective. Our article aims to address this gap by introducing a novel instrument that can significantly contribute to the assessment and development of the NoSTEM approach.

While approaches like NoS and STS have inspired the development of various instruments, they generally do not capture the interdisciplinarity and critical reflection that NoSTEM aims to reflect. Most existing instruments are designed to address specific aspects of science education, such as emotional aspects (Sainz de Baranda Andújar et al., 2021), attitudes (Guzey & Harwell, 2014; Mateos-Núñez et al., 2020), self-efficacy (Grimalt-Álvaro et al., 2021), or engagement (Barlow et al., 2020; Carrasquilla et al., 2023). Even some of them measure the degree of interdisciplinarity of particular interventions or problems (Gao et al., 2020). Still, they do not do so in an integrated manner with the humanistic and social aspects of NoSTEM (Tripp et al., 2020). Although these tools provide relevant information about student motivation and perceptions, they do not explore the epistemological integration of disciplines or the application of knowledge to real-world problems, which are key elements in NoSTEM. This lack of evaluative tools highlights the need to create an instrument that holistically addresses the complexity of technoscientific knowledge. A NoSTEM instrument must go beyond merely understanding technoscientific concepts by integrating social, epistemological, and ethical aspects in solving real-world problems.

We will review several key instruments developed within traditional frameworks that can inspire the design of NoSTEM assessments. Many of these instruments primarily focus on analyzing attitudes toward science and engineering, often neglecting a more holistic approach encompassing interdisciplinary integration and critical reflection. By examining these existing tools, we can identify both strengths and limitations, paving the way for creating more comprehensive instruments that address the complex and multifaceted nature of NoSTEM perspective. This review will highlight the need to move beyond merely measuring attitudes and instead develop assessments that capture a broader spectrum of cognitive, epistemological, and socio-institutional dimensions inherent to NoSTEM.

The Views of Nature of Science (VNOS), developed by Lederman et al. (2002), assesses students' epistemological understanding of science. It evaluates how students perceive science as a tentative, empirical, and creative process, emphasizing the richness of their conceptualization of the nature of scientific knowledge. While this instrument provides valuable insights into students' epistemological conceptions, it has limitations in addressing disciplinary integration and applying STEM knowledge to real-world contexts, which are central elements in the NoSTEM approach.

The Views of Scientific Inquiry (VOSI), as described by Schwartz et al. (2008), targets students' conceptions of scientific inquiry, aiming to assess their understanding of research methods and the processes involved in scientific investigation. This instrument provides a detailed analysis of how students perceive and approach scientific inquiry, contributing to a deeper comprehension of their ideas about the methods and processes used in science. However, like the VNOS, the VOSI falls short in addressing interdisciplinary integration and the practical application of STEM knowledge in real-world situations, which are essential components of the NoSTEM framework. As a result, while the VOSI offers a thorough evaluation of students' inquiry skills, it does not capture the broader context of how these skills intersect with other STEM disciplines in tackling complex, real-world problems.

STS-related instruments, such as the Views on Science-Technology-Society (VOSTS), proposed by Aikenhead and Ryan (1992), focus on measuring students' perceptions of the social and ethical impact of science and technology, which is relevant to NoSTEM. This instrument promotes critical reflection on the social implications of technoscientific decisions, partially aligning with NoSTEM's objectives. However, VOSTS falls short in terms of interdisciplinary integration, as it focuses only on perceptions of the science-society relationship without evaluating how STEM disciplines interact to address real-world problems. This highlights the need for a more comprehensive instrument, able to capture interdisciplinarity and the practical application of knowledge in complex situations.

Allchin (2011) introduces a more comprehensive approach to evaluating NoS through the "Whole Science" concept, which incorporates epistemological, social, and contextual dimensions. This approach is valuable for assessing NoSTEM as it emphasizes the importance of evaluating knowledge in real-world scenarios and promotes the critical assessment of the reliability of scientific claims. However, Allchin's instrument does not explicitly address interdisciplinary integration, nor does it effectively combine quantitative and qualitative assessments, which would be preferred for a NoSTEM instrument.

The article by Ioannidou and Erduran (2021) on the diversity of scientific methods provides another relevant example. This study highlights the need for instruments that capture methodological plurality in science education, challenging the traditional view of a "single scientific method." This methodological diversity is crucial for NoSTEM, which emphasizes the integration of multiple scientific approaches in solving complex problems. However, although the Brandon Matrix used in this study provides a solid basis for evaluating methodological diversity, it does not fully address interdisciplinary integration or reflection on the ethical and social implications of technoscientific decisions. The analysis of Petersen et al. (2020) and Kaya et al. (2019) reinforces the relevance of the Family Resemblance Approach (FRA) in evaluating NoS, as it holistically integrates epistemological and social dimensions. The FRA has been used to capture both general and specific aspects of NoS, which is a valuable component for NoSTEM, as it also seeks a critical understanding of the construction of scientific knowledge and its relationship with society (Dagher & Erduran, 2023). However, as observed in these studies, the FRA does not include the practical application of knowledge in solving real-world problems, which is central to NoSTEM. The adaptation of the FRA for a NoSTEM instrument would allow addressing interdisciplinarity more directly and practically, capturing not only cognitive-epistemic aspects but also the social and ethical dimensions of STEM knowledge.

The development of a specific instrument for assessing NoSTEM is justified not only by the absence of tools that measure it but also by the need to complement and expand existing NoS and STS approaches (Drumond Vieira et al., 2017). To achieve this, a NoSTEM instrument must integrate several key dimensions that will be discussed below. By combining the strengths of NoS and STS approaches but going further in the assessment of interdisciplinary integration and critical reflection, the NoSTEM instrument will provide a more holistic understanding of how students relate to STEM knowledge and how they apply it critically in the contemporary world. To achieve this, it is necessary to define the key characteristics that such an instrument should encompass, ensuring that it effectively captures the epistemological, social, and interdisciplinary dimensions central to the NoSTEM approach.

2.6 Characterizing a NoSTEM Instrument

To justify the characteristics of an assessment instrument for NoSTEM, it is essential to consider multiple dimensions that reflect the complexity of this emerging perspective, focusing on interdisciplinary integration, critical reflection on knowledge production, and the social dimensions of STEM disciplines in the contemporary context. These instruments should be capable of capturing not only student progress but also how students mobilize knowledge from various STEM disciplines to address complex situations, as well as critically reflect on the impact of their decisions on society and the environment. In this way, assessment instruments become not only tools for evaluating students but also valuable means for teacher training in NoSTEM. Educators can use them to identify areas for improvement in their practice, such as teaching interdisciplinarity, integrating ethical and social aspects, or conveying the epistemological foundations of science (Roehrig et al., 2021).

The creation and validation of instruments for NoSTEM pose significant challenges. These must be accurate, reliable, and broad enough to reflect the entirety of the approach. This requires a proper identification of the dimensions to be assessed in the classroom, effectively capturing both the cognitive-epistemic and the social and ethical aspects of STEM teaching (Mayes & Rittschof, 2021). In this context, incorporating the FRA is appropriate, as it offers a flexible and plural framework for conceptualizing both the nature of STEM knowledge and its social and ethical impact. FRA, traditionally used to conceptualize NoS, allows examining not only the epistemological dimensions of STEM knowledge but also its social relevance, making it a suitable tool for guiding the development of a NoSTEM instrument.

The cognitive-epistemic dimension in NoSTEM evaluates how students understand and apply STEM knowledge from an integrated perspective, measuring their ability to connect methodologies from different disciplines and address complex problems with a multidimensional approach. A NoSTEM instrument should assess how students mobilize specific methods, such as experimentation, modeling, evidence-based argumentation, and informed decision-making, in a learning environment that fosters interdisciplinarity and critical thinking.

Meanwhile, the socio-political dimension of knowledge in NoSTEM requires an assessment approach that includes critical reflection on the ethical and social implications of technoscientific solutions. A NoSTEM instrument should measure students' ability to identify the impact of their technological decisions on society and the environment and to recognize the underlying values that guide these decisions. Unlike the mentioned authors, we prefer the term political instead of institutional in order to raise awareness that the political and social issues are intimately interconnected and involve the organization of societies and communities, independently of the work of politicians and political parties.

Like FRA, the NoSTEM perspective emphasizes the importance of understanding the mechanisms of scientific knowledge certification, such as peer review and research ethics, which should be reflected in the assessment instruments. This includes interdisciplinary collaboration, participation in innovation projects, and solving global issues like climate change or sustainability. Additionally, the instrument should evaluate how students understand the collaboration of researchers across disciplines and the communication of scientific findings ethically and effectively, adapting language and concepts to different audiences. A crucial aspect of NoSTEM implementation is identifying the most appropriate educational level for applying these instruments. Since the approach requires advanced cognitive development, the upper levels of secondary school, high school, and university are the most suitable (Mayes & Rittschof, 2021). At these stages, students possess the necessary maturity to connect knowledge from different disciplines and critically reflect on the ethical implications of their decisions.

Finally, the creation of an assessment instrument for NoSTEM should adopt a mixed approach, combining quantitative and qualitative components (Turner et al., 2017). While traditional approaches often rely on standardized tests and questionnaires, a NoSTEM instrument should incorporate case studies and developed responses, allowing it to capture the complexity of technoscientific knowledge in its interdisciplinary, ethical, and social dimensions (Herreid & Schiller, 2013; Krell et al., 2020). This mixed approach ensures a more comprehensive and in-depth assessment, reflecting the true nature of learning in NoSTEM and providing more complete feedback for students and teachers. Given these characteristics, the instrument should focus on areas where the relationship between science, technology, engineering, and mathematics is evident. In this study, we use the example of fire ecology to illustrate how these interdisciplinary connections can be effectively assessed and understood.

3 Method

3.1 Research Questions

Recent developments in STEM education have highlighted the need for interdisciplinary and socially engaged approaches to science and technology. The Nature of STEM (NoSTEM) framework emerges as a response to traditional reductionist perspectives, emphasizing the integration of epistemological, social, and ethical dimensions in STEM education. Despite its relevance, there is a lack of assessment tools specifically designed to evaluate NoSTEM competencies in educational settings. Addressing this gap requires a systematic effort to conceptualize, design, and validate instruments that capture the multidimensional nature of NoSTEM knowledge and its application to real-world challenges.

This study seeks to explore the following research questions:

1. What epistemological and sociopolitical dimensions should be considered in an assessment instrument for NoSTEM?
2. To what extent does the EPISTEMIK-Fire instrument capture interdisciplinary integration and critical reflection on science and technology in education?

3. Does the instrument effectively capture differences between dimensions, educational levels, and the specific aspects assessed?

To address these questions, the study pursues the following objectives:

- Design a process for creating valid instruments regarding NoSTEM knowledge (EPISTEMIK)
- Develop a mixed-method instrument to assess NoSTEM knowledge through the lens of fire ecology as an example of the EPISTEMIK itinerary

By developing and validating EPISTEMIK-Fire, this study contributes to integrating NoSTEM perspectives into STEM education, ensuring that assessment methodologies reflect the complexity and interdisciplinarity inherent in modern scientific literacy.

3.2 Samples and Procedures

The study's sample includes secondary and postgraduate education participants, selected through a convenience sampling approach based on accessibility to these student groups. Secondary education was chosen because it represents the final stage of formal scientific education for many students, with a significant portion of them discontinuing their engagement with science beyond this level. Understanding how these students conceptualize STEM knowledge at this critical juncture provides valuable insights into the impact of their formal education on scientific literacy.

Postgraduate students, on the other hand, were included to examine how epistemological reflection and interdisciplinary integration develop at more advanced academic stages. This dual-level sampling enables the exploration of developmental patterns in NoSTEM-related competencies and the assessment of the applicability of the EPISTEMIK-Fire instrument across diverse educational contexts. The sample size was considered adequate based on previous validation studies of similar instruments (Costello & Osborne, 2005), ensuring statistical robustness for both exploratory and confirmatory analyses.

A total of 428 participants took part in developing the EPISTEMIK instrument and were divided into different samples, as shown in Fig. 2. Sample 1 (recruitment: from March 28, 2022, to May 10, 2022) consisted of 57 secondary school students residing in a provincial capital in Castilla y León, Spain. Sample 2a (recruitment: from July 7, 2022, to December 4, 2022) consisted of 233 subjects residing in Spain and Argentina with educational levels ranging from secondary school to postgraduate studies. Sample 2b included 57 subjects from Sample 2a. Finally, Sample 3 (recruitment: from May 5, 2023, to May 18, 2023) consisted of 139 students between secondary school and undergraduate students. The Committee on Bioethics of University of Burgos approved the procedures according to the Principle of Transparency Regulation (EU) 2016/679 (General Data Protection Regulation) and Organic Law 3/2018 of 5 December on the protection of personal data and guarantee of digital rights. Informed consent (part of the instrument) was obtained from all subjects involved in the study and written consent was obtained from their legal guardians in the case of minors.

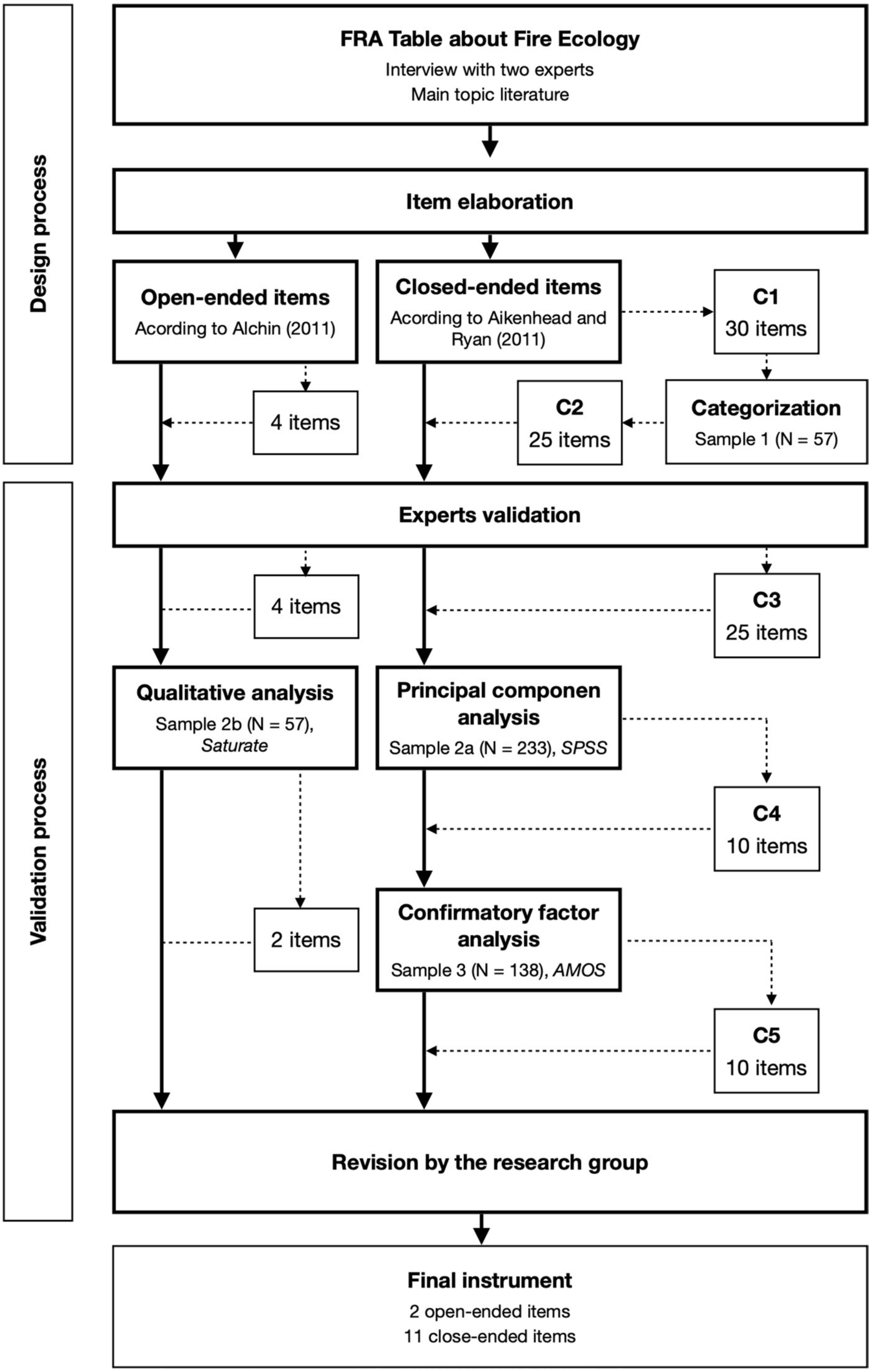


Fig. 2 Scheme of the design and validation process for EPISTEMIK-Fire

4 Results

In this section, a detailed description of both the design and validation phases will be provided. Since the study involves several steps, it is advised to refer to Fig. 2 as an aid to understanding. The instrument uses a mixed-method research approach (Creswell, 2009); this type of instrument was chosen for its versatility and the ability to gather useful information.

4.1 Designing EPISTEMIK-Fire

To determine which items were suitable for inclusion in the instrument (Martínez-Martínez et al. 2024a), a proposal on the debate about NoSTEM was considered: to follow a theoretical framework that would allow for the integration of the seamless web theory with Wittgenstein's family resemblance approach. Therefore, Irzik and Nola's proposal (2014) and its subsequent adaptations (Dagher & Erduran, 2014) were considered appropriate tools. These views allow for structuring the epistemic elements of STEM disciplines, as well as the epistemological components that are to be addressed in the classroom, in this case, related to fire ecology. These characteristics can be grouped into dimensions belonging to two systems: the cognitive-epistemic system (CES) and the socio-political system (SPS).

To create a similar table to the one suggested by Erduran et al. (2019) in their research but specifically addressing the chosen topic, interviews were conducted with two experts in fire ecology, and a bibliographic search on the main aspects of the discipline was performed. This table helped organize the concepts to be addressed, and the different items were drafted based on it.

A summary of the construction of Tables 2 and 3 can be found in Martínez-Martínez et al. 2023. Both tables display the different dimensions of both systems, the relevant epistemological aspects within each dimension, the references used to construct the instrument on fire ecology, and the list of closed and open-ended items extracted from each dimension.

Based on this new FRA table for fire ecology, the EPISTEMIK-Fire instrument was developed and then reviewed and validated by a total of six interdisciplinary experts: two researchers from the University of León who participated in the mentioned interviews, experts in Fire Ecology; three researchers from the University of Burgos, one who specialized in environmental problems and two researchers in STEM Didactics; and a researcher from the University of Granada, an expert in the field of environmental education.

As the instrument was intended to be designed as a mixed type, the two kinds of items are described below.

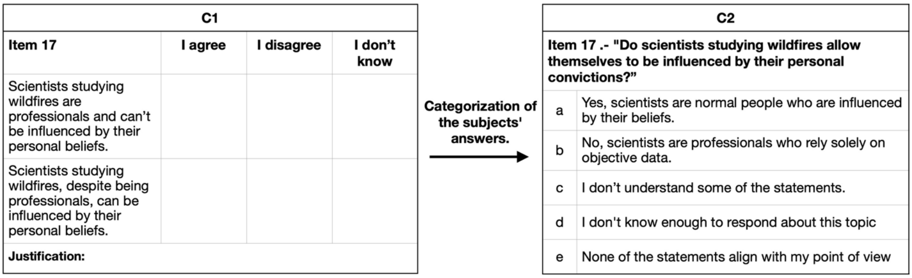
Aikenhead and Ryan (1992) argue that, when composing questionnaires of closed-ended items, the researcher can bias subjects' responses by the wording of the items, favoring one response over others. To avoid this limitation, the authors propose that an intermediate questionnaire (C1) be prepared, in which a group of subjects create the options for the questionnaire to be validated (C2). As seen in Fig. 3, each item in C1 consisted of two contradictory statements, a matrix where the subject could mark whether they agree, disagree, or do not know how to answer each statement and a space to explain their choice. This justification helped formulate the different options for the closed-ended questionnaire C2. For this step, instrument C1 was administered in Sample 1: a population of 57 subjects, all secondary school students aged between 14 and

Table 2 Cognitive-epistemic system

Dimension of CES	Epistemological aspects that could be addressed in the classroom	References for EPISTEMIK-Fire	Closed-ended items	Open-ended items
Aims and values	Fire ecology interdisciplinarity and scientific values such as predictive capacity, skepticism, verifiability, and innovation	Pausas (2015); Pausas and Keeley (2019)	AV1 AV2 AV3	O1
Scientific practices	Cognitive practices (GIS or sampling), epistemic practices (creation of mathematical models or databases), and discursive practices (forecasting and scientific production)	Caldararo (2002); Gomes et al. (2018); Thompson and Calkin (2011)	SP1 SP2 SP3 SP4 SP5	O2
Methods and methodological rules	Procedures established in the study of wildfires and the firefighting	Gomes et al. (2018); Gómez-Sánchez et al. (2019); Pérez Rodríguez et al. (2019)	MMR1 MMR2 MMR3	
Scientific knowledge	Fire ecology as a producer of scientific knowledge: firefighting methods; the role of fire in the ecosystem; wildfires and climate change…	Gómez-Sánchez et al. (2019)	SK1 SK2 SK3	-

Table 3 Socio-political system

Dimensions of SPS	Epistemological aspects that could be addressed in the classroom	References for the EPISTEMIK-Fire	Closed-ended items	Open-ended items
Professional activities	Technicians, scientists, engineers, officials, and politicians, among others, are part of the study of wildfires	Ley 43/2003, de 21 de Noviembre, de Montes (2003)	PA1 PA2	-
Scientific ethos	Fire ecology provides ethics debates such as the dichotomy between publishing data for the public good or keeping them confidential for scientific competitiveness	Hetemäki (2019); Pielke and Roger (2007)	SE1 SE2	-
Social values of science	The socioeconomic consequences of fires and effective recovery from them	Gomes et al. (2018); Lake et al. (2017)	SVS1 SVS2 SVS3 SVS4	O3
Social certification and dissemination	Discoveries about fires are subject to peer review and shared with citizens and public administrations	Minor and Boyce (2018)	SCD1 SCD2	O4
Social organizations and interactions	As in other scientific fields, there is a research hierarchy for seeking assistance through European and national projects or collaborating with the private sector	European Commission, 2018	SOI1 SOI2	-
Political power structures	In Spain, the political management of this field is carried out by the Ministry of Ecological Transition, and its competencies are delegated to the autonomous communities	Hetemäki (2019); Ley 43/2003, de 21 de Noviembre, de Montes (2003)	PPS1 PPS2	-
Financial systems	The differences between investment in prevention and the cost of firefighting	García-Ruiz et al. (2020); Ley 43/2003, de 21 de Noviembre, de Montes (2003)	FS1 FS2	-



C1			
Item 17	**I agree**	**I disagree**	**I don't know**
Scientists studying wildfires are professionals and can't be influenced by their personal beliefs.			
Scientists studying wildfires, despite being professionals, can be influenced by their personal beliefs.			
Justification:			

C2	
Item 17 .- "Do scientists studying wildfires allow themselves to be influenced by their personal convictions?"	
a	Yes, scientists are normal people who are influenced by their beliefs.
b	No, scientists are professionals who rely solely on objective data.
c	I don't understand some of the statements.
d	I don't know enough to respond about this topic
e	None of the statements align with my point of view

Fig. 3 Example of Aikenhead and Ryan's proposal process

18 years old. This sample type was chosen because the subjects belonged to the most basic level for which the instrument was designed.

Following Aikenhead and Ryan, a qualitative analysis was conducted by reading the justifications provided by the subjects and grouping them into categories. Each category would constitute one of the C2 options. Those categories were supplemented with three additional options: "I don't understand some of the statements," "I don't know enough to respond about this topic," and "none of the statements align with my point of view." These options were included to gather useful information about the subjects' knowledge and avoid forcing them to choose from the other options in the item.

4.2 Designing open-ended items

The preparation of the open-ended items was done following the approach proposed by Allchin (2011), aiming to provide students with a scientific context through multimedia material, news, or narratives so that they could develop their responses through such critical abilities as inquiry and reflection. For the elaboration of this part of EPISTEMIK-Fire, dimensions from the FRA table (Tables 1 and 2) were selected, and a search for materials accessible to nonexperts in fire ecology was conducted. The categories of FRA for the open-ended items were selected to complement the content of the closed-ended items, ensuring that the final instrument would be more comprehensive.

Four items were created, which were the categories most suitable for addressing through items of this nature. All shared the same structure: proposing a reading (news, interviews, dialogues, etc.) or a video and presenting a series of open-ended questions (personal reflections, creation of slogans for fire prevention campaigns, decision-making, improvement proposals, etc.).

4.3 Data Analysis

Questionnaire C1 was administered to Sample 1. The subjects in this sample consisted entirely of secondary school students, so the closed items were designed based on the most basic level of education. The categorization process resulted in a closed-ended instrument with 25 closed-ended items (C2). A total of 5 items were excluded following different criteria, such as low response level or the tendency for misunderstanding by the subjects. Instrument C2 and the open-ended items were reviewed and validated by the six mentioned experts. Corrections or suggestions were implemented, such as simplifying the language of some questions or using different examples.

The resulting instrument C3 was administered to Sample 2b as a Google Forms questionnaire. The obtained results were coded in a data matrix, where responses identified with appropriate views of NoSTEM scored 1, and inappropriate views or "no response/not sure" options scored 0. Using SPSS software, a dimension reduction was applied to this data matrix through principal component analysis, resulting in an instrument with 10 closed-ended items (C4).

Simultaneously, 57 subjects from Sample 2b (Sample 2a) responded to the open-ended items, and their answers were analyzed through qualitative analysis by thematic saturation. Finally, instrument C4 was administered to a sample of 139 subjects, and their results were coded like the previous test to conduct a confirmatory analysis.

4.4 Sample Adequacy and Preliminary Calculations

For each version of the closed-ended part, appropriate sample sizes were achieved. For C1, Sample 1 fell within the parameters proposed by Aikenhead and Ryan. In samples 2 and 3, the rule-of-thumb for this kind of instrument was followed, where the item-to-subject ratio exceeded the 1:5 proportion (Osborne & Costello, 2004). Sample 3, used in the confirmatory factor analysis (CFA), fell within the recommended sample size limits (150–200 subjects) (Kline, 2016).

4.5 Initial Test

To check for outliers or items that introduced significant noise into the data matrix, the Mahalanobis distance was calculated with p-values greater than 0.001. Likewise, the sampling adequacy measures (MSA) at the item level (anti-image correlation matrix) confirm that there is no need to remove any items in C2 (Ferrando et al., 2022), thus consolidating the instrumental version C3.

The values for the Kaiser–Meyer–Olkin test and Bartlett's test of sphericity reached optimal values in both C3 ($\mathrm{KMO} = 0.823$, $p < 0.001$) and C4 ($\mathrm{KMO} = 0.819$, $p < 0.001$), indicating that the magnitude of the correlations between the measured variables is satisfactory. Similarly, since Bartlett's sphericity test was significant, the data matrix can be considered suitable for factorization (Lloret-Segura et al., 2014).

4.6 Principal Component Analysis (PCA)

Given that EPISTEMIK is based on a solid theoretical background that recognizes two distinct factors (the epistemic-cognitive system and the socio-political system), it is preferable to conduct confirmatory factor analysis (CFA) rather than exploratory factor analysis (EFA) (Wan et al., 2022). Nonetheless, a scree plot was generated to confirm this hypothesis, demonstrating an evident factor change in the two factors. It should be noted that several authors argue that this criterion is more reliable than the Kaiser criterion, which tends to extract an excessive number of factors (Schmitt, 2011).

Table 4 Loading values for each factor extracted from PCA

Item	Factor 1 (CES)	Factor 2 (SPS)
SP1	0.678	
AV2	0.661	
MMR2	0.615	
SP4	0.573	
MMR1	0.566	
SK2	0.562	
SVS4		0.711
SE1		0.592
SOI1		0.576
PPS2		0.569

A dimensionality reduction approach was used, employing principal component analysis (PCA) with varimax rotation. This test was conducted using IBM SPSS v. 25. Several standard criteria found in the literature were followed during the APC. In this regard, the standards proposed by Costello and Osborne were considered (Costello & Osborne, 2005). These criteria involve ensuring the absence of cross-loadings and assessing the robustness and practical relevance of factors with 4–5 items when their factor loadings equal or exceed the value of 0.50. Therefore, items with cross-loadings or loadings below 0.5 were eliminated (Espinosa-Montero et al., 2016; Schönrock-Adema et al., 2009; Schreiber, 2021). Consistency with the instrument's theory was maintained throughout the analysis, leading to the removal of items that were theoretically expected to load on the opposite factor. As seen in Table 4, the PCA resulted in a set of 10 closed-ended items (C4) distributed into two factors that together explained 40.7% of the total variance.

Since the PCA lets the instrument with this number of items, high values for Cronbach's alpha are not expected (Taber, 2018). Additionally, some authors argue that when assessing a complex construct such as NoSTEM knowledge, it often occurs that the internal consistency of the factors is not high, as conceptual knowledge may not form a coherent latent factor for individuals (Berger & Hänze, 2015; Nehring et al., 2015). The alpha values were 0.72 for the total set of items, 0.692 for the cognitive-epistemic system (Factor 1), and 0.509 for the social-political system (Factor 2). As the alpha values do not provide solid evidence for instrument validation on their own, the instrument was subjected to confirmatory factor analysis to test it (Taber, 2018).

4.7 Confirmatory Factor Analysis

Based on the PCA, a CFA was conducted using IBM AMOS v.25 to validate the two-factor structure of the set of closed-ended items. A maximum likelihood test was performed to obtain two of the most valuable validation descriptors in a CFA: the comparative fit index (CFI) and the root-mean-square error of approximation (RMSEA) (Bentler, 1990; Ferrando et al., 2022).

The software-validated model is represented in Fig. 4, where all regression weights are significantly different from zero at the 0.05 level. It demonstrates optimal values for both CFI (0.933) and RMSEA (0.029) (Espinosa-Montero et al., 2016; Ingusci et al., 2022).

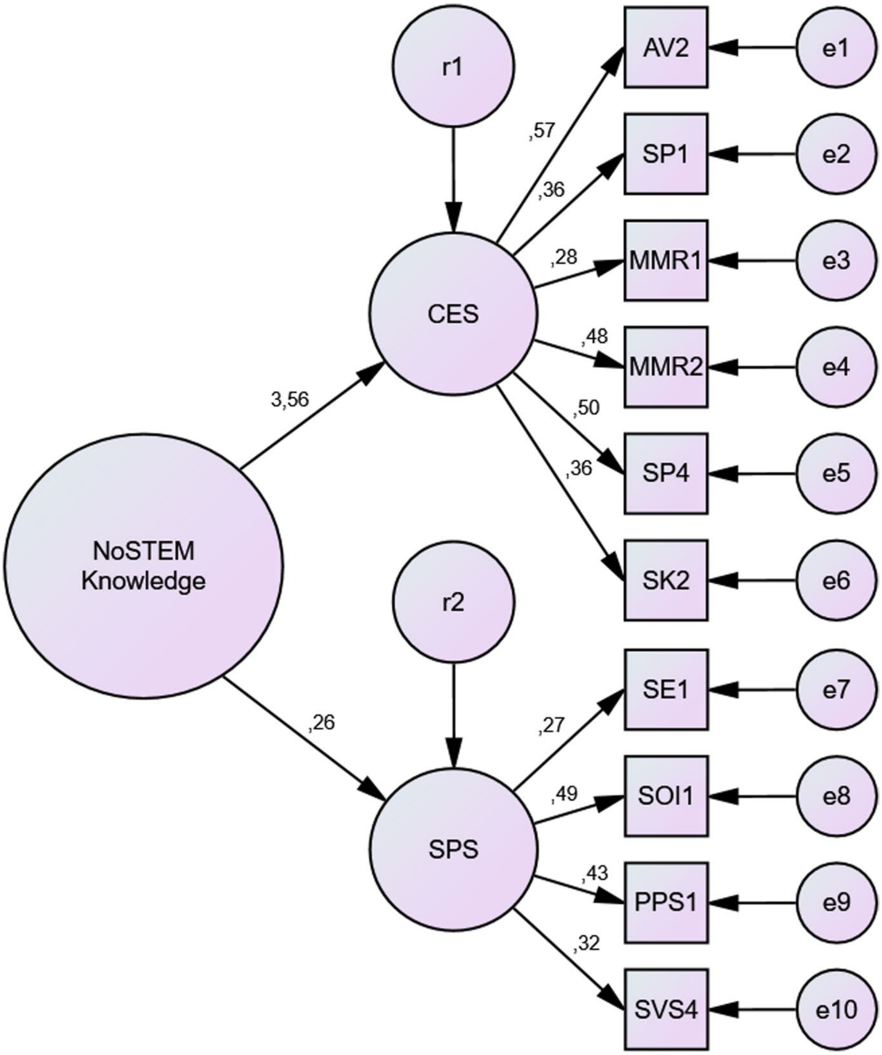


Fig. 4 Structure of the final confirmatory model for the EPISTEMIK-Fire

4.8 Thematic Saturation for Open-Ended Items

A qualitative thematic saturation analysis was conducted to thoroughly explore participants' responses regarding the initial four open-ended items (Braun & Clarke, 2006). Two of the researchers of this article carried out the analysis using the online program Saturate (http://www.saturateapp.com). Following an iterative process of coding and categorization, emerging patterns and FRA categories were identified in the data (Corbin & Strauss, 2008). This process involved multiple research team members to ensure a more enriching analysis perspective.

As the analysis progressed, it was observed that two of the items (O1 and O3) did not provide significant additional information. These items were related to the scientific objectives and social values of science; however, the responses were vague and covered a wide range of opinions that did not reach a sufficient saturation level. Therefore, the decision was made to eliminate these two redundant items.

Thematic saturation was achieved after analyzing and coding participants' responses to the remaining two items (O2 and O4). These two items, related to social communication and scientific practices and methods, effectively captured key perspectives and experiences related to NoSTEM knowledge while also complementing the aspects covered by the closed-ended items.

It is important to highlight that thematic saturation was determined when no new ideas or relevant information were found through the analysis and categorization of the data. This indicates that a comprehensive understanding was achieved with the final two items (Francis et al., 2010).

4.9 Overview of the Items

On the one hand, the cognitive-epistemic system is represented by the following questions: AV2 ("From what perspective are wildfires studied?") and SK2 ("Can data on fires from one climatic zone be applied to a different zone?"), which help to investigate the necessary perspectives to address a scientific problem and evaluate the understanding of scientific knowledge in the specific area being studied; both items SP1 ("Can predictions be made about fires by studying fire conditions?") and SP4 ("In terms of fires, can decisions be made based on scientific criteria even if there is not 100% certainty?"), as well as items MMR1 ("Can a fire be studied while it is occurring, or due to its danger, should we wait for it to be extinguished?") and MMR2 ("Do you believe that computer simulations play an important role in fire research?"), address the epistemological techniques and methods practiced in various STEM fields, as well as the predictive capacity of the sciences; finally, the FRA system is also represented by Item O2 ("Mathematics for preventing wildfires") based on a newspaper article that allows subjects to delve into and discuss the importance of mathematical models and to better understand scientific uncertainty.

On the other hand, the socio-political system is represented by the following items: SOI1 ("Regarding wildfires, what is the collaboration relationship between companies, universities, and institutions?") and PPS1 ("A large portion of the land that catches fire is privately owned. What should the government do about it?") which allows for understanding perspectives on how subjects perceive the relationships between sciences and different social institutions; items SE1 ("Sometimes scientific findings of a research group are kept secret until their publication due to competitiveness between scientific groups. What is your opinion on this?") and SVS4 ("How does the abandonment of rural populations affect forest fires?") provide insights into the ethical and social perspectives of STEM subjects; Item O4 (Communication and citizen awareness) helps address the aspect of dissemination and social awareness while gaining knowledge of the views of the evaluated individuals. Last, after a research group meeting, it was decided to purposely add item SVS1 ("When finding solutions for wildfires, should the environment be prioritized at all costs without being influenced by social or economic factors?"). As some members believed, this item could provide a very interesting perspective on how subjects perceive science when addressing social problems.

Table 5 NoSTEM knowledge by item and dimension

Dimension	Item	Mean (*M*)	SD	Dimension mean	Dimension SD
Cognitive-epistemic system (CES)	SP1	0.151	0.359	0.315	0.209
	AV2	0.360	0.482		
	MMR1	0.381	0.487		
	SK2	0.273	0.447		
	MMR2	0.295	0.458		
	SP4	0.432	0.497		
Socio-political system (SPS)	SOI1	0.446	0.499	0.430	0.265
	SVS1	0.216	0.413		
	SE1	0.504	0.502		
	PPS1	0.446	0.499		
	SVS4	0.540	0.500		

4.10 Baseline Data Analysis

To contextualize the instrument's validation and conduct a preliminary evaluation of its ability to differentiate varying levels of understanding of NoSTEM, a statistical analysis was performed on responses from Sample 3, which also participated in the confirmatory factor analysis (CFA). The analysis adhered to the previously established 0/1 coding system used throughout the validation process.

The overall results indicate a mean score of 0.455 (SD = 0.099) in the cognitive-epistemic dimension and 0.430 (SD = 0.126) in the socio-political dimension, suggesting slight variations in NoSTEM knowledge across these two domains (Table 5). This difference implies that participants demonstrated a slightly higher understanding of NoSTEM concepts related to epistemology and scientific knowledge compared to those concerning the socio-political aspects of science and technology.

Within the cognitive-epistemic dimension, the highest-scoring items were SP4 ($M = 0.432$, SD = 0.497) and MMR1 ($M = 0.381$, SD = 0.487), whereas SP1 ($M = 0.151$, SD = 0.359) had the lowest mean score. This suggests that participants struggled more with the idea that predictions about fires can be made based on fire conditions, while they showed relatively stronger agreement with the notion that decisions can be made using scientific criteria even under uncertainty.

In the socio-political dimension, the highest mean score was observed for SVS4 ($M = 0.540$, SD = 0.500), followed by SE1 ($M = 0.504$, SD = 0.502). Conversely, the lowest mean score was found in SVS1 ($M = 0.216$, SD = 0.413), indicating that participants had greater difficulty understanding the potential solutions after a wildfire, particularly regarding the balance of social, economic, and environmental factors in decision-making.

The Kolmogorov–Smirnov test indicated that the assumption of normality was violated for all dimensions ($p < 0.001$), justifying the use of non-parametric tests in subsequent analyses.

To explore potential differences in NoSTEM knowledge based on gender, the Mann–Whitney *U* test was conducted, revealing no statistically significant differences between male and female participants.

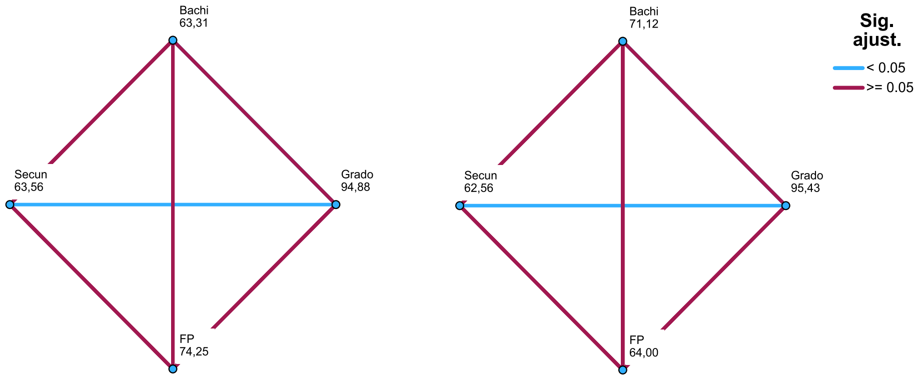


Fig. 5 Node diagram representing pairwise comparisons between educational levels regarding NoSTEM knowledge. The left side represents CES, while the right side corresponds to the SPS. In each diagram, all educational levels are represented: top, post-secondary high school; left, secondary education; right, university degree; and bottom, vocational training

Table 6 Kruskal–Wallis test results for NoSTEM by educational level

Dimension	Educational level	*N*	Mean rank
Cognitive-epistemic system (CES)	Secondary	96	63.56
	High school (post-secondary)	13	63.31
	Vocational training	2	74.25
	University degree	28	94.88
	Total	**139**	
Socio-political system (SPS)	Secondary	96	62.56
	High school (post-secondary)	13	71.12
	Vocational training	2	64.00
	University degree	28	95.43
	Total	**139**	
Overall NoSTEM knowledge	Secondary	96	61.39
	High school (post-secondary)	13	67.81
	Vocational training	2	72.25
	University degree	28	100.39
	Total	**139**	

The Kruskal–Wallis test was performed to examine differences in NoSTEM knowledge across educational levels. The results indicated statistically significant differences among some groups in both dimensions (secondary education and university degree), as shown in Fig. 5.

As shown in Table 6, data suggest that individuals with higher educational levels tend to score higher in both NoSTEM dimensions. This pattern aligns with expectations, as advanced education likely provides more opportunities for interdisciplinary reflection on the socio-political aspects of science and technology. The increase in the cognitive-epistemic dimension is also evident but less pronounced, suggesting that while exposure to scientific knowledge may begin at earlier educational stages, it is refined further at higher levels of study.

It is important to note that this analysis focuses exclusively on quantitative data from the instrument's closed-ended items. A more in-depth study of the open-ended responses is currently in progress, as these require detailed and rigorous qualitative analysis. The results of this qualitative examination will be presented in future publications to ensure a thorough and nuanced interpretation of participants' conceptual understandings.

These initial results provide a preliminary characterization of participants' NoSTEM knowledge and suggest that the instrument effectively differentiates between dimensions, educational levels, and specific aspects assessed within each category.

5 Discussion

The policies for democratizing scientific knowledge have become a priority for multiple countries and are shaping the future agendas of relevant institutions (European Commission., 2021) The refore, developing assessment tools that provide insight into the knowledge and biases that citizens hold about science is essential, particularly considering the increasing complexity of socio-scientific challenges (Romine et al., 2017). While existing assessment frameworks have largely focused on conceptual knowledge or procedural skills in STEM education, this study presents an alternative approach that incorporates epistemological and socio-political dimensions, thereby broadening the scope of scientific literacy research (Bezzi, 1999; Simonneaux, 2014).

A key contribution of this study is the development of a structured protocol for designing NoSTEM assessment instruments, anchored in the seamless web and FRA approaches. By establishing a solid philosophical framework, this work aligns with broader efforts to redefine scientific literacy beyond factual knowledge, emphasizing the integration of cognitive-epistemic and socio-political dimensions (Erduran & Dagher, 2014).

The confirmatory factor analysis results indicate strong construct validity for the closed-ended items ($CFI > 0.90$, $RMSEA < 0.05$), supporting the robustness of the instrument's design. However, beyond these statistical results, the instrument's ability to differentiate across educational levels provides compelling evidence of its practical relevance. This suggests that students at different educational stages develop distinct ways of engaging with interdisciplinary knowledge, reinforcing the argument that scientific literacy evolves through educational experiences rather than being a static competency (Rissanen et al., 2023).

The validation confirmed that the instrument effectively captures epistemological and socio-political dimensions. The cognitive-epistemic system items, for instance, revealed that students often struggle with applying epistemological concepts such as uncertainty, modeling, and interdisciplinary integration to real-world problems. This aligns with previous research indicating that students typically develop a fragmented understanding of science, viewing disciplines as separate rather than interconnected fields (Ortiz-Revilla 2020). Including predictive reasoning and methodological reflection within the instrument contributes to addressing this issue by explicitly assessing students' ability to engage with scientific uncertainty and methodological plurality (Shtulman & McCallum, 2014). Similarly, the socio-political dimension highlights the complex interplay between science and society (Sadler, 2014). Responses to items related to institutional collaboration, ethical concerns in scientific publishing, and the role of economic factors in environmental decision-making suggest that students' perceptions of science are often shaped by external sociocultural influences rather than an intrinsic understanding of the scientific process (Sherman et al., 2022). This reinforces the importance of integrating critical science education approaches that encourage students to reflect on the social structures that influence scientific research and technological development (Chowdhury, 2016).

6 Conclusions

This study successfully developed and validated a novel instrument, EPISTEMIK-Fire, aimed at evaluating the NoSTEM approach by integrating both the cognitive-epistemic and socio-political aspects of STEM knowledge. The emergent nature of STEM enables the formulation of fundamental questions about the nature of science, technology, engineering, and mathematics and their interaction with society. This fosters a more critical conceptualization of STEM education (McComas & Nouri, 2016), highlighting the need for a more holistic evaluative approach that incorporates both interdisciplinarity and critical reflection. EPISTEMIK-Fire addresses the traditional dimensions of STEM understanding and provides a framework for integrating the social, ethical, and political considerations inherent in contemporary technoscientific decisions, making the instrument a valuable resource for educational transformation.

The design and structure of EPISTEMIK-Fire respond to the need for evaluative tools capable of reflecting the complexity of technoscientific knowledge and its application to real-world problems. Unlike other instruments focused on isolated aspects such as attitudes or self-efficacy in STEM, EPISTEMIK-Fire stands out for its ability to capture interdisciplinary integration and critical reflection, which are fundamental components of the NoSTEM approach. The statistical validation, based on principal component analysis and confirmatory factor analysis, confirmed the bifactorial structure of the instrument, reinforcing its reliability and robustness. These results highlight the clear differentiation between the cognitive-epistemic and socio-political systems proposed in the theoretical framework of NoSTEM, confirming its adequacy as an effective tool for evaluating both students' conceptual understanding and their critical reflection on the social and ethical implications of science.

The educational implications of EPISTEMIK-Fire are significant, as its application not only enhances STEM teaching and learning but also promotes a more critical and integrated scientific literacy. By enabling a holistic evaluation that encompasses epistemological, social, and ethical dimensions, the instrument provides educators with a practical tool to foster deeper interdisciplinary learning. This approach has the potential to help students connect scientific concepts with real-world complex problems, developing the critical skills necessary to address contemporary technoscientific challenges.

In terms of teacher training, EPISTEMIK protocol could play a crucial role by providing an empirical foundation for identifying areas of improvement in STEM pedagogy. The instrument facilitates the collection of precise data on students' understanding, allowing teachers to adjust their pedagogical strategies more effectively and promoting a more reflective, student-centered teaching approach. In this way, EPISTEMIK protocol contributes to learning evaluation and supports educational transformation by fostering a more critical, conscious, and participatory STEM literacy among students.

However, despite these promising results, the study has some limitations that should be considered. While the instrument's bifactorial structure has been validated, moderate internal consistency was observed in some categories, particularly in the socio-political system, suggesting the need for further refinement of the items to improve precision and reliability. Additionally, the interpretation of the open-ended items, although valuable for capturing students' critical perspectives, can be subjective and context-dependent, presenting a challenge for obtaining more consistent and comparable results. It is recommended to adjust the wording of these questions to reduce variability in responses and allow for more uniform analysis of the evaluated dimensions.

Another limitation is that the instrument was primarily tested in the context of fire ecology, which could restrict the generalization of the results to other STEM knowledge areas. However, ongoing research is addressing this limitation by applying EPISTEMIK to the study of extreme weather phenomena. Preliminary results, such as those presented in another work from our research group (Martínez-Martínez et al. 2024b), suggest that the testing approach is effective and adaptable, supporting its broader applicability and robustness across different educational contexts. Future research should focus on conducting longitudinal studies that can evaluate how NoSTEM understanding evolves in students over time and at different stages of their education. This could help identify learning patterns and enable more precise adjustments to the instrument to better reflect the dynamics of students' cognitive and critical development. Additionally, exploring the application of EPISTEMIK protocol cross various educational levels, from secondary school to university, and in different STEM disciplines could help refine its structure to align with the particularities of each knowledge area.

Moreover, future research could aim to improve the integration of the socio-institutional dimensions of NoSTEM within the instrument by developing more specific and detailed items that reflect the complexity of the social and ethical factors associated with technoscientific knowledge. It would also be relevant to conduct comparative studies in different cultural and geographical contexts to evaluate the instrument's cultural sensitivity and its ability to adequately capture variations in STEM understanding based on social, economic, and educational factors.

In conclusion, EPISTEMIK protocol not only provides a solid tool for evaluating STEM understanding, but it also acts as a catalyst for a more critical and interdisciplinary education. By promoting the integration of epistemological, social, and ethical perspectives, the instrument contributes to a more democratic scientific literacy, empowering students to critically analyze and question the technoscientific decisions that affect society and the environment. This reinforces the relevance of the NoSTEM approach in today's education, emphasizing the need to continue promoting teaching that combines interdisciplinarity with ethical reflection, fostering a society that is more aware and responsible in facing contemporary technoscientific challenges.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11191-025-00643-2.

Acknowledgements The authors would like to thank the collaboration of the participants and experts in the development of the research. Special thanks to Delfín Ortega-Sánchez for his assistance and advice.

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Funding Open access funding provided by FEDER European Funds and the Junta de Castilla y León under the Research and Innovation Strategy for Smart Specialization (RIS3) of Castilla y León 2021-2027.

Data Availability All data and materials have been collected and prepared in accordance with the research protocols established by the Ethics Committee of the University of Burgos. They are available on the Editorial Manager platform as attachments.

Declarations

Ethics Approval and Consent to Participate This study involved human participants, including minors, who completed questionnaires designed by the authors. The research protocol was reviewed and approved by the University of Burgos Bioethics Committee, which confirmed compliance with ethical standards, including the Declaration of Helsinki (2013), the UNESCO Universal Declaration on Bioethics and Human Rights (2005), the EU General Data Protection Regulation (GDPR 2016/679), and the Spanish Organic Law 3/2018 on Data Protection and Digital Rights.

All participants, or their legal guardians in the case of minors, provided informed consent before participating. The study ensured anonymity and confidentiality, and all responses were processed following ethical guidelines. No personally identifiable information was collected, and data were used exclusively for research purposes.

Conflict of Interest The authors declare that they have no conflict of interest.

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