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EXPLORING SCIENCE TEACHERS' TRANSLATION OF NATURE OF SCIENCE (NOS) KNOWLEDGE TO PEDAGOGICAL CONTENT KNOWLEDGE (NOS PCK)

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ABSTRACT

Purpose - This study is part of a comprehensive investigation conducted in Malaysia, examining science teachers' understanding of the Nature of Science (NOS) and their ability to translate this knowledge into Pedagogical Content Knowledge (PCK) for NOS. This paper specifically examines how teachers apply their NOS knowledge to develop NOS PCK in classroom settings.

Methodology - A qualitative approach was employed, involving observations of both practical and non-practical lessons, as well as semi-structured interviews with five in-service science teachers from a school in Petaling Perdana, Selangor. The teachers were chosen based on their experience in teaching science and their understanding of NOS. Lesson observations were guided by a structured checklist, while thematic analysis was used to interpret interview data, providing insights into the rationale behind their teaching methods related to NOS PCK.

Findings - The study found that Malaysian in-service science teachers face significant challenges in translating their understanding of NOS into effective teaching practices. There is a noticeable gap between teachers' conceptual knowledge of NOS and their PCK implementation. Teachers frequently missed opportunities to integrate key NOS concepts into their lessons and often portrayed scientific methods as fixed procedures while presenting science as static knowledge. These practices reflect a limited understanding of NOS principles.

Significance - The findings underscore the urgent need for ongoing professional development to improve teachers' NOS knowledge and their ability to integrate it into their teaching. The science curriculum should include clear guidelines to support the incorporation of NOS concepts, ultimately fostering improved scientific literacy among students.

Keywords*:* In-service science teachers, nature of science (NOS), nature of science pedagogical content knowledge (NOS PCK).

INTRODUCTION

In today's dynamic economic, social, and technological landscape, individuals must acquire a diverse set of skills to remain relevant. Among the most sought-after skills in job markets include language proficiency, creativity, and the increasingly rare ability to generate new knowledge. These skills are deeply rooted in an understanding of scientific progress (National Science Teachers Association [NSTA], n.d.). Therefore, continuous exposure to scientific knowledge and the ability to make informed decisions in daily life are essential.

There is substantial agreement in the literature that achieving scientific literacy requires a comprehensive understanding of the Nature of Science (NOS) as a structured discipline (Holbrook & Rannikmae, 2007). Lederman (1992), as cited in Hanuscin et al. (2010), defines NOS as understanding science as a way of knowing, encompassing the values and characteristics of knowledge essential for intellectual growth. Globally, NOS is recognised in educational systems, especially in countries aiming to promote scientific literacy, such as the United States (Rudolph, 2004), Singapore (Vinodhen, 2010), Thailand (Yuenyong & Narjaikaew, 2009), and Malaysia (Jain & Luaran, 2020; Mok & Jain, 2023).

NOS is globally recognised as a critical body of knowledge that contributes to the development of scientific literacy. The recently published PISA 2025 Framework emphasises the importance of students' ability to "research, evaluate, and use scientific information for decision-making and action," a skill closely related to NOS (Organisation for Economic Co-operation and Development [OECD], 2023a).

Despite its importance, existing research highlights a lack of advanced NOS knowledge among teachers. For instance, Bloom et al. (2015) found that a significant proportion of teachers lack sophisticated NOS knowledge. Studies by Dogan and Abd-El-Khalick (2008), Guerra-Ramos et al. (2010), Akerson et al. (2009), and Kartal et al. (2018) have identified several misconceptions about NOS among teachers. Leden et.al (2013) has reported the connection between teachers' NOS understanding and their ability to effectively teach NOS. Insufficient NOS-understanding often hinders teachers from delivering effective NOS instruction in science classrooms. This situation is also evident in Malaysia, where lower-secondary in-service science teachers generally lack advanced NOS understanding (Mok & Jain, 2023). NOS is often regarded as a complex and challenging concept (Sumranwanich & Yuenyong, 2013), requiring considerable effort to master.

Undeniably, teachers play a pivotal role in education. A shortfall in science education was pointed out by Jain et al. (2013) who noted that students often learn science without developing accurate conceptions of the Nature of Science (NOS). This issue is particularly concerning because science teachers, as the primary facilitators of NOS knowledge, are crucial in ensuring students receive accurate scientific conceptions. Alarmingly, 10 years after the findings reported by Jain et al. (2013), Mok and Jain (2023) revealed that Malaysian in-service science teachers still lack a sophisticated understanding of NOS. Nevertheless, having a sound understanding of NOS alone is insufficient.

Studies such as Supprakob et al. (2016) and Bennetts (2021) argue that there is no direct link between NOS knowledge and its enactment in science teaching. This underscores the urgent need to focus on how Malaysian in-service teachers translate their knowledge of NOS into Nature of Science Pedagogical Content Knowledge (NOS PCK).

For teachers to effectively integrate NOS into science instruction, they require a specialised form of knowledge known as NOS PCK. Shulman (1986) identified seven essential knowledge bases for teaching, which include: (i) content knowledge (ii) pedagogical content knowledge (iii) curriculum knowledge (iv) knowledge of learners (v) general pedagogical knowledge (vi) knowledge of educational aims, purposes, and values and (vii) knowledge of educational contexts. However, other researchers, such as Shing et al. (2015), argue that teaching is too complex to be confined to these categories. A review of the literature conducted prior to this study identified the different knowledge bases required by science teachers to effectively integrate NOS into science lessons. These include: (i)

NOS knowledge, (ii) Pedagogical Knowledge (iii) Content Knowledge about Science, and (iv) Pedagogical Content Knowledge. These knowledge bases align with, although do not entirely encompass, Shulman's (1986) framework. These knowledge bases equip teachers with the basis of what to teach, how to teach and why they teach what they are teaching. This enables teachers to not only be subject matter experts but also effective guides, helping students grasp the epistemology of science.

Lederman and Lederman (2019) emphasized that teachers require a comprehensive understanding of both NOS content and the pedagogical knowledge (NOS PCK) to effectively teach NOS. NOS PCK plays a significant role in enhancing students' understanding of NOS, as it bridges content knowledge and teaching strategies. Translating NOS into NOS PCK is essential for fostering scientific literacy among students, enabling them to develop an informed and critical understanding of NOS and its impact on human perception of the world (Lederman & Lederman, 2019). This understanding helps students perceive science lessons as meaningful learning opportunities (Mohan et al., 2017).

For students to truly grasp scientific concepts, they need to feel connected to the material. This connection is fostered when teachers effectively translate content knowledge (CK) into pedagogical strategies (PCK), which engage students and motivate them to learn, ultimately advancing scientific literacy (du Toit-Brits, 2022). However, in many Asian countries, including Malaysia, teaching often relies on the drill-and-training approach, which focuses on repetitive exercises assigned by teachers to ensure content mastery (Yahaya & Chu, 2010). While this method helps students master content, it does not necessarily create meaningful learning experiences in the classroom.

Researchers argue that teachers proficient in translating NOS into NOS PCK are better equipped to implement scientific inquiry methods, which promote students' reasoning skills and their ability to engage with and negotiate scientific ideas (Schwartz et al., 2004). Nevertheless, the limited research on this topic suggest that these insights may not fully apply to Malaysian classrooms. Therefore, exploring the practice of NOS PCK in Malaysian classrooms is essential to understand how teachers' instructional methods influence students' science learning experiences.

A crucial factor in advancing the nation towards scientific literacy is fostering motivation in learning. However, international assessment studies, such as Trends in International Mathematics Science Studies (TIMSS), that focuses on assessing students' science achievement, and the Programme for International Student Assessment (PISA), which measures students' scientific literacy have highlighted a lag in Malaysia's science achievement. According to the OECD (2023b), Malaysia's PISA science score declined from 438 points in 2019 to 416 points in 2022. Additionally, Fatin Aliah Phang et al. (2020) reported that Malaysian students perform poorly in science, lack confidence and show limited interest in the subject. This stems from the examination-oriented teaching methods prevalent in Malaysian science classrooms. Other contributing factors to declining student interest in science have also been identified. For instance, The Star (2023) reported that Malaysian teachers are pressured to meet a key performance index (KPI) requiring them to complete the syllabus within the academic year. This pressure often prevents teachers from ensuring that students gain a comprehensive understanding of the material, leaving students unable to comprehend the purpose behind what they are taught.

Despite awareness of the importance of NOS and achieving scientific literacy as important goals in education, inconsistencies persist between research findings and curriculum policies. NOS is often listed as a generic and high-level objective but is rarely addressed as a specific cognitive outcome in science lessons. This issue is also evident in Malaysia. Among the seven objectives outlined in the Standard Based Curriculum for Secondary Schools (commonly known as Kurikulum Standard Sekolah Menengah, KSSM), only one relates to NOS. However, the curriculum lacks clear guidelines on what aspects of NOS to teach, how to teach them and when to integrate them into science instruction. This ambiguity raises questions about whether NOS is effectively taught in Malaysian science classrooms.

Teachers play a pivotal role in nation-building by developing students' scientific literacy through effective teaching (Klemenčič et al., 2023). However, a literature search utilising established platforms such as Springer and ResearchGate revealed a lack of research on Malaysian teachers' ability to translate their NOS knowledge into NOS pedagogical content knowledge (NOS PCK). This gap highlights the urgent need to examine how teachers translate NOS into NOS PCK to understand the current state of science education in Malaysia. This study seeks to address the following research question:

> Are Selangor lower secondary in-service science teachers able to translate their NOS conceptions into NOS PCK? If so, how?

LITERATURE REVIEW

Nature of Science (NOS)

The Nature of Science (NOS), also commonly known as Nature of Scientific Knowledge (NOSK), is a concept that is inherently difficult to define. Its abstract and complex nature has resulted in ongoing debates about the actual meaning of NOS and what it should encompass. Lederman (1992), as cited in Hanuscin et al. (2010), defined NOS as “understanding science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge.”

In a study by Lederman et al. (2002), seven tenets of NOS were identified as non-controversial and essential for achieving science literacy. These tenets, widely agreed upon by philosophers and sociologists, include: (1) The empirical nature of scientific knowledge; (2) The nature of scientific theories; (3) Inference and theoretical entities in science; (4) Creativity in science; (5) The distinction between scientific theories and laws; (6) Subjectivity in science (theory-ladenness); (7) Social and cultural influences on science. Despite this agreement, alternative definitions and frameworks for NOS have been proposed by other scholars, reflecting diverse perspectives on its scope and significance (Jain & Luaran, 2020; Mok & Jain, 2023). Thus, a universally accepted list of NOS tenets remains elusive (Lederman & Lederman, 2019).

For the purposes of this study, a pragmatic definition of NOS was adopted, drawing from Clough and Olson (2007) and the National Science Teaching Association (NSTA) (n.d.). This definition emphasizes the "what" and "how" of science as a foundation for fostering scientific literacy. This definition supports the idea that understanding NOS enables individuals to make informed decisions in their daily lives. Additionally, the study further incorporated Chen's (2006) seven NOS tenets which were integral to the questionnaire developed for the first stage of this research. These tenets served as a basis for exploring teachers' conceptions of NOS.

Tenet One, Tentativeness of Scientific Knowledge acknowledges that while scientific knowledge is robust, it is inherently subject to change, occurring either incrementally, as described by Popper (1975), or through paradigm shifts as proposed by Kuhn (1970). Tenet Two, Nature of Observation, depicts that observations in science are not purely objective; they are influenced by theoretical frameworks and the observer's preconceptions (Chen, 2006). Tenet Three, Scientific Methods emphasizes that the employment of scientific methods is context-dependent; no single scientific method is used to investigate a phenomenon (Chen, 2006). Tenet Four, Hypotheses, Laws, and Theories underscores the distinct roles that these three elements serve in science. Hypotheses serve as immature theories, theories provide explanations for phenomena and laws describe observed regularities in nature (Chen, 2006; McComas et al., 1998).

Tenet Five, Imagination, acknowledges that creativity and imagination are crucial for scientific innovation, although students often fail to associate these concepts with science (Chen, 2006). Tenet Six, Validation of Scientific Knowledge, emphasizes that the acceptance of scientific theories involves the provision of empirical evidence; however, this process is also influenced by social conventions and the norms of the scientific community (Chen, 2006). Tenet Seven, Objectivity and Subjectivity in Science, acknowledges that while science strives for objectivity, it cannot entirely eliminate subjectivity as personal, cultural and societal factors shape scientific endeavours (Chen, 2006).

Pedagogical Content Knowledge (PCK)

Shulman (1986) introduced the concept of Pedagogical Content Knowledge (PCK) to challenge the simplistic view of teaching as mere information transmission. Shulman (1986) defined PCK as the specialized knowledge that effective teachers possess, which includes:

- Knowledge of commonly taught topics within a subject area.
- Effective representations and instructional methods for these topics.
- Understanding students' preconceptions and difficulties in mastering these topics.

PCK is thus a blend of content knowledge (what teachers know) and pedagogical knowledge (how they teach), making it a complex and dynamic form of knowledge that evolves with experience (Pompea & Walker, 2017). Kathirveloo and Puteh (2014) expanded on this by emphasizing the importance of adapting teaching to cater to students' diverse interests and competencies. Shulman's work underscores the discipline-specific nature of teaching, a theme further explored by Zhang (2015), who investigated the impact of teachers' PCK quality on student learning.

Nature of Science Pedagogical Content Knowledge

Integrating NOS into science teaching requires a specialised form of PCK. Wahbeh and Abd-El-Khalick (2014) identified NOS PCK as encompassing the following elements: a heuristic understanding of NOS tenets, deep content knowledge, integration of NOS with science content, and skills to create inquiry-based learning environments. This definition underscores the importance of teachers' NOS knowledge, science content knowledge, and the pedagogical strategies in fostering students' understanding of science. Previous studies consistently highlight the critical role of robust subject matter knowledge in teaching NOS effectively (Lederman et al., 2013; Schwartz & Lederman, 2001). Teachers must seamlessly integrate NOS tenets into their instruction, linking theoretical knowledge with practical examples from the science curriculum. However, a systematic literature review by Jain et al. (2024) revealed additional nuanced elements in the development of NOS PCK, such as teachers' perceptions of their students' understanding of NOS and teachers' pedagogical preferences. Typically, foundational PCK is developed during pre-service training or teacher preparatory programs (Schiering et al., 2023; Sorge et al., 2019). Previous studies conclude that developing PCK is particularly challenging for pre-service teachers without explicit instruction on teaching content knowledge (Schiering et al., 2023; Sorge et al., 2019). Integrating NOS into teaching adds another layer of complexity, as it requires integrating NOS instruction with science content knowledge. The studies reviewed by Jain et al. (2024) indicate that NOS instruction often takes a backseat when the primary focus of science teaching is on students' acquisition of science content.

Constructivism

Constructivism is a well-known and widely discussed foundational theory in education introduced by Piaget in the 1960s, emphasizes how individuals construct knowledge through the learning process. According to Constructivism, "human learning is self-constructed, where learners build new knowledge upon the foundation of previous learning" (Jain et al., 2013). This theory posits that individuals actively construct their understanding of the world by interacting with others and their surroundings.

Constructivism has profoundly influenced educational policies and practices. Its application can be seen in areas such as research methodologies, curriculum design, and pedagogical recommendations (Taber, 2019). Karakas (2007, p. 1) highlighted that Constructivism has significantly shaped research on the teaching and learning of the Nature of Science (NOS) and the design of science instruction. This transformation aims to enhance students' understanding of science by adopting instructional approaches rooted in Constructivist principles.

The concept of NOS PCK is built upon the foundation of Constructivism. It underscores the importance of educators' ability to link their NOS knowledge with PCK. To effectively integrate NOS into science instruction, teachers must possess: robust content knowledge of the subject, mastery of appropriate pedagogies, proficiency with relevant teaching tools and an understanding of students' prior knowledge.

METHODOLOGY

This study constitutes a pivotal component of a broader investigation designed to explore how teachers acquire and apply NOS knowledge, with a specific focus on its translation into NOS PCK. In the first phase of this study, a quantitative questionnaire developed by Chen (2006) was used to assess teachers' NOS conceptions. These conceptions were categorized into three groups: naive, mixed, or sophisticated. (i) Naïve: Teachers with a limited understanding of how science knowledge is developed. (ii) Mixed: Teachers exhibiting a blend of both naive and sophisticated NOS conceptions, often in equal measure, indicating a partial comprehension of NOS. (iii) Sophisticated: Teachers demonstrating a comprehensive and nuanced understanding of NOS (Chen, 2006). The study targeted lower-secondary science teachers in Selangor, Malaysia.

A stringent selection process was implemented to identify suitable participants. The criteria included lower-secondary in-service science teachers with a minimum of five years of teaching experience in the subject. Initially, the plan was to observe and interview six teachers, each representing one of the NOS conception categories. Nevertheless, despite concerted efforts to recruit across all categories, participation was as follows: five teachers with mixed NOS conceptions and one teacher with naive NOS conceptions. Notably, no teachers with sophisticated NOS conceptions opted to participate in this phase of the study.

The data collection process involved detailed observations and interviews with the participating teachers. Efforts were made to ensure comprehensive coverage and information saturation. It became evident that data saturation was achieved after observing and interviewing five teachers, namely four with mixed NOS conceptions and one with naive NOS conceptions. This conclusion was drawn after thoroughly exploring all pertinent themes and insights. Consequently, data collection was concluded at this point.

DATA COLLECTION AND ANALYSIS

Data pertinent to the research question were collected through a combination of classroom observations and interviews. Each participant was observed twice during science lessons and interviewed once, adhering to restrictions set by school authorities. Observations were conducted during one-hour science lessons at the participants' schools. The researchers assumed the role of non-participant observers, using a validated observation checklist. This checklist, developed and endorsed by two senior research fellows with over three decades of experience in science teaching and research, focused on: (i) identifying whether participants linked NOS tenets to science activities or science lesson content to enhance students' understanding of content knowledge, (ii) assessing how NOS tenets were integrated into science activities, and (iii) evaluating the types of instructional tools used during lessons. Field notes were recorded during observations to capture detailed insights and nuances beyond the checklist items.

Interviews were conducted at the schools following the observation sessions, with each interview lasting about 40 minutes. This study utilised a semi-structured interview format, incorporating a combination of open-ended, closed-ended, and follow-up questions (Adams, 2015). The bilingual interview protocol was rigorously validated by the same senior research fellows who validated the observation checklist. The interview questions focused on: teachers' exposure to formal NOS learning, their decisions to include or exclude NOS elements in their lesson planning and teaching, and follow-up questions based on lesson observations to understand the rationale behind their pedagogical choices. The interview data were analysed thematically. To ensure confidentiality, all participants were assigned pseudonyms.

FINDINGS

Table 1 displays the profiles of the five teachers who participated in this study, along with details regarding the nature of the observed lessons and the teaching aids utilized. These profiles provide context for the observations and subsequent interview sessions with the participants. This study aimed to investigate how teachers translate, if at all, their NOS conceptions into NOS PCK in their science lessons.
The analysis of findings revealed four key themes that reflect how the participants' NOS conceptions influenced their NOS PCK:

Theme 1: Compartmentalisation of NOS Understanding and Teaching

This theme highlights the disconnect between the interviewees' understanding of Nature of Science (NOS) principles and their actual teaching practices, resulting in a lack of integration of NOS concepts into their pedagogy. While all participants demonstrated a clear understanding of the tentative nature of science during interviews, their classroom practices did not reflect this understanding. For example, during lesson observations, none of the participants provided opportunities for students to explore alternative experimental outcomes or introduced the notion that scientific knowledge is subject to change.

Aisyah shared an experience that underscored the dynamic nature of scientific knowledge. During trial experiments with a lab assistant, she encountered discrepancies between the experimental results and the information in the teaching guide. Aisyah's prior understanding, shaped by textbook content, was that all shampoos are alkaline. However, the experiments revealed that many commercial shampoos were acidic. This discrepancy led Aisyah to reconsider her preconceptions, recognising that advancements in shampoo production had introduced variations in pH levels. Aisyah reflected:

> "*Saya tahu shampoo alkali, kita dah test banyak kali, dia tetap tunjukkan asid. Ha. Jadi kita rasa kita pun kaji lagi sebenarnya. Mungkin dekat bahan dalam shampoo tu, ada bahan tambahan yang lain." [My prior conception is that shampoo is alkali. But when it was tested many times, the results kept showing that it was acidic. Hence, we feel that there is a need to investigate further about the discrepancy in the results obtained and the results stated in the teaching guide. Maybe there are other substances that were added into the shampoo in the market that contribute to the change in pH level making it acidic."]* (Aisyah)

However, when asked why she did not discuss this dynamic aspect of scientific knowledge with her students during the lesson, Aisyah shrugged and replied, *"tak payah kot. I kena ikut objectif pembelajaran"* [*"I do not see the need; I need to adhere to the lesson learning outcomes."]* The learning outcomes outlined by Aisyah for her lesson: At the end of the lesson, students should be able to:

1. Test the effect of litmus paper on acidic and alkaline substances.
2. State the use of acidic and alkaline substances in the neutralisation process.

In another instance, Participant Nadia concurred with the notion of science's tentativeness, providing an example related to the reclassification of planets. Nadia referenced the shift in understanding from the solar system having nine planets to the current recognition of eight planets following the exclusion of Pluto.

> *"Macam dulu planet ada 9 tapi sekarang yang dikatakan sebagai planet adalah 8 sahaja." [We used to have 9 planets in the solar system but now only 8".]* (Nadia)

Nadia's response illustrated her awareness of the dynamic nature of scientific knowledge, wherein previously accepted facts can be reevaluated and revised based on new evidence or redefined criteria. This acknowledgment of scientific uncertainty highlights the importance of fostering a flexible and open-minded approach to teaching science, helping students to understand that scientific knowledge is subject to refinement and evolution. However, this perspective was not reflected in Nadia's teaching practices. When asked about this during the interview, Nadia indicated that she was unfamiliar with the concept of Nature of Science (NOS). Her understanding on the change in the number of planets in the solar system was confined to the specific example of planetary reclassification. Nadia did not see that this example could be generalised to other areas of scientific knowledge.

Similarly, the fifth participant, Norliza, the only participant who had formally learned about NOS during her undergraduate programme-shared her understanding of the Nature of Science. She explained that she was aware that scientific theories are subject to change:

> *"Teori, dia boleh berubah, jadi kita faham sains ni, tidak tetap lah. Itu salah satu contoh Sifat Sains." [Theories will change—it is not fixed. That is one aspect of the Nature of Science.]* (Norliza)

However, observations of Norliza's teaching revealed that this belief was compartmentalised and not translated into her classroom practices. When further asked about this during the interview, she attributed it to time constraints and the priority to complete the syllabus. She stated:

> *"Jadi, cikgu buat apa-apa pun, mesti habiskan syllabus lah. Kalau tak, semua tu bebanan atas bahu kita lah. Maksud tak habis syllabus." [We are expected to finish teaching the syllabus no matter what. If not, the responsibility lies on us.]* (Norliza)

The experiences shared by Norliza, along with those of the other participants, highlighted a recurring theme: a disconnect between their understanding of NOS principles and their actual teaching practices. This pattern was consistently observed across all five participants. During non-practical lessons, a uniform teaching approach was evident across all participants. Science instruction was predominantly textbook-driven, with a notable emphasis on rote learning and repetitive reinforcement of newly introduced concepts. Towards the end of each lesson, teachers typically assigned practice questions to reinforce students' understanding. This pedagogical approach appeared to prioritize content delivery over the integration of broader NOS principles into classroom instruction. Based on the interviews, the participants consistently attributed this to two main factors: the priority in completing the syllabus and the limited time available during lessons.

Table 1

Profile of study participants, nature of observed lessons, and teaching aids utilised.

Participant	Educational background	Received formal education for NOS	Level of NOS conceptions	Years of teaching Science	Nature of lesson	Teaching aids used during lesson
Aisyah	Bachelor of Science (Teaching)	No	Mixed	16 years	a) Non- Practical Lesson: The Change in State of Matter caused by the Absorption and Release of Heat b) Practical Lesson: Acid and Alkali Litmus Paper Experiment	a) Slides, textbook, handouts. b) Experiment materials, videos, slides, handouts.
Hafiz	Science with a Post-Graduate Diploma in Teaching	No	Mixed	23 years of teaching experience, with 7 years specifically teaching science	a) Non- Practical Lesson: (i) The Loudness and Pitch of Sound and Phenomenon (ii) The Application of Reflection of Sound Waves b) Practical Lesson: Oxygen Content of Inhaled and Exhaled Air Experiment	a) Textbook, workbook. b) Experiment materials, video, mahjong paper.
Nadia	Mathematics but offered a position to teach Science	No	Mixed	8 years	a) Non- Practical Lesson: Introduction of Matter b) Practical Lesson: Combustion Experiment	a) Textbook and workbook. b) Experiment materials, videos, slides, handouts.
Radiah	Electrical Telecommunication, with a Post Graduate Diploma in Teaching	No	Mixed	19 years of experience teaching Physics and 1 year of teaching science	Non- Practical Lesson: (i) Electric Current (ii) Interference	i) Slides, textbook, handouts. ii) Video, textbook, handouts.
Norliza	Major in Chemistry, Minor in Mathematics	Yes	Naive	13 years	Non- Practical Lesson: (i) Three States of Matter (ii) Magnetism	i) Slides, textbook, workbook. ii) Slides, textbook, workbook.

Theme 2: Missed Opportunities to Address NOS Tenets

This theme highlights instances where opportunities to incorporate Nature of Science (NOS) tenets into teaching were overlooked, as observed during a practical lesson on acids and alkalis.

During one lesson, Aisyah facilitated an experiment using litmus paper to determine the acidity or alkalinity of various substances. Students were given the freedom to design and conduct the experiment without explicit procedural instructions. They independently decided on the experimental setup, such as the selection of litmus paper colour and the number of pieces to use. This autonomy allowed students to demonstrate agency and problem-solving skills as they devised their own methods for conducting the experiment. However, this occurrence of student-led experimentation was unintentional. This was confirmed during the interview with Aisyah, when she acknowledged that she omitted clear guidance on the experimental procedures. She explained:

> *"Ah. Saya tak nyatakan pulak. Memang saya tertinggal benda yang tu kan? Tapi saya tengok, nampak macam adalah nampak ada, dia buka tu, dia nak ambil, satu tu, siapa nak letak. Nak letak satu ke? dua? Letak biru ke atau letak merah? Lepas tu dia kata, kita uji dua-dua lah. Letak dua lah, sebab nak tengok kan? Ah. Sebab yang merah tukar ke tak? Yang biru tukar ke tak? Ah. Maknanya, ikut kreativiti mereka. Walaupun kita tak cakap, dia ada idea. Sebab mungkin kaedahnya, dalam satu group ada empat orang. Jadi ada empat fikiran. Mungkin." [I really did not tell them exactly how to conduct the experiment. I left out explaining how to conduct the experiment. Based on my observation, I saw the students opening the box containing the litmus paper, taking one piece of it and discussing who to put the litmus paper to test the substance, how many pieces to use, and whether they should test it with blue litmus paper or red litmus paper. Eventually they decided to test the substance with both litmus papers because they wanted to observe the colour change—either the blue or red litmus paper would change colour. Hence, they followed their creativity on how to conduct the experiment. Although it wasn't explained, they had an idea of how to proceed. I think this was made possible because there were four students in a group. Hence, four different ways of perspectives, four brains. Maybe.]* (Aisyah)

Aisyah attributed the students' autonomy to group dynamics, suggesting that collaboration within groups facilitated diverse perspectives and ideas. Nevertheless, the incident highlights a missed opportunity to explicitly address NOS tenets during the lesson. Had Aisyah intentionally planned for student autonomy in experiment design, she could have used the activity to discuss the scientific process and the role of creativity in scientific inquiry. By framing the experiment as a reflection of real-world scientific practices, Aisyah could have emphasised the importance of testing hypotheses, exploring alternative methods in scientific research and fostering a deeper understanding of the dynamic and creative nature of science.

Theme 3: Translation of Scientific Methods as Fixed Procedures

This theme delves into teachers' perceptions regarding the procedural aspects of scientific experiments, revealing a prevalent belief that experiments adhere to fixed, singular procedures—a misconception of the Nature of Science (NOS) principles. Among the five interviewees, three conducted practical lessons during the study, all of whom demonstrated a shared belief that scientific experiments follow rigid, unalterable procedures.

Aisyah exemplified this perspective, emphasising the existence of a singular correct method for conducting experiments:

> *"Ah. Selalunya ada procedure". [For every experiment there is a procedure.]* (Aisyah)
> *"Tapi tadi cara betul…Cuma satu je la". [There is only one correct procedure for that experiment.]* (Aisyah)

Similarly, Hafiz highlighted the importance of students adhering strictly to the steps outlined in the experiment guide. He emphasised that the simplicity of the guide's language ensured clarity and ease of understanding for students.

> *"Kebanyakan mereka boleh faham. Sebab dia punya step tu, dia tak dia. Step tu yang paling senang untuk pelajar faham. Ayat itu ayat yang simple." [Most of the students are able to understand the procedures stated in the guide as the sentences in the guide are very simple and easy to follow.]* (Hafiz)

In another lesson, Nadia's approach reflected her belief in the necessity of strict adherence to established procedures. Despite her students demonstrating the ability to handle experiments independently, Nadia provided assertive guidance and close supervision, ensuring that students followed the "correct" methods:

> *"Banyak yang saya bantu. Tadi ahh. Macam uh uh memang kamu nampak mereka boleh buat sebenar saya pergi, mereka tanya dekat saya uh cikgu macam mana nak buat. Macam saya pun terangkan sikit -sikit ah. Apa nak buat ah. Dia orang memang perlu dibantu lah." [I provided a lot of guidance to the students. From your observation, it may seem that they were able to carry out the experiments. However, they came near to me to ask for guidance on how to conduct the experiment. So, I provided some explanations on what needs to be done. The students really needed guidance.]* (Nadia)

These responses collectively reveal a prevalent misconception among participants regarding the procedural nature of scientific experiments. The emphasis on singular, fixed procedures reflects a narrow understanding of NOS principles, portraying scientific inquiry as rigid and devoid of flexibility or exploration. This approach may inadvertently limit students' opportunities for authentic scientific inquiry, hindering the development of critical thinking skills essential for scientific literacy.

Theme 4: Translation of Science as Static Knowledge

This theme highlights the pedagogical practices employed by teachers that inadvertently restrict students' opportunities for inquiry and critical thinking, reinforcing the perception of science as static knowledge.

Across all ten observations, a predominantly teacher-centered approach to instruction was evident. During non-practical lessons, students were positioned as passive recipients of information, while in practical lessons, they were confined to following rigid, recipe-like procedures. This emphasis on rote learning was particularly evident through the repetitive practice of answering predetermined questions. For example, in a lesson conducted by Radiah:

> *"The students immediately started to attempt the practice questions independently after Radiah's instruction. However, the students started discussing in their small groups on how to solve the practice questions assigned by Radiah after a few minutes…Radiah invited her students to try out the questions on their own. Radiah assured her students that they would discuss the questions together after everyone had completed the practice questions. During the discussion, it was found that most of the students were able to get the answers for the practice questions correctly. Radiah then revealed the correct answer with step-by-step solutions."* (Field note —Radiah, L1, NP)

This instructional strategy transformed scientific knowledge into a series of memorisable facts, emphasising recall and repetition over active inquiry or conceptual exploration. By positioning students as passive learners and prioritising knowledge transmission over the cultivation of inquiry skills, teachers inadvertently reinforced the perception of science as a static, immutable body of knowledge. This approach stifled students' curiosity, limited their ability to challenge preconceived notions or explore alternative perspectives, and hindered the development of critical thinking skills essential for scientific literacy.

The findings underscore the importance of adopting inquiry-based teaching approaches that empower students to actively engage with scientific concepts, ask questions, and construct their own understanding of the natural world. By fostering a classroom environment conducive to inquiry and exploration, teachers can cultivate a deeper appreciation for the dynamic and evolving nature of scientific knowledge among students. Transitioning to student-centered pedagogy, based on the constructivist paradigm of learning is essential for nurturing a generation of scientifically literate individuals equipped to navigate and contribute to an increasingly complex world.

DISCUSSION

This study highlights a significant gap between teachers' understanding of the Nature of Science (NOS) principles and their application in classroom practices. While the teachers demonstrated a general awareness of the tentative nature of scientific knowledge, this understanding was often compartmentalized and not reflected in their teaching. These findings align with concerns raised by Supprakob et al. (2016) and Bennetts (2021), who pointed out that the pressures teachers face in meeting syllabus requirements—a challenge also emphasised in reports by *The Star* (2023) regarding the demands of fulfilling key performance indicators.

Interestingly, our results differ from Lederman (1999), as we found no clear link between years of teaching experience and successful NOS integration. Although Pedagogical Content Knowledge (PCK) typically evolves with experience, the limited NOS understanding observed in this study appeared to hinder effective integration. Demirdöğen et al. (2015) stressed that a strong grasp of NOS is essential for teaching it effectively, while Nouri et al. (2021) identified seven key elements vital for NOS instruction.

Similarly, Jain et al. (2024) identified four critical elements for developing strong NOS PCK: teachers' understanding of NOS and its connection to the subject matter, their subject knowledge, their pedagogical preferences, and their perceptions of students. Our findings align with this framework, revealing that teachers often separated their NOS understanding from their teaching practices, pointing to a clear gap in integrating NOS into their PCK. This underscores the need for targeted interventions and professional development programs to help teachers deepen their conceptual understanding of NOS and embed it into their instructional practices.

In the context of Malaysia's aspirations for achieving scientific literacy, teachers play a crucial role. However, their limited NOS knowledge remains a significant barrier. Research shows that explicit instruction and professional development can enhance NOS understanding (Abd-El-Khalick, 2012; Herman et al., 2013), yet our study underscores the ongoing need for consistent support and continuous development (Leden et al., 2013; Khisfe, 2015). For instance, despite receiving formal NOS instruction, Norliza still held naive views about NOS, underscoring the need of sustained support.

Missed opportunities to address NOS in classrooms further reinforce the importance of its formal inclusion in teacher education programs (Sakar & Gomes, 2010). NOS should be a mandatory component of teacher training to promote scientific literacy (Dani, 2009; Mok & Jain, 2023). Furthermore, establishing clear guidelines and conducting regular classroom observations could enhance the effectiveness of NOS teaching. Persistent misconceptions about scientific methods and viewing science as static knowledge (Themes 3 and 4) remain significant challenges. If left unaddressed, these issues risk undermining national efforts to promote scientific literacy (McComas et al., 1998).

Ultimately, this study underscores the need for a deeper understanding of NOS and better support for teachers in translating this understanding into practice. Achieving meaningful integration of NOS in science education ongoing dialogue, targeted interventions, and continuous professional development.

CONCLUSION

The study investigated how Malaysian in-service science teachers translate their understanding of the Nature of Science Knowledge (NOS) into their Pedagogical Content Knowledge (PCK). The findings revealed that teachers faced challenges in applying their NOS knowledge to classroom practices, often perpetuating misconceptions of NOS during instruction. These results highlight the urgent need for targeted interventions and ongoing professional development to address this gap. Achieving scientific literacy in Malaysia depends significantly on teachers' ability to effectively integrate NOS into their teaching. This emphasises the necessity of incorporating formal NOS-PCK training into teacher preparatory programmes.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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