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How Scientists' Narratives on AI Signal a New Era for Science Education

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Abstract
Artificial intelligence (AI) has become a central topic in scientific and public discourse, raising important questions about its impact on science, society, and education. The paper reports an empirical study on 151 scientist commentaries published from 2021 to 2024 in the top scientific outlets of *Nature* and *Science* to examine evolving trends in AI-related communication in science. Using epistemic network analysis, we explored how scientists' narratives frame the nature of science (NOS), a central area of science education research since at least the 1960s. The current impact of AI on science needs to be understood in order to ensure that contemporary depictions of NOS in science education are consistent with the fast-changing landscape of scientific research. Findings show that expert commentaries address multiple dimensions of NOS, with scientific practices as the central concept. Surrounding these practices, scientific and social values emerge as key considerations for utilising AI as a tool for scientific research and social contributions. While epistemic aspects of NOS remain a focus, the findings suggest that the launch of ChatGPT in late 2022 shifted attention toward social-institutional dimensions, emphasising more the social and political structures that underpin NOS. These trends highlight the evolving relationship between epistemic and societal aspects of AI, reflecting broader debates on ethics, governance, and applications. Expert commentaries serve as valuable resources for aligning science education with contemporary accounts of scientific research, and as such they signal a new era for science education in the age of AI where the social and institutional aspects of science play a major role. The implications for science education are discussed highlighting how socially embedded NOS can potentially prepare future scientists and citizens to critically engage with AI and other emerging technologies.

Keywords Science communication · Artificial intelligence · Nature of science · Family resemblance approach · Epistemic network analysis

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Introduction

Artificial intelligence (AI) has emerged as a transformative force, reshaping industries, economies, and societies while raising complex ethical, political, cultural and epistemological questions. As AI technologies advance, debates surrounding their implications—such as transparency, accountability, and fairness—have intensified, making AI a central topic in science communication (Heaton et al., 2024; Li et al., 2024; Yeo et al., 2023) as well as science education (Clark, 2023; Tang, 2024a). These discussions not only highlight AI's technological capabilities but also underscore deeper issues related to the nature of science (NOS) (Cheung et al., 2025a; 2025b; 2025c; Erduran & Levrini, 2024). Investigating how AI is framed through the lens of NOS is critical for understanding how scientific knowledge is constructed, validated, and communicated in an era of rapid socio-technological change (Chan et al., 2023; Cheung et al., 2023; Nielsen, 2013). In the context of AI, where debates often involve contested claims about algorithmic transparency, biases, and societal impacts, examining how nature of science (NOS) is defined, communicated and learned becomes especially relevant for science education.

NOS is defined in the literature as "epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development" (Lederman et al., 2002, p. 498). It also encompasses broader themes such as the social, and institutional dimensions of science, the interplay between evidence and interpretation, and the role of uncertainty and tentativeness in scientific claims (Erduran & Dagher, 2014). Promoting public understanding of NOS is widely recognised as essential for fostering scientific literacy and enabling informed engagement with scientific issues (Bonney et al., 2016; Lederman et al., 2014). Although NOS has been a major area of research in science education for many decades, and various perspectives have been proposed to characterise NOS such as the "consensus view" (Lederman et al., 2002), "features of science" (Matthews, 2012), "whole science" (Allchin, 2011) and "family resemblance approach" (Erduran & Dagher, 2014; Irzik & Nola, 2014), research literature is yet to address the impact of AI on NOS. Apart from an exploration of the impact of AI on scientific practices (Erduran & Levrini, 2024) and a systematic review at the intersection of NOS and AI literature (Cheung et al., 2025a, b), there is limited understanding of how AI might be influencing NOS and what the implications might be for science education.

A potential source for identifying how NOS might be influenced by AI is to trace the discourse of scientists themselves. The ways scientists communicate have long been a central focus of science communication research (Bubela et al., 2009; Bucchi, 1996; Fischhoff, 2019; Horst, 2013; Kueffer & Larson, 2014). Scientist commentaries published in influential journals, such as *Nature* and *Science*, serve as platforms for shaping academic and policy debates. While these journals are not widely accessible to the general public, they influence educators, policymakers, and journalists who mediate public understanding of scientific developments (Medin & Bang, 2014; Scheufele, 2014). Analysing how such commentaries frame AI provides insights into the ways scientific expertise is communicated and how evolving narratives reflect broader societal concerns and priorities. The rise of AI, particularly with the launch of tools like ChatGPT in late 2022, has amplified concerns about ethical governance and political power structures, shifting the focus of public debates (Heaton et al., 2024; Li et al., 2024; Yeo et al., 2023). These developments underscore the importance of examining whether expert commentaries continue to emphasise foundational scientific values, methods, and practices or pivot toward broader socio-political dimensions. Tracking these shifts helps reveal how scientists frame AI's evolving role and societal implications, providing valuable lessons for science communication and education.

The paper reports an empirical study that investigated 151 expert commentaries published from 2021 to 2024 in *Nature* and *Science* to explore how AI-related discussions communicate NOS, particularly focusing on how aspects of NOS may be discussed in an interconnected manner. Relying on these elite scientific outlets ensures access to authoritative voices shaping AI discourse, though it may reflect a perspective skewed toward established scientific priorities and institutional contexts, potentially underrepresenting diverse or marginalised viewpoints. This focus, however, provides a critical lens for understanding how expert narratives inform science education and public engagement. The study aimed to map evolving trends in expert narratives, focusing on the balance between the epistemic aspects of science with scientific values and broader ethical or political concerns. By analysing the scientists' narratives, the research contributes to understanding of how scientific expertise is framed and how such framing can inform strategies for science education in the age of AI. The theoretical background is informed by how NOS relates to science communication and AI.

Theoretical Framework

Science Communication and Nature of Science

Although there is a longstanding tradition of research on NOS in science education (e.g., Lederman & Lederman, 2014; McComas & Olson, 1998), there is limited research exploring science communication efforts in the context of NOS (Nielsen, 2013). Some recent efforts have explored the teaching and learning of NOS in informal science learning contexts such as citizen science projects (e.g., Dvir & Tsybulsky, 2025). Science communication is a critical field of study that explores how scientific knowledge is conveyed to the public, decision-makers, and other stakeholders (Baram-Tsabari & Lewenstein, 2017). It involves a diverse range of topics, including the framing of scientific information, the public's understanding of science, and the role of media in science dissemination (Lewenstein, 2022). Research on NOS, on the other hand, focuses on the philosophical, epistemological, and sociological foundations of scientific knowledge (Erduran & Dagher, 2014; Lederman et al., 2002). It explores questions about how science works, how knowledge is constructed, and the criteria by which scientific claims are evaluated and accepted.

Although research on science communication and NOS have had separate origins and progression, the two fields are inextricably linked. Science communication research often incorporates insights from NOS and vice versa. This relationship is essential because effective science communication depends not only on the accurate transmission of scientific facts but also on an understanding of how scientific knowledge is constructed, validated, and understood within society (Nielsen, 2013). Both lines of research contribute to the broader goal of fostering a scientifically literate public and supporting informed decision-making in a society increasingly shaped by science and technology. Research on NOS encompasses the philosophical and methodological foundations of scientific inquiry (McComas & Olson, 1998). Researchers in this field address fundamental questions about science, such as the following: *What counts as scientific knowledge? How do scientists generate and validate knowledge? What are the limitations of science? How does science relate to other forms of knowledge (e.g., religion, ethics, or the humanities)?* These questions are crucial for understanding the dynamic nature of scientific practice but traditionally they have often overlooked the social context in which science is situated particularly in the science curriculum context (e.g., Yeh et al., 2019). The social-institutional contexts of science are critical in the formulation, validation and dissemination of scientific knowledge (Erduran & Dagher, 2014).

Science communication research involves investigating how scientific knowledge is disseminated and understood across different audiences, including the general public, policy-makers, educators, and the media (Lewenstein, 2022). A major concern of science communication is not only to convey scientific facts but also to convey how science works—its processes, limitations, and tentativeness (Wilkinson, 2021). Science communication can benefit from NOS perspectives in numerous ways including clarifying the tentativeness of scientific knowledge, addressing misconceptions about objectivity in science, explaining the creativity involved in science and framing science as a social process. One of the most important aspects of the nature of scientific knowledge is its tentativeness (Lederman et al., 2002). Scientific knowledge is always subject to revision based on new evidence. This characteristic poses a challenge for science communicators because the public often perceives science as offering absolute truths or definitive answers. Science communicators must help audiences understand that scientific knowledge evolves over time and that uncertainty is a natural part of the scientific process. For example, when discussing topics like climate change or the origins of life, science communicators need to emphasise the tentative nature of scientific theories while also stressing the strength of the evidence supporting those theories (Cobern et al., 2022). Misunderstanding the provisional nature of science can lead to misinterpretations or mistrust of scientific findings.

Another core concept of NOS is the objectivity of scientific inquiry (Niaz, 2018). Science is often perceived as a neutral, unbiased search for truth. However, science is conducted by humans, and human biases—conscious or unconscious—can influence research (Chan, 2025). Social, cultural, and political factors can also shape the research questions posed, the funding available, and the interpretation of results (Erduran & Dagher, 2014). Science communicators must navigate the complexity of conveying science's objectivity while acknowledging that science is not entirely free from biases. While objectivity and empirical evidence are critical in science, creativity plays a crucial role in scientific discovery (Savojardo, 2024). Scientific breakthroughs often emerge from creative thinking, the formulation of innovative hypotheses, and the development of new methodologies (Callaway, 2022). A further area of potential cross-fertilisation of science communication and NOS research is the social context of science. Science is not an isolated, individual endeavour. It is a social process, involving collaboration, peer review, and the influence of societal values. The development of scientific knowledge is shaped by funding structures, political contexts, and cultural norms (Erduran & Dagher, 2014). Understanding science as a social process allows communicators to explain how scientific knowledge is not only shaped by evidence but also by the contexts in which it is produced.

The ultimate goal of both science communication research and research on NOS is to enhance public scientific literacy. Scientific literacy refers to the ability to understand and make informed decisions about scientific issues that affect individuals and society. Similar to the scarcity of research on the intersection of scholarship in science communication and NOS, there is limited research exploring scientists' own views and perceptions of NOS (e.g., Poor et al., 2025; Schwartz & Lederman, 2008; Wong & Hodson, 2010; Wu & Erduran, 2022). Relatively little attention has been afforded to investigating the conceptions and values of scientists regarding communicating NOS to the public. These are significant gaps in the science education literature, considering that the public would greatly benefit from scientists' communicating the nature and validity of their research on contemporary, socially contentious scientific issues (Hodson, 2009).

Artificial Intelligence and the Nature of Science

Artificial intelligence (AI) is now widely used by scientists to generate hypotheses, design experiments, collect and interpret data in ways that were not previously possible with traditional methods alone (e.g., Wang et al., 2023). A well-known example of an AI tool used by scientists which led to the 2024 Nobel Prize in Chemistry is *AlphaFold*. The tool has enabled scientists to predict protein folding with great accuracy, already considered to have initiated a revolution in biology (Callaway, 2022). A recent survey conducted by the publisher Wiley involving nearly 5,000 researchers in more than 70 countries explored how scientists are using AI tools in their work. The survey asked researchers how they are currently using generative AI tools — which include chatbots such as ChatGPT and DeepSeek — as well as how they feel about various potential applications of the technology. The results suggested that majority of researchers see AI becoming central for scientific research and publishing. More than half of the respondents think that AI currently outperforms humans at more than 20 of the tasks given as example use cases, including reviewing large sets of papers, summarizing research findings, detecting errors in writing, checking for plagiarism and organizing citations. More than half of the survey participants expect AI to become mainstream in 34 out of 43 use cases in the next 2 years.

Although AI has become an important tool for scientists, science education research is still in its infancy in exploring its implications for how AI is impacting NOS. Much research in science education has been focusing on the pedagogical (Talanquer, 2023) and assessment (Clark, 2023) aspects of AI. In a recent systematic review of science education research articles published between 2012 and 2023, Cheung et al. (2024) investigated how AI technologies are being used in science education. Employing the Family Resemblance Approach to NOS as the analytical framework, the authors examined epistemic insight into relationships between science and AI documented in the literature. The analysis focused on some key categories of FRA as defined by Erduran and Dagher (2014): aims and values, methods, practices, knowledge, and social–institutional aspects. Of the original 627 articles identified, only 15 satisfied the coding criteria that focused on NOS. Of these 15 articles, epistemology was the targeted learning outcome of a small proportion of studies ($N=3$) suggesting that only a few studies considered developing learners' ways of knowing in AI and science as an important instructional outcome.

Although broad epistemological aspects of AI in science are now being considered (e.g., Billingsley et al., 2025), very few studies have explored the impact of AI on NOS for school science (Erduran, 2023; Erduran & Levrini, 2024). Drawing on the conceptualisation of scientific practices as a key aspect of NOS, Erduran and Levrini (2024) illustrated some recent examples from the work of research scientists in highlighting how scientists are using AI in their work and what such observations imply for the science curriculum. For example, by drawing on the emerging literature on the use of AI in scientific practices, they illustrated how biologists are engaging in modelling practices using AI.

Epistemic Authority of Generative AI in Science and Education

The rise of generative AI, such as ChatGPT and large language models, introduces a new layer of epistemic authority into science and education, challenging the traditional dominance of human experts and peer-reviewed knowledge (Cooper et al., 2024; Tang & Cooper, 2025). Building on the science communication focus outlined above, Generative AI's (GenAI) ability to produce fluent, authoritative content from probabilistic datasets redefines how scientific knowledge is mediated, aligning with the NOS emphasis on understanding the social and political aspects of knowledge construction and validation (Erduran & Levrini, 2024). This shift prompts critical questions about human epistemic agency—the capacity to actively shape and critique knowledge—particularly as science communication increasingly incorporates AI-driven narratives (Leslie, 2025; Oh & Lee, 2025).

Critics warn that GenAI risks eroding this agency by fostering over-reliance and epistemic passivity, especially in educational contexts where its outputs may lack empirical grounding or transparency (Peters et al., 2024; Tang & Cooper, 2025). This resonates with the AI-NOS literature's concern about disconnecting from material realities, as noted by Cheung et al. (2024), where GenAI's probabilistic nature contrasts with science's evidence-based epistemology. However, proponents suggest GenAI can enhance epistemic development when critically integrated, serving as a scaffold for hypothesis generation or data analysis, provided humans verify its contributions (Tang, 2024b). This dual perspective mirrors the evolving NOS frameworks in the AI context, where social-institutional dimensions gain prominence alongside epistemic ones (Erduran & Levrini, 2024).

Close examination of scientists' narratives about how AI is impacting their work can potentially reveal useful insight into how science education can be enhanced to represent an updated version of NOS in school science. In other words, current conceptualisations of NOS in the literature can potentially benefit from reflections on how AI is influencing NOS. Various methodological approaches can be utilised for such a purpose including surveys, interviews, case studies, focus groups and observational studies. Our main objective in this paper is to understand how a broad range of scientists are communicating about science impacted by AI in their publications. In other words, drawing on the earlier discussion on science communication and NOS, we aim to investigate the nuances of how scientists view different aspects of NOS given the developments in AI. Hence, in the rest of this paper, we report an empirical study that has used Epistemic Network Analysis (ENA) as a methodological approach to map scientists' narratives about AI use in science as captured in the top science journals *Nature* and *Science*. ENA is suitable for addressing the main objective of the paper as it enables the analysis of the relational comparisons of different aspects of NOS. Furthermore, given existing studies that have used ENA to investigate similar NOS content in science curricula (Caramaschi et al., 2022), concrete recommendations can thus be made for curriculum reform to reflect how scientists are emphasising NOS in the age of AI.

Methodology

Research Questions

The empirical study was guided by the following research questions:

1. What do scientists' narratives published in *Nature* and *Science* suggest about how AI is impacting NOS?
2. What are the implications of scientists' narratives for science education?

Data, Content Analysis and Analytic Framework

The study examines expert commentaries on artificial intelligence (AI) published in two leading scientific journals, *Nature* and *Science*. These journals were selected for their reputation for providing timely and forward-looking perspectives on scientific advancements. Articles were sourced using the keyword 'Artificial Intelligence' through their official search engines, yielding 242 commentaries from *Nature* and 226 from *Science*. The retrieved articles were screened and classified by the research team of three into three categories: (1) Core AI Focus – Articles where AI is central, as evidenced by its prominence in titles (i.e., explicit mention of 'AI,' 'artificial intelligence,' or related terms in the title or subtitle) and frequent mentions throughout the text (i.e., AI discussed substantively in at least 30% of the paragraphs, indicating it as a primary theme rather than a peripheral element); (2) Partial AI Focus – Articles that discuss AI in specific sections or paragraphs without making it the primary focus; and (3) Incidental Mentions – Articles that mention AI briefly, such as in author affiliations or as passing references to technological advancements. To establish and validate the classification scheme of screening, the team reviewed and discussed the first author's codes from 20% of the sample to refine the scheme through discussion of discrepancies on a subset of data. After discussion to reach consensus on ambiguous cases and refine the scheme, the first author completed the classification for the remaining sample. For this analysis, only category 1 was selected ($N = 151$), as the articles in this category provide substantive engagement with AI-related concepts.

To analyse the selected commentaries, the study employed the Family Resemblance Approach to the Nature of Science (FRA-NOS) as an analytical framework (Erduran & Dagher, 2014). The FRA-NOS has been used as an analytical tool for various purposes including document analysis in the context of science curricula (e.g., Xie et al., 2025) and newspapers (e.g., Cheung et al., 2023, 2025a, b). It offers a comprehensive lens for examining the multifaceted nature of science, integrating both cognitive-epistemic and social-institutional dimensions. Furthermore, it emphasises science as a dynamic process involving the production, validation, and dissemination of knowledge, influenced by broader societal, economic, and political factors. A key strength of the framework lies in its ability to depict science as a system of interconnected practices and values shared across disciplines. This perspective is particularly relevant for analysing AI—a field that merges computational methods, data-driven approaches, and ethical considerations while intersecting with social and political systems. AI thus serves as a compelling case for investigating how scientific knowledge is constructed, communicated, and contested. The framework categorises science into 11 interconnected dimensions that encompass both epistemic processes and social contexts (see Table 1). These dimensions capture aspects such as knowledge production, methodological practices, professional activities, and political influences.

A deductive coding approach guided by the FRA-NOS framework was used to analyse the commentaries. Each article was examined for explicit and implicit references to these dimensions (see examples in Table 1). The coding scheme was established through an initial coding of 20% of the sample by the first author independently, followed by a team review and discussion of the codes for refining the coding scheme through discussion of (dis)agreements on a subset of data. This follows Cheung and Tai (2021) arguments of the debatable necessity of full dataset intercoder reliability in interpretive qualitative research, emphasizing its use for refining the coding scheme through discussion of disagreements on a subset of data, after which a single expert coder can reliably apply the scheme to the remainder. After discussion to reach consensus on ambiguous cases and refine the scheme, the first author coded the remaining sample. This approach facilitated the identification of patterns in how AI is framed as both a scientific and societal phenomenon. The analysis also captured how expert narratives evolved in response to technological developments, such as the release of ChatGPT, and how they balanced epistemic concerns with ethical, political, and economic considerations. By leveraging the FRA-NOS framework, the study highlights how AI is communicated and contextualised within broader scientific and societal debates. These insights have important implications for science education, public engagement, and policymaking."

Epistemic Network Analysis

Epistemic Network Analysis (ENA) is a quantitative method for modelling connections between concepts within data, enabling the identification of patterns in discourse (Shaffer, 2017; Shaffer et al., 2016). ENA is grounded in the assumption that meaningful insights can be derived from analysing how predefined features co-occur within structured segments of data referred to as conversations. This method is particularly useful for examining the relational structure of ideas, making it well-suited for analysing complex topics like AI and its societal dimensions. ENA models connections among codes by quantifying their co-occurrence within defined conversational contexts, producing weighted network graphs and visualisations for each unit of analysis. These visualisations allow researchers to interpret connections and differences across datasets, offering insights into the framing of scientific narratives. Given its adaptability, ENA has been applied in diverse fields (Reid et al., 2024), including curriculum and assessment in science education (Cheung, 2020), science communication (Chan et al., 2023), and policy analysis (Nguyen et al., 2024). The current study leverages ENA to explore how expert commentaries frame the NOS in discussions about AI.

We conducted ENA using the ENA Web Tool (version 1.7.0) (Marquart et al., 2018) to analyse the structure of connections among NOS concepts within expert commentaries. The dataset included 468 commentaries published in *Nature* and *Science*, categorised by year and journal. Each commentary was coded according to the FRA-NOS framework (Erduran & Dagher, 2014), which defines 11 key dimensions of NOS as described in the previous section. Units of analysis were defined as all lines of data associated with a single year. Conversations were delineated by grouping text based on the year, allowing the modelling of temporal and contextual patterns. Codes were aggregated using binary summation, capturing the presence or absence of connections between pairs of NOS categories. Visualisation included two outputs: (1) a plotted point representing the network's position in low-

Table 1 Aspects of NOS situated in AI and excerpts from articles

Aspect	Definition	Keyword	Excerpts from Articles
Aims and Values	The scientific enterprise is underpinned by adherence to a set of values that guide scientific practices.	Accuracy, robust, objective	'[S]cientists are human and full of biases. In reality, it is the scientific method that allows biased and passionate people to *objectively* and *systematically* assess information and draw conclusions' (Garg, 2024).
Methods	The scientific enterprise encompasses a range of cognitive, epistemic and discursive methods.	Hypothesis, method,	'[A] *neural network trained* to classify images correctly identified a photograph of a panda. Then Goodfellow's team added a small amount of carefully calculated noise to the image' (Makin, 2024).
Practices	Scientists engage in disciplined inquiry by utilising a variety of observational and experimental activities to generate reliable evidence.	Experiment, data, modelling, prediction	'[T]here are *systematic experiments* done with artificial intelligence in order to test out how artificial intelligence can help us to keep public places safe' (Byrne, 2024).
Knowledge	Theories, laws, and models are interrelated products of the scientific enterprise that generate and/or validate scientific knowledge and provide logical and consistent explanations to develop scientific understanding.	Shown by study, law, theory,	'AI-assisted studies *have found* that both African savannah elephants (Loxodonta africana) and common marmoset monkeys (Callithrix jacchus) bestow names on their companions' (Savage, 2024).
Social Certification and Dissemination	Scientists engage in professional activities to enable them to communicate their research, including conference attendance and presentation, writing manuscripts for peer-reviewed journals, reviewing papers, developing grant proposals, and securing funding.	Review, evaluate, validate, assess	'Activities […] will focus on innovation and technology, including artificial intelligence (AI) and how it can be used to automate administrative tasks in the *peer-review process*' (Feinmann, 2024).
Scientific Ethos	Scientists are expected to abide by a set of norms both within their own work and during their interactions with colleagues and scientists from other institutions.	Bias, ethics, scientific norms, misinformation	'[I]f used *irresponsibly*, LLMs risk undermining the integrity of the scientific process' (Zou, 2024).
Social Values	By presenting their work at conferences and writing manuscripts for peer-reviewed journals, scientists' work is reviewed and critically evaluated by their peers.	Culture, beliefs, equity, diversity, sustainable	'*Safety* and *security* are core aspects of the *wellbeing* of nations, of countries, of people' (Byrne, 2024).

Table 1 (continued)

Aspect	Definition	Keyword	Excerpts from Articles
Professional Activities	The scientific enterprise embodies various social values including social utility, respecting the environment, freedom, decentralising power, honesty, addressing human needs, and equality of intellectual authority.	Conference, publish, presentation	'[T]he AI x Education *conference* in 2023 […] bring together secondary and university students and educators to have candid discussions about the future of AI in learning' (Wells, 2024).
Social Organisation and Interaction	Science is socially organised in various institutions including universities and research centres.	Institution, organisation, university, forum, platform	'It is unlikely that a single African *institution*, city or even country will have all the necessary components […] to be able to conduct world-class pharmacogenetics research' (Turon et al., 2024).
Financial Systems	The scientific enterprise is mediated by economic factors that influence research priorities, and who benefits from the produced knowledge.	Funding, economy, finance	'Africa is being managed, against its will, as the least rewarded link in the *global chain of the AI economy* by the big powers in the field' (Palmer, 2024).
Political Power Structures	The scientific enterprise operates within a social and political environment that imposes its own values and interests.	Power, government, united nation	'[T]he *US National* Science Foundation created the Directorate for Technology, Innovation and Partnerships to support use-inspired research and translate discoveries into real-world applications' (Wang, 2024).

dimensional space and (2) a weighted network graph showing the relative frequency of code co-occurrences. The network graphs were co-registered with the plotted points, ensuring interpretability. This methodological approach enables a systematic examination of how AI is framed within the NOS framework, providing insights into evolving narratives and their implications for public understanding and policy discourse. By leveraging ENA, the study uncovers patterns in the conceptual framing of AI, offering evidence for shifts in emphasis on political, ethical, and scientific values over time.

Results and Findings

The results of the ENA on scientists' narratives from the *Nature* and *Science* commentaries are summarised in Figs. 1 and 2. In Fig. 1, the horizontal axis of the ENA space (ENAx) illustrates the representation of the NOS in the examined articles, with scientific values positioned on the right and social values on the left. The vertical axis (ENAy) reflects the depiction of NOS, with political and financial systems at the top and professional activities and social interactions at the bottom. For each ENA network, the arithmetic mean of edge weights is represented by squares. Comparing the mean loci across years reveals patterns and shifts in the representational structure of NOS. A series of t-tests were conducted to compare the x- and y-loci means between pairs of ENA networks (Table 2). However, two-sample t-tests assuming unequal variance indicated no statistically significant differences between years. This finding suggests that the overall structure of NOS representations

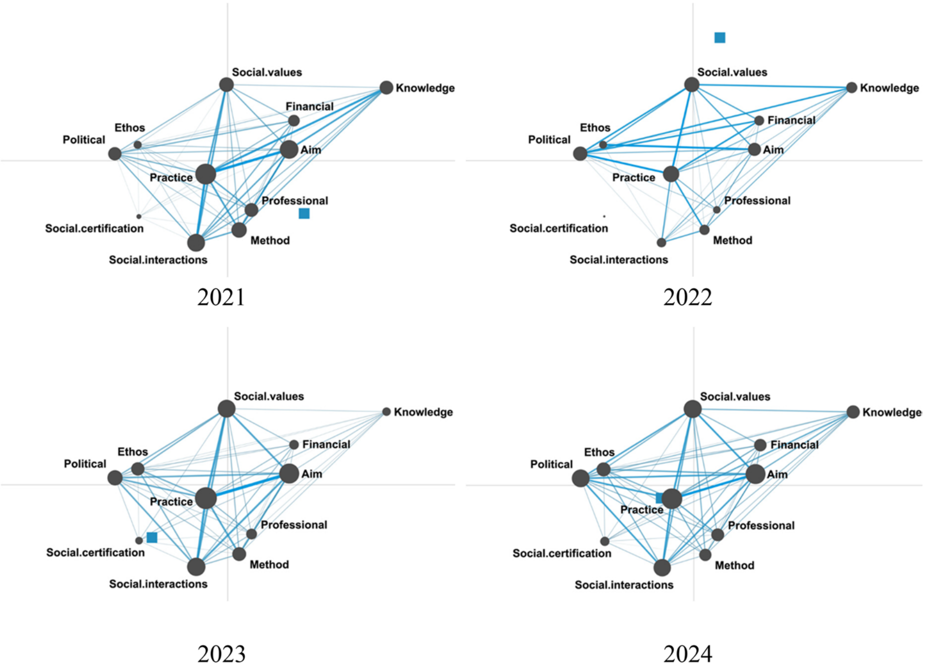

Fig. 1 Epistemic networks showing connections of NOS categories across 4 years

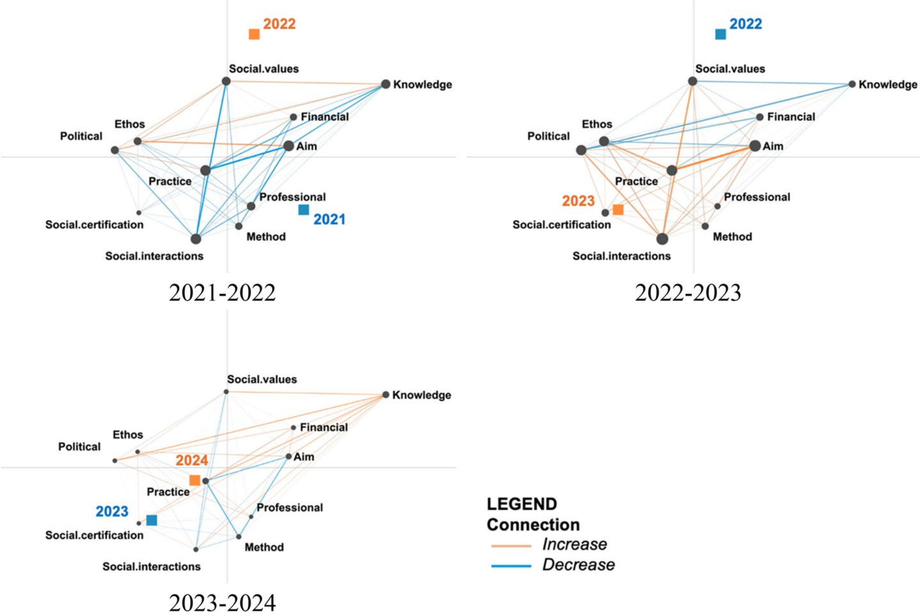

Fig. 2 Changes in connectivity in epistemic networks of NOS categories across 4 years

Table 2 Effect sizes of differences in positions of means of the epistemic networks in terms of its x-axis and y-axis positions, as computed by two-sample t-tests

	x-axis		y-axis	
2021	Cohen's d	p-value	Cohen's d	p-value
vs. 2022	0.83	0.54	−0.77	0.58
vs. 2023	3.57	0.11	0	1
vs. 2024	2.74	0.15	−1.28	0.33
2022				
vs. 2023	1.50	0.29	0.77	0.58
vs. 2024	0.89	0.48	0.59	0.66
2023				
vs. 2024	−0.83	0.49	−1.17	0.37

remained holistic and interconnected throughout the studied period. Unlike prior findings in Cheung et al. (2023), which observed fragmented patterns in newspaper coverage of NOS using the same analytical framework, expert commentaries consistently addressed multiple dimensions of NOS in a more integrated and balanced manner.

While the t-tests on the mean loci positions reveal no statistically significant differences in the overall network structures across years (p-values > 0.05, indicating that the observed differences in x- and y-loci means are not unlikely to occur by chance given the null hypothesis of no difference)—likely due to the exploratory nature of the study, the small number of temporal units (N = 4 years), and potentially limited statistical power from the sample size—these tests focus solely on aggregate positional shifts in the ENA space. The p-value, ranging from 0.11 to 0.66 across comparisons (e.g., p = 0.11 for 2021 vs. 2023 on the x-axis), suggests that the evidence is insufficient to reject the null hypothesis at the conventional 0.05 significance level, reflecting the study's exploratory design rather than a lack of effect. However, ENA is particularly valuable for its descriptive and visual capabilities, allowing for the identification of meaningful trends through qualitative examination of specific connection coefficients (edge weights) and network patterns. Such observable shifts in how NOS dimensions interconnect, even without statistical significance in overall loci, can still provide substantive insights into evolving narratives, as they highlight changes in emphasis and relational dynamics over time. For instance, effect sizes (Cohen's d) for the comparisons range from small to large (e.g., d = 3.57 for 2021 vs. 2023 on the x-axis, despite p = 0.11), where a d value above 0.8 indicates a large effect, suggesting a substantial difference in means relative to variability, even if not statistically significant due to sample constraints. This approach complements the quantitative tests by focusing on the nuanced, domain-specific interpretations inherent to discourse analysis.

Despite the lack of statistical significance in overall mean loci differences, a closer descriptive examination of the connection coefficients (edge weights) across the four years (Fig. 2 and Appendix A) reveals interpretable dynamic shifts in how expert commentaries frame NOS dimensions in relation to AI. These visual and relational patterns—such as changes in the strength of specific ties between epistemic and social-institutional categories—remain meaningful for understanding narrative evolution, as they reflect contextual influences (e.g., the launch of ChatGPT) and align with ENA's emphasis on modelling interconnected discourse rather than strict hypothesis testing. Scientific practices (P) consistently occupied a central position throughout the period investigated. In 2021, practices (P) showed the highest connectivity (0.3 with aims and values (A) and 0.26 with social organisations (SO)). Connections among epistemic dimensions, such as knowledge (K) and methods (M), were also relatively strong, emphasising AI as a tool for knowledge production. Social values (SV) and political structures (PS) showed moderate connections, reflecting

Table 3 Summary of key connection coefficients (CCs) and their implications across NOS categories (2021–2024)

Year	Findings	Implications
2021	CC(P-SV) = 0.14, CC(P-SO) = 0.26, CC(P-K) = 0.24; Early emphasis on epistemic practices (P) with moderate social ties.	Suggests initial focus on AI as a knowledge tool, with emerging societal awareness.
2022	CC(P-SV) = 0.23, CC(P-SO) = 0.15, CC(P-K) = 0.11; Shift toward social-ethical concerns (SE = 0.23 with A) and SV, with weaker epistemic links.	Indicates growing recognition of AI's social impact, pre-ChatGPT transition.
2023	CC(P-SV) = 0.25, CC(P-SO) = 0.26, CC(P-K) = 0.09; Stronger P-SV (0.25) and P-SO (0.26) post-ChatGPT, with reduced P-K.	Highlights intensified focus on governance and ethics, aligning with social-institutional shift.
2024	CC(P-SV) = 0.21, CC(P-SO) = 0.21, CC(P-K) = 0.16; Balanced P-SV and P-SO, with increased P-F (0.11) and P-PS (0.20).	Return to practical applications, embedding AI in economic and political contexts.

early considerations of AI's societal impact. By 2022, the focus shifted toward social and ethical dimensions, with social-ethical concerns (SE) (0.23 with A) and social values (SV) (0.23 with P) emerging as key nodes. Discussions highlighted AI's role in addressing social values, scientific ethos, and political power, while connections between epistemic practices (P) and social-institutional aspects (SV, SE) became more pronounced.

Following the launch of ChatGPT in late 2022, the 2023 focus turned further toward social-institutional dimensions. Practices (P) maintained strong connections (0.34 with A and 0.26 with SO), while SE (0.16 with SO) and SV (0.25 with P) gained prominence. Discussions emphasised the aims and values of science, focusing on governance and ethical frameworks. In 2024, narratives returned to AI as practices, with high connectivity observed between P and A (0.27) and P and SO (0.21). Financial (F) and political systems (PS) also became more integrated with practices (0.2 each), shifting focus to AI's applications in economic and political systems and its embeddedness in societal structures. These findings (Table 3) illustrate evolving patterns in AI-related communication—transitioning from epistemic practices to societal values and governance, and back to practical applications. Such observations highlight AI's dual role as both a scientific tool and a societal force, emphasising the need to balance epistemic and social dimensions when addressing AI's broader implications.

Implications for Science Education

The study provides insights into the evolving landscape of AI-related communication through the lens of the FRA-NOS framework. By analysing connection coefficients across 4 years, it highlights the shifting interplay between epistemic and societal dimensions of NOS in scientists' narratives as being shaped by AI. These findings contribute to the science communication literature by demonstrating how expert commentaries not only frame complex scientific issues but also adapt to technological and societal changes. The study's insights extend beyond communication strategies to implications for science education and public engagement. By highlighting the socially embedded NOS, the findings underscore the importance of integrating epistemic and societal dimensions into educational practices.

A key contribution of this study is its identification of dynamic shifts in how expert commentaries frame the NOS over time. Initially, there was an emphasis on epistemic dimensions—such as knowledge and methods—which reflected a traditional portrayal of AI as a tool for scientific inquiry and knowledge production. This approach aligns with Miller's (2001) deficit model of science communication, which prioritises transferring technical knowledge from experts to the public. However, as AI technologies advanced and became more integrated into society, the focus shifted toward broader societal concerns, including social values, ethical considerations, and governance structures. This transition mirrors a move toward dialogic models of science communication (Trench, 2008), where the relationship between science and society is more explicitly acknowledged. For example, the heightened emphasis on social values and political structures in 2023—following the launch of ChatGPT—demonstrates how technological milestones can shape the framing of scientific narratives. This pattern corresponds to prior research showing that public narratives around innovations often evolve as technologies progress from experimental phases to widespread adoption (Valente & Rogers, 1995; Xu et al., 2024). Early stages typically stress technical and epistemic aspects, while later stages focus on ethical considerations and societal impacts (Scheufele, 2014). These findings confirm this trajectory, illustrating how AI-related communication has shifted from epistemic practices to ethical concerns and back to practical applications. Such patterns align with Davies and Horst (2016)'s argument that science communication must address governance, ethics, and equity to remain relevant in discussions about emerging technologies.

The observation that scientific practices consistently occupied a central position in scientists' narratives throughout the period investigated is consistent with similar trends in the science curriculum coverage conducted in different countries with the same analytical framework of FRA to NOS (e.g., Caramaschi et al., 2022; Yeh et al., 2019; Xie et al., 2025). However, the shift toward social and ethical dimensions in scientists' narratives is reflected in only a few curriculum documents in the world, with Norway being a notable exception (Mork et al., 2022). Curriculum content analysis on the coverage of NOS using the FRA framework as an analytical tool has highlighted a trend of overemphasis on the cognitive and epistemic features of science. Such trends have been observed in science curricula of countries such as Brazil (Pimenta et al., 2025), Italy (Caramaschi et al., 2022) and Taiwan (Yeh et al., 2019). However, the emphasis on the social-institutional dimensions of NOS is consistent with the way that major news outlets tended to cover science stories during the pandemic (Cheung et al., 2023).

The trends in the findings in relation to existing literature in science education point to an urgent need for science curriculum reform to reflect the changing NOS in the age of AI. The increasing emphasis on the social and institutional aspects of science in scientists' narratives suggest that curricula would benefit from such broader contextualisation of NOS in the curriculum as other studies have also argued (e.g. Xie et al., 2025). There is emerging evidence on the positive impact of including social-institutional aspects of NOS in science teaching even in the education of young children (Akbayrak & Kaya, 2020). The precise nature of the inclusion of specific aspects of the social-institutional aspects of NOS need to take on board the global impact of the emerging AI technology, including the economic and political dynamics between developed and low-income countries (Palmer, 2024). Furthermore, given the changing nature of the traditional cognitive and epistemic aspects of science such as scientific practices and scientific methods also need to be revisited. For example, the capacity of AI tools in interpreting large set of data and the implications of such analyses for modelling point to the need to incorporate data literacy, a theme that has been gaining attention among science education researchers (Qiao et al., 2024). The theme of data literacy includes also critical data literacy (Sander, 2020) as well as broad themes such as data citizenship (Carmi et al., 2020).

Existing educational approaches to the teaching and learning of NOS need to update how AI is influencing science. Expert commentaries can serve as valuable resources for the teaching of NOS. Incorporating scientists' narratives into curricula can help students develop a deeper understanding of how scientific knowledge is constructed and applied, preparing them to critically evaluate emerging technologies (Cheung et al., 2024). Discussions about AI governance and ethics, for example, can provide a platform for exploring broader themes, such as the role of science in democracy, equity, and human rights. Although emerging research in the use of AI in science education is increasingly addressing the ethical dimensions of AI (Barak & Green, 2020; Usher et al., 2025), research on the contextualisation of ethics in relation to science itself in the age of AI is limited. By fostering critical thinking and ethical reasoning, educators can empower students to navigate contemporary debates about AI. Moreover, the findings highlight the importance of interdisciplinary approaches to science education. Addressing AI's societal impacts requires integrating perspectives from ethics, law, and social sciences, reflecting the interconnected nature of modern scientific challenges (Dijk, 2011). Such approaches resonate with calls for pedagogical models that emphasise real-world applications and societal relevance that have long been advocated in science education (Hodson, 2014).

Although the present study points to an urgent need to reform the science curriculum to cohere with the developments in AI-infused NOS, innovation in the science curriculum without complementary innovations in assessment and teacher education is unlikely to have significant impact on teaching and learning in everyday schools (Brink et al., 2024; Kärkkäinen, 2012). Zhai (2024) argues that machine learning can contribute to assessment of complex skills such as "understanding knowledge-in-use" but that assessment tools need to enhance model generalizability, addressing unbalanced data challenges, developing user guidelines, and improving the interpretations and uses of scores. Similar arguments can be made about the assessment of social, economic and political aspects of NOS that involve nuance and complexity of interpretation. Furthermore, assessment of multimodal representations of NOS is likely to prove fruitful when students are provided with the opportunity to express their learning in a diversity of formats (Cheung & Erduran, 2025). Accordingly, it is important to reconsider science teachers' professional development on a range of NOS teaching in the age of AI, including data literacy and modelling as well as their understanding of the traditionally underspecified aspects of NOS such as the social-institutional dynamics of NOS.

Discussion and Conclusions

The paper signals a new era for science, science communication and science education in the age of AI. Expert commentaries, as observed in this study, play a pivotal role in shaping nuanced and reflective accounts of science, particularly in the context of complex technologies like AI. The observation about the increasing emphasis on the social-institutional aspects of NOS in scientists' narratives while still maintaining a strong focus on scientific practices highlights the changing dynamics in the scientific enterprise. The new layer of epistemic authority introduced by AI is challenging the traditional dominance of human experts and peer-reviewed knowledge (Tang & Cooper, 2025). Generative AI's (GenAI) ability to produce authoritative content from probabilistic datasets redefines how scientific knowledge is mediated, aligning with the NOS emphasis on understanding the social and political aspects of knowledge construction and validation. This shift prompts critical questions about human epistemic agency—the capacity to actively shape and critique knowledge—particularly as science communication increasingly incorporates AI-driven narratives (Leslie, 2025).

Unlike news media, which often prioritises immediacy and sensationalism (Cheung et al., 2023), expert commentaries provide a balanced perspective that integrates epistemic, social, and ethical dimensions. This integrative approach contrasts with the fragmented narratives commonly found in mainstream media (Scheufele & Krause, 2019). By emphasising multiple dimensions of NOS, expert commentaries not only provide insight into recent developments about NOS but also can be used to foster critical thinking and scientific literacy, aligning with broader goals of science communication and education (Nisbet, 2009). These narratives illustrate how science communication can move beyond simply disseminating information to engage the public in deeper discussions about values, ethics, and societal implications. For instance, the strong connectivity between scientific practices and societal values in later years emphasises AI's dual role as a tool for knowledge production and a driver of social transformation. This observation aligns with the concept of co-production, which highlights the mutual shaping of science and society (Adelle et al., 2020).

The findings resonate not only with the literature on science communication (Baram-Tsabari & Lewenstein, 2017; Mercer-Mapstone & Kuchel, 2017; Oliveira et al., 2024) but also NOS in science education (Erduran & Dagher, 2014; Lederman et al., 2002; Matthews, 2012). Both literatures advocate for considering the social, political, and cultural contexts of scientific information although they may frame issues differently. Expert commentaries exemplify how science communication works by encouraging dialogue and negotiation around AI's implications, fostering a more participatory and democratic form of science communication. Rather than positioning science as an isolated authority, these narratives invite stakeholders to critically examine how AI shapes, and is shaped by, societal norms, governance systems, and ethical principles. Through this lens, expert commentaries emerge as effective tools for bridging the gap between specialised knowledge and broader public understanding. They enable a more inclusive and adaptive approach to science communication, addressing both epistemic uncertainties and societal concerns. Similarly, experts' narratives provide a source of understanding for considering how NOS is being affected by AI potentially leading to renewed conceptualisations of how science is considered in school science.

The focus on scientists' narratives provides a detailed perspective on professional discourse but may not capture broader public perceptions (Vaupotič et al., 2022) nor students' or teachers' perceptions of AI. Future studies can analyse media coverage, public debates, and social media discussions to examine how AI narratives circulate and evolve across different platforms impacting everyday citizens' perceptions of NOS. Likewise, school-based research could elucidate how teaching and learning of NOS can be enhanced through reflections on the impact of AI on NOS. Longitudinal studies spanning longer time frames (McKinnon & Lamberts, 2014) could also provide a more comprehensive view of how AI-related communication adapts to technological, societal and educational changes. Additionally, cross-cultural comparisons could reveal differences in how NOS is framed in diverse socio-political contexts, offering insights into global variations in science education (Medin & Bang, 2014). Finally, further research could investigate how audiences including science teachers interpret and respond to expert commentaries (McCarthy & Grant, 2024) exposing where further work is needed for updating understanding and perceptions of NOS in science teaching.

Appendix

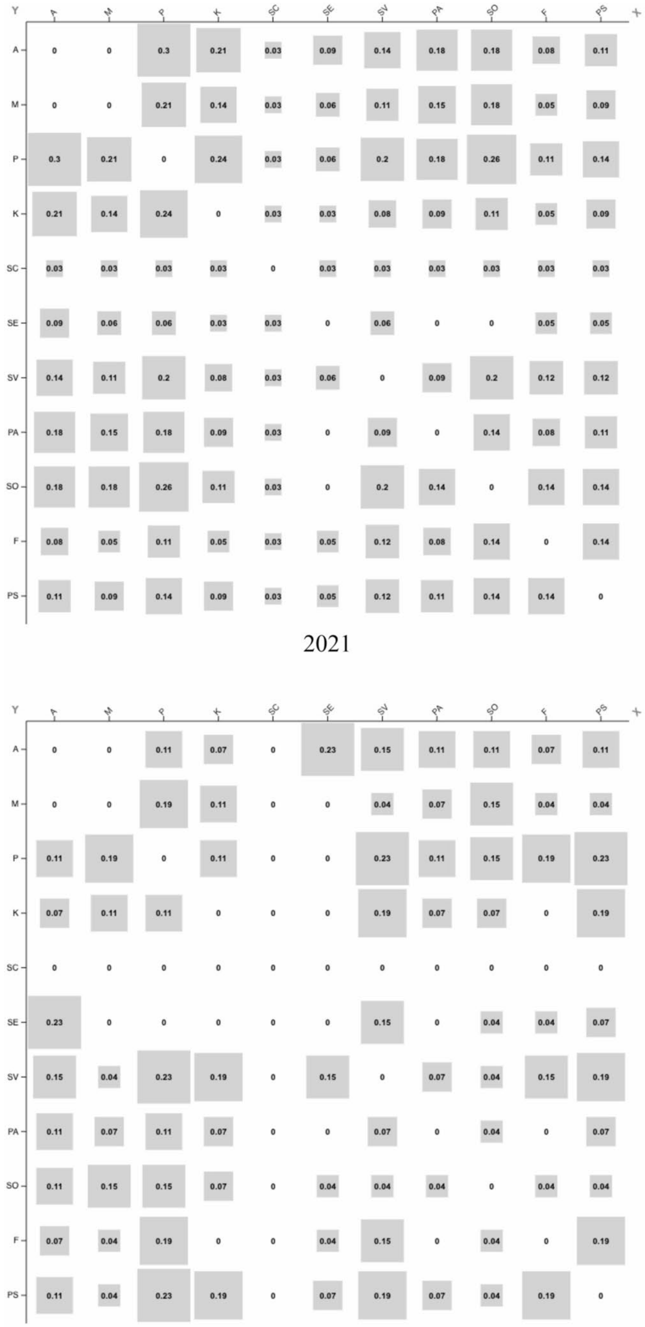

Fig. 3 Connection coefficients (CCs) among NOS categories across 4 years

Author Contributions Ho-Yin Chan conducted the data analysis and contributed to the literature review. Sibel Erduran wrote the literature review and conceptualised the theoretical framework as well as the implications for science education.

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Data Availability Data sharing is not applicable as the data are secondary data drawn from already published literature.

Declarations

The research did not have any research participants. It was based on document analysis which followed ethical guidelines. The project under which the research was undertaken was granted ethics clearance from the University of Oxford Department of Education Ethics Committee. Reference: CUREC EDUC_C1A_24_179

Conflict of interest The authors declare no conflict of interest.

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