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**Research Article**

# Implementing NGSS practices in primary science classrooms: Lessons from an Arab context for advancing global science education

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**ABSTRACT**

The effective implementation of the next generation science standards (NGSS) practices is widely recognized as central to promoting scientific literacy and early development of critical thinking skills in primary education. Grounded in constructivist learning theory and inquiry-based science education, this study addressed the limited empirical understanding of how teachers in non-NGSS contexts interpret and report their engagement with science and engineering practices (SEPs). The study employed a qualitative research design, using semi-structured interviews to examine teachers' self-reported perceptions of the frequency, nature, and challenges associated with implementing the eight NGSS-aligned SEPs. The sample comprised 12 primary science teachers teaching grade 4-grade 6 in Omani schools. Data were analyzed thematically to identify patterns in teachers' reported practices and perceived constraints. The findings indicated that practices such as *planning and carrying out investigations* and *analyzing and interpreting data* were reported as more frequently enacted, reflecting alignment with inquiry-based instructional approaches. In contrast, practices including *asking questions*, *developing and using models*, and *engaging in argument from evidence* were reported less consistently. Teachers identified limited resources, time constraints, and variability in students' abilities as key challenges influencing their engagement with NGSS practices. Overall, the study provides insight into teachers' professional reasoning and perceived enactment of NGSS-aligned practices within a centralized and examination-driven educational context. The findings underscore the need for targeted professional development, structured instructional frameworks such as claim-evidence-reasoning, and improved resource support to strengthen the implementation of epistemically demanding NGSS practices in primary science classrooms.

**Keywords:** next generation science standards, primary science education, inquiry-based learning, scientific literacy, teacher professional development

## INTRODUCTION

Since its introduction in 2013, the next generation science standards (NGSS) framework has served as a major catalyst for reforming science education, particularly in the USA, by promoting a shift from teacher-centered, knowledge-transmission models toward student-centered, knowledge-generating learning environments (NGSS Lead States, 2013). Grounded in constructivist learning theory, NGSS conceptualizes science learning through three integrated dimensions, one of which is science and engineering practices (SEPs). These practices are designed to foster scientific reasoning, creativity, and scientific literacy by engaging students in authentic inquiry and problem-solving processes (Chen & Terada, 2021). The eight SEPs include: asking questions and defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations and designing solutions, and engaging in argument from evidence, as well as obtaining, evaluating, and communicating information (NGSS Lead States, 2013). Collectively, these practices emphasize learning science as an epistemic activity rather than a procedural one (Miller et al., 2018).

Internationally, similar reform orientations are evident in large-scale assessment frameworks that increasingly prioritize scientific reasoning and inquiry competencies (OECD, 2019). The program for international student assessment (PISA) 2018 science framework defines scientific literacy as the ability to engage with science-related issues and ideas as a reflective citizen, emphasizing three core competencies: explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence scientifically (OECD, 2019). These competencies require the integration of content, procedural, and epistemic knowledge, aligning closely with the epistemic orientation embedded in NGSS. Results from PISA 2018 and PISA 2022 indicate that many education systems continue to experience challenges in students' scientific reasoning and their ability to apply knowledge to unfamiliar contexts. For example, the OECD (2019) reported that only a small proportion of students across participating education systems reached the highest proficiency levels in scientific literacy (level 5 and level 6), reflecting advanced reasoning and evaluation skills, while a considerably larger share performed at or near baseline proficiency levels. Similarly, early analyzes of PISA 2022 results highlight persistent gaps in students' capacity to interpret data, evaluate evidence, and transfer scientific understanding to real-world situations (OECD, 2023). These findings underscore an ongoing international challenge in translating inquiry-oriented frameworks into classroom practice (Mullis et al., 2021; OECD, 2019, 2023).

A substantial body of international research has shown that the successful enactment of inquiry-oriented and practice-based frameworks depends heavily on teachers' epistemic understanding and instructional decision-making (e.g., Berland et al., 2016; Park et al., 2022; Sukor et al., 2021). Teachers play a central role in shaping learning environments that support student engagement with scientific practices, including modeling, argumentation, and evidence-based reasoning (Osborne, 2014). However, studies across diverse contexts have documented persistent tensions between reform-oriented expectations and classroom realities. Teachers often employ SEPs in superficial or fragmented ways, for example, using investigations as confirmatory activities or treating practices as add-ons rather than as central drivers of learning (Sandoval et al., 2016; Windschitl et al., 2021). Such limited enactment constrains opportunities for students to develop deeper epistemic understanding of science.

Recent international studies further highlight structural and professional barriers that complicate the implementation of NGSS-aligned practices. These include limited access to sustained professional development, curriculum pacing pressures, assessment-driven accountability systems, and variability in teachers' professional preparation and epistemic orientations (Haverly et al., 2022; Suh et al., 2022). Importantly, these challenges are not confined to the U.S. context but have been reported in systems attempting to adapt inquiry-based reforms within centralized or examination-oriented curricula (Shahat et al., 2026).

Within this broader international landscape, Oman provides a relevant comparative case. Omani students have participated regularly in international large-scale assessments such as TIMSS. Results from TIMSS 2019 indicate that Omani students performed below the international benchmark in science achievement, particularly on items requiring reasoning, interpretation of evidence, and application of scientific concepts. TIMSS 2019 results show that Omani grade 8 students achieved an average science score of approximately

457, compared with the international CenterPoint of 500, placing Oman below the TIMSS international mean (Mullis et al., 2020). These outcomes underscore the need to examine classroom practices that support scientific literacy and inquiry-based learning. While NGSS is not formally adopted in Oman, the national science curriculum and the widely implemented Cambridge curriculum emphasize competencies such as critical thinking, inquiry, and problem-solving, competencies that conceptually align with NGSS SEPs (Al-Hinai et al., 2026).

In this study, NGSS is therefore used not as a prescriptive reform model but as an analytical and comparative framework for examining how internationally endorsed science practices are understood and interpreted within a non-U.S., centralized educational system. Employing NGSS in this way enables systematic analysis of teachers' reported instructional practices while contributing to international discussions on the transferability and contextualization of global reform frameworks.

## Research Problem and Research Questions

International large-scale assessments such as the PISA and the TIMSS consistently document substantial variation in students' science achievement and scientific reasoning across participating education systems (Mullis et al., 2020; OECD, 2019). These patterns have intensified global attention on instructional frameworks that integrate scientific knowledge with inquiry-oriented practices. Introduced in 2013, the NGSS respond to this need by foregrounding SEPs as core mechanisms for developing scientific literacy, critical thinking, and problem-solving skills through inquiry-based and constructivist learning approaches (NGSS Lead States, 2013).

Despite the conceptual strength of the NGSS framework, international research indicates persistent challenges in translating SEPs into classroom practice, particularly in primary science education (Haverly et al., 2022). Studies across diverse contexts report that teachers often experience difficulty enacting epistemically demanding practices, such as modeling and argumentation, due to limited understanding of SEPs, misalignment between teachers' epistemic orientations and reform principles, and insufficient access to sustained, practice-focused professional development (Cherbow et al., 2020; Sandoval et al., 2016; Suh et al., 2022). Moreover, the role of teacher characteristics, including professional background, pedagogical expertise, and career pathways, in shaping the uptake of NGSS-aligned practices remains underexplored, particularly at the primary level.

Grounded in constructivist learning theory, which emphasizes learners' active construction of knowledge through meaningful engagement with ideas and practices (Jonassen, 1991), this study addresses a critical gap in the literature concerning how teachers make sense of and interpret NGSS-aligned practices within their instructional contexts. Specifically, the core research problem concerns the limited empirical understanding of how primary science teachers in non-NGSS-adopting systems conceptualize and report their engagement with SEP, and how contextual constraints shape these interpretations.

Within this broader international landscape, Oman serves as a relevant comparative context. Although NGSS is not formally adopted in the Omani education system, the national science curriculum and the widely implemented Cambridge curriculum emphasize inquiry, critical thinking, and problem-solving, competencies that conceptually align with NGSS SEPs. However, little empirical evidence exists regarding how teachers in such contexts understand and describe their engagement with these practices. Consequently, this study focuses on teachers' self-reported perceptions and interpretations of SEP-aligned practices, recognizing that such accounts reflect experiential and epistemic understandings rather than direct measures of classroom enactment or instructional quality (Chen & Terada, 2021; Park et al., 2022; Sandoval et al., 2016).

Guided by this research problem, the study addresses the following research questions (RQs):

1. **RQ1.** How do primary science teachers in Oman conceptualize NGSS-aligned SEPs in their instructional approaches?
2. **RQ2.** How do these teachers self-report their strategies and perceived opportunities for enacting NGSS-aligned SEPs in primary science classrooms?
3. **RQ3.** What challenges do primary science teachers in Oman identify when attempting to integrate inquiry-based and SEP-aligned practices within their classroom realities?

## THEORETICAL BACKGROUND

Through the NGSS and the OECD (2019) program for PISA framework, efforts have been made since 2013 to improve science education methods both domestically and abroad. Since its publication in 2013, the NGSS has served as the impetus for reforming scientific education in the USA. With an emphasis on student-centered science teaching practices in a knowledge-generating learning environment, the NGSS framework updated and repackaged the prior inquiry-based science standards (Nollmeyer & Bangert, 2017). SEPs, which equates to the knowledge and skills scientists and engineers need to study, design and create, are the focus of the NGSS framework (NGSS Lead States, 2013). The SEPs developed in the NGSS framework are

(1) asking questions (science) and defining problems (engineering),

(2) developing and using models,

(3) planning and carrying out investigations,

(4) analyzing and interpreting data,

(5) using mathematics and computational thinking,

(6) constructing scientific explanations,

(7) designing solutions (engineering), and

(8) engaging in argument from evidence, and obtaining, evaluating, and communicating information (NGSS Lead States, 2013).

The NGSS framework deemphasizes the need for students to know all the scientific facts associated with each field and focused on knowledge generation and SEPs (NGSS Lead States, 2013). When teachers design a learning environment that encourages information generation rather than simple transfer and allows students to build their own learning, they are applying the theory of constructivist learning. Constructivism, according to Jonassen (1991), encourages people to make meaning of observations, experiences, and events to construct ideas by interpreting reality and knowledge through living experiences, past events, beliefs, and mental processes.

The PISA 2018 science framework also focused on scientific literacy as the leading construct to inform science education in many contexts. PISA 2018 outlined three competencies for scientific literacy: explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence scientifically (OECD, 2019). To achieve these three scientific literacy competencies, PISA 2018 recommended that students acquire content knowledge about science and technology, procedural knowledge about various scientific methods and practices, epistemic knowledge about the terminology used in scientific practices, and the rationale behind scientific procedures and science inquiry.

### Science Teachers' Epistemic Understanding of SEPs

Osborne (2014) asserts that to assist students in comprehending the epistemic foundations of science, the science and engineering procedures described in the NGSS framework are necessary. According to Osborne, for students to maximally gain from the incorporation of SEPs, teachers should have the following questions in mind when engaging in any science related activities in the class:

(a) is there a more efficient way to develop such knowledge?

(b) does it give a more realistic view of the endeavor that is science? and

(c) does it help students gain a deeper and wider understanding of what we know, how we know, and the epistemic and procedural constructs that guide the practice of science?

It is argued that much can be learned about current approaches to the use of SEPs in classrooms by assessing

(a) science teachers' objectives for teaching science,

(b) their comprehension of the NGSS-aligned practices, and

(c) the opportunities they give their students to interact with these practices (Sandoval et al., 2016).

Sandoval et al. (2016) discovered that most teachers' instructional objectives for having students participate in classroom activities were to learn the scientific method, reinforce concepts learned during direct instruction, engage with topics as an introductory activity, and assess students' comprehension of a concept at the conclusion of the topic. According to Sandoval et al. (2016), only a small percentage of teachers' objectives were centered on creating true knowledge or using science and engineering techniques; the activities used in class were summed up as mostly practical work aimed at discovering or acquiring topics. Sandoval et al. (2016) argue that for students to effectively grasp scientific concepts, they need to be more involved in science and engineering processes as stipulated by the NGSS. Thus, they argue that instructors need to better understand the NGSS SEPs and the positive effect they can have on student engagement and the learning process.

Beyond foundational accounts of SEPs, recent scholarship continues to debate whether teachers' enactments of practices function as procedural routines or as epistemic tools for knowledge-building. For instance, Gutierez (2024) documents misalignments between professed beliefs and enacted dialogic argumentation, underscoring the challenge of translating epistemic aims into classroom discourse. In a related vein, Choi et al. (2021) show that teachers' views of argument in scientific inquiry shape how they design and value argument-based instruction. Earlier comparative work also indicates that teachers' epistemic orientations vary across school contexts, with implications for equitable access to authentic scientific practices (Katsh-Singer et al., 2016). Despite extensive debate in Western contexts, little is known about how teachers in non-Western systems—such as Oman—conceptualize and implement epistemic practices embedded in NGSS. The present study addresses this gap by examining how upper primary science teachers describe the frequency, depth, and challenges of enacting SEPs, with particular attention to practices that signal epistemic work (e.g., modelling, explanation, and argument from evidence).

In addition to understanding scientific and engineering practices, teachers' epistemic beliefs and professional orientations play a crucial role in shaping how they interpret and enact inquiry-based pedagogies. Teacher belief systems influence their willingness to shift from teacher-centered instruction to student-centered learning environments where students construct and defend scientific ideas (Katsh-Singer et al., 2016; Park et al., 2022). Research indicates that when teachers view science as knowledge to be transmitted, instructional practices tend to emphasize recall and procedural activities. Conversely, teachers who see science as a process of knowledge construction are more likely to integrate questioning, argumentation, and modeling into their lessons (Choi et al., 2021; Gutierez, 2024). Therefore, examining classroom practices through the NGSS lens requires an understanding of teachers' epistemic orientations, as these beliefs fundamentally shape the nature and depth of SEP implementation.

## NGSS and Primary Science Education

Primary education is a critical entry point for developing students' scientific literacy, as early experiences with science strongly influence their long-term achievement and attitudes toward the subject (Appleton, 2007; Eshach & Fried, 2005). The NGSS framework emphasizes that SEPs are not limited to secondary or advanced levels but can be adapted for developmentally appropriate experiences in the primary years (NGSS Lead States, 2013). Practices such as asking questions, developing simple models, and engaging in hands-on investigations help young learners connect everyday experiences with scientific reasoning. These experiences are vital for building the epistemic foundations of science—understanding not only what we know but also how we come to know it (Bybee, 2014; Osborne, 2014).

This study focuses specifically on upper primary classrooms (grade 4-grade 6, ages 8-11), which serve as a critical transitional stage. At this point, the foundational skills cultivated in early childhood—curiosity, questioning, and exploration—are consolidated and expanded through more structured engagement with NGSS-aligned practices. Investigating how Omani teachers implement these practices in grade 4-grade 6 therefore provides valuable insights into how early competencies can be sustained and developed. It also allows for benchmarking local practices against internationally recognized frameworks, contributing both to national reform efforts and to the broader literature on adapting NGSS principles in non-U.S. contexts.

## Measuring the Use of SEPs by Omani Teachers

Extensive research has been conducted into the impact of NGSS science practices and knowledge-generating teaching strategies on student learning. Chen and Terada (2021) designed a protocol called IONIC, which stands for interactive-constructive-active-passive (ICAP) to measure by observation NGSS-aligned SEPs in the classroom and was created to measure student behavior during the three phases of the learning process. Teachers found it challenging (and overwhelming for those new to the NGSS) to think about eight distinct practices according to McNeill et al. (2015), who first proposed grouping the eight scientific and engineering practices into three distinct categories - sense-making, investigating, and critiquing. Chen and Terada (2021) applied the IONIC protocol to measure the impact of teacher PD on student engagement in the three categories of SEPs during learning. Student engagements were rated as passive (receiving information), active (manipulating information and data), constructive (knowledge generating), and interactive (dialoguing to generate knowledge) for each observed learning activity. The Cronbach's alpha for the three phases ranged from 0.91 to 0.98, indicating that the three-phase model was able to measure the underlying factors consistently with an excellent (0.9 or higher) internal consistency factor. Chen and Terada (2021) found that teachers with less than three years of NGSS professional development struggled most with engaging students in phase 3, particularly in practices 5, 7, and 8, with practice 8 showing the lowest engagement. This indicates challenges in understanding and teaching these practices effectively. Chen and Terada (2021) concluded that consistent engagement in continuing professional development focused on the NGSS SEPs has potential to change teachers' epistemic orientation toward knowledge-generating learning environments and teaching approaches.

Teachers now bring a variety of educational and professional backgrounds to the classroom because of the worldwide teacher shortage (Park et al., 2022). Teachers with a range of experiences, epistemic orientations, and beliefs about teaching and how students learn have entered the profession because of the availability of multiple career entry pathway alternatives (e.g., emergency certification routes) that have emerged in light of the global teacher shortage (Windschitl et al., 2021). Variations in teacher preparation programs are significant, for instance, research driven teacher preparation programs may introduce SEPs very early on, but second-career teacher preparation programs might not introduce NGSS practices until the teacher is already teaching in the classroom. Also, some 'traditional' science teacher education programs can be actually based on NGSS SEPs (Windschitl et al., 2021). Thus, it is crucial to comprehend how these different career paths impact the application of NGSS-aligned science and engineering techniques.

## METHOD

### Participants

The study involved 12 science teachers teaching grade 4-grade 6 within the basic education system in the Oman. Although the term primary education is not formally used in the Omani system, it is employed in this study for clarity and international readability, as grade 4-grade 6 correspond to the upper primary and lower middle years in many international education systems. In Oman, these grades span the transition between cycle one (grade 1-grade 4) and cycle two (grade 5-grade 10) of basic education. All participating teachers were employed in public schools implementing the Cambridge curriculum. A purposive sampling strategy was employed to recruit teachers with relevant experience in inquiry-oriented instruction, rather than to achieve statistical representativeness. This approach ensured that participants were able to meaningfully reflect on their pedagogical reasoning and perceived enactment of NGSS-aligned practices (Creswell & Poth, 2018). The sample included two grade 4 teachers, five grade 5 teachers, and five grade 6 teachers, all with a minimum of three years of teaching experience and demonstrated familiarity with inquiry-based methods.

In line with qualitative research principles, the intent of the sampling design was to generate rich, contextually grounded insights rather than nationally generalizable claims. Purposive selection allowed for variation in instructional experiences and grade-level contexts, supporting an in-depth exploration of teachers' conceptualizations and self-reported strategies related to NGSS practices (Sandoval et al., 2016). While the findings are not positioned as representative of all Omani teachers, capturing perspectives across grade levels provides valuable exploratory evidence regarding contextual factors influencing early-stage uptake of inquiry-driven science practices within the local educational system (Chen & Terada, 2021; Haverly et al., 2022).

## Research Instruments

The study employed individual semi-structured interviews (see **Appendix A**, adapted from Chen & Terada, 2021, and used with the authors' permission) to examine teachers' self-reported strategies for engaging with NGSS-aligned practices, the challenges they encountered, and their professional reasoning related to inquiry-oriented instruction. The interview protocol was explicitly structured around the eight NGSS SEPs:

(1) asking questions,

(2) developing and using models,

(3) planning and carrying out investigations,

(4) analyzing and interpreting data,

(5) using mathematics and computational thinking,

(6) constructing explanations,

(7) engaging in argument from evidence, and

(8) obtaining, evaluating, and communicating information (Chen & Terada, 2021).

For each NGSS practice, a set of three to four core questions was prepared and used as guiding prompts during the interview. These questions were designed to elicit teachers' descriptions of instructional strategies, examples of classroom practice, perceptions of student engagement, and perceived challenges associated with each practice. In total, the NGSS-focused section of the interview protocol included approximately 28-30 practice-specific questions, in addition to introductory and concluding questions related to teaching context and overall instructional reflections (Creswell & Poth, 2018).

The interview protocol followed a semi-structured, key-event-oriented approach, whereby questions were anchored, when possible, to specific instructional episodes observed during the lesson. While the number of prepared questions per NGSS practice was consistent across interviews, the flexible nature of the protocol allowed the interviewer to probe selectively based on the relevance and salience of each practice within a given teacher's lesson. Consequently, not all questions were asked verbatim in every interview; rather, questioning depth varied to avoid redundancy and to ensure analytic focus on practices that were meaningfully referenced or observable in teachers' instructional narratives (Creswell & Poth, 2018).

Each interview lasted approximately 30-40 minutes and was conducted in person and audio-recorded with participants' consent. All recordings were transcribed verbatim. The semi-structured format allowed participants to elaborate on their instructional reasoning and experiences, resulting in context-rich and detailed accounts. Open-ended prompts, such as "How do you engage students in [specific NGSS practice] during your lessons?" and "What challenges do you encounter when attempting to apply this practice?", encouraged reflective responses and illustrative examples. The interview protocol consisted of three integrated sections. First, four background questions were used to document participants' teaching experience, subject specialization, and professional preparation. Second, three general inquiry-oriented questions explored teachers' overall instructional approaches and their integration of inquiry-based teaching within the observed lesson. Third, the NGSS-focused section included practice-specific clusters of questions aligned with the eight SEPs. For most practices, four guiding questions were prepared using a key event recall structure to prompt teachers to reflect on concrete instructional episodes; constructing explanations included only three core questions, resulting in a total of 31 NGSS-related prompts across the eight practices. These questions explored teachers' reported strategies, examples of classroom implementation, perceived challenges, and instructional decision-making processes. Not all prompts were asked for verbatim or in sequence; instead, the interviewer used them flexibly to sustain a conversational flow while ensuring that each SEP domain was addressed when relevant to the participant's lesson context. This approach aligns with established qualitative research conventions for eliciting professional reasoning and experiential insight (Berland et al., 2016).

Consistent with the purpose of the study, interview responses are interpreted as reflective and perceptual accounts rather than as evidence of verified classroom enactment. Accordingly, the findings represent teachers' reported understandings, professional reasoning, and perceived instructional decisions related to NGSS-aligned practices, rather than direct measures of instructional fidelity or quality.

To establish the credibility and adequacy of the adapted interview instrument, multiple validation procedures were employed. Content validity was examined by three experts in science education and NGSS-oriented pedagogy. Item-level content validity index (I-CVI) values ranged from 0.83 to 1.00, and the scale-level CVI (S-CVI/Ave) reached 0.92, exceeding the recommended threshold of 0.80 (Creswell & Poth, 2018). A pilot administration with two teachers outside the study sample confirmed the clarity and relevance of the interview questions, resulting in minor linguistic refinements.

Analytical reliability was supported through inter-coder agreement procedures. Twenty percent of the transcripts were independently coded by two trained qualitative researchers, yielding a Cohen's (1960) kappa value of 0.87, which indicates substantial agreement (Miles & Huberman, 1994). An audit trail and iterative code-refinement discussions were maintained to enhance dependability (Lincoln et al., 1985). In addition, member checking was conducted with all participants, who confirmed the accuracy of their interview summaries, thereby strengthening credibility (Birt et al., 2016). Peer debriefing sessions were held during the analysis phase to further support interpretive rigor.

## Research Design

The study adopted a qualitative research design (Creswell & Poth, 2018) to examine how Omani primary science teachers conceptualize and self-report their engagement with NGSS-aligned SEPs. This design was selected to foreground teachers' professional reasoning, epistemic orientations, and perceived instructional enactment within an inquiry-oriented framework (Chen & Terada, 2021).

Data were collected during the second semester of the 2024-2025 academic year. Semi-structured interviews were conducted in person at participating schools, following approval from relevant educational authorities and informed consent from all participants. The first author served as the principal investigator and was responsible for recruiting participants and overseeing the overall data collection process. This close involvement enabled the researcher to establish rapport with participants and to probe more deeply into teachers' instructional reasoning and reported practices. The co-authors contributed to the study design, conducting all interviews, refinement of the interview protocol, and provided methodological guidance throughout the data collection phase, ensuring alignment with the study's theoretical framework and RQs.

Given that NGSS has not been formally adopted in Oman and that teachers are neither trained nor evaluated against NGSS implementation criteria, the study was not intended to assess instructional fidelity. Instead, the research design emphasized teachers' experiential interpretations of practice as articulated through their narratives. While self-reported data may be influenced by personal interpretation or social desirability, such accounts provide analytically valuable insight into how teachers make sense of inquiry-based reform expectations. Future research may extend this work through triangulation using classroom observations, instructional artefacts, and student work analysis (Wheeler et al., 2019).

Data analysis followed a thematic, deductive approach guided by the eight NGSS SEPs as an overarching analytical framework. Rather than mapping responses directly onto interview questions or treating SEPs as a checklist, the analysis focused on interpreting teachers' narratives and instructional reasoning in relation to inquiry-based science teaching (Berland et al., 2016; Creswell & Poth, 2018).

The analysis proceeded through four systematic stages to ensure methodological rigor and analytic transparency. First, all interview recordings were transcribed verbatim by the research team and carefully reviewed to preserve participants' original language. Second, a deductive coding framework grounded in the eight NGSS SEPs was applied. Within this framework, an initial set of analytic codes was developed to capture three interrelated dimensions:

(a) teachers' reported instructional actions (e.g., *structured investigations*, *teacher-led questioning*, *worksheet-based activities*, *guided explanation building*, *pre-made modeling*, and *limited argumentation*),

(b) perceived contextual constraints (e.g., *time pressure*, *resource limitations*, and *student readiness*), and

(c) epistemic orientations reflected in teachers' descriptions (e.g., *procedural engagement*, *confirmation-focused reasoning*, and *curriculum alignment*).

Coding was conducted independently by two researchers, followed by collaborative discussions to resolve discrepancies, refine code definitions, and ensure consistency in interpretation. Third, cross-case pattern analysis was conducted to identify recurring codes, variations in reported enactment across the 12 participants, and contextual influences shaping teachers' interpretations of SEPs. Frequency references were used descriptively to support analytic claims without transforming the qualitative analysis into quantitative scoring. Finally, codes were iteratively clustered into higher-order thematic categories aligned with the three RQs: teachers' conceptualizations of SEPs (**RQ1**), their self-reported strategies and perceived opportunities (**RQ2**), and the challenges they identified when attempting to integrate SEP-aligned practices (**RQ3**). Throughout the analytic process, representative excerpts were selected to demonstrate how interpretations were grounded in participants' accounts rather than inferred classroom enactment, thereby strengthening the transparency and credibility of the qualitative analysis

## RESULTS

### RQ1. How Do Primary Science Teachers in Oman Conceptualize NGSS-Aligned SEPs?

Analysis of the interview transcripts followed a practice-level coding process in which teachers' responses were first coded according to the eight NGSS-SEPs and then grouped into thematic categories reflecting teachers' conceptualizations, reported strategies, and perceived constraints. Across the dataset, teachers' conceptualizations were predominantly procedural and activity-oriented rather than epistemic in nature. Teachers tended to describe SEPs in terms of classroom tasks (e.g., experiments, worksheets, and structured activities) rather than as processes of knowledge generation, justification, or critique.

#### *Planning and carrying out investigations*

All 12 teachers referred to investigations as a central feature of science teaching. Conceptually, investigations were framed as structured activities embedded within textbook lessons rather than as student-designed inquiries. Teachers frequently described modifying lessons to include "an activity" when none was provided, indicating a procedural understanding of inquiry. Participant 6 noted, "If the lesson doesn't include an investigation, I try to adjust it so students still do an activity." Analytically, this category was coded as structured procedural engagement, reflecting an emphasis on activity completion rather than epistemic decision-making.

#### *Analyzing and interpreting data*

Ten teachers described supporting students in organizing data using tables or charts. Conceptualizations of data analysis focused on identifying expected patterns and confirming results, typically through teacher-guided discussion. Representative excerpt: "After students record the data, we discuss why the results might be different between groups." Coding indicated a category of teacher-guided sense-checking, suggesting that data interpretation was viewed as verifying outcomes rather than evaluating uncertainty or competing explanations.

#### *Obtaining, evaluating, and communicating information*

Nine teachers referred to communication practices, usually positioned at the end of an activity. Communication was conceptualized primarily as reporting findings or summarizing results rather than evaluating the quality of information or comparing claims. Representative excerpt: "Each group shares what they found and explains their results to the class." This theme was categorized as reporting-oriented communication, indicating limited epistemic critique.

#### *Asking questions*

Eight teachers acknowledged questioning as an important element of instruction; however, questioning was primarily conceptualized as a teacher-led scaffolding strategy. Student-generated questioning was rarely described. Representative excerpt: "I usually ask the questions to guide them toward the concept." Coding reflected a theme of instructional guidance through questioning, rather than questioning as a student-driven epistemic practice.

### *Developing and using models*

Only four teachers mentioned modeling practices, and conceptualizations were generally unclear. Models were described mainly as diagrams or pre-constructed representations provided by the teacher. Statements such as students "move toward designing their own models" were not accompanied by detailed examples of construction, testing, or revision. Analytically, modeling was coded as representational support, indicating a superficial conceptualization rather than modeling as a reasoning tool. Importantly, the analysis relies solely on teachers' reported accounts and does not claim verified classroom enactment.

### *Engaging in argument from evidence*

Three teachers referred to practices resembling argumentation. These were described as informal discussions rather than structured activities involving claims, evidence, and reasoning. Representative excerpt: "Sometimes students disagree, and we talk about which answer makes more sense." This practice was categorized under informal discussion rather than structured argumentation, reflecting limited epistemic framing. Overall, **RQ1** findings indicate that teachers' conceptualizations of SEPs were largely aligned with procedural classroom routines and curriculum structures, with less emphasis on epistemic agency or knowledge construction.

## RQ2. How Do Teachers Self-Report Their Strategies and Perceived Opportunities for Enacting NGSS-Aligned SEPs?

Whereas **RQ1** addressed conceptualizations, analysis of strategy-focused codes revealed that teachers described implementation primarily through scaffolded and teacher-directed approaches designed to manage time and curriculum demands.

### *Reported instructional strategies*

Through interviews, teachers described several recurring strategies:

- Using worksheets and guided experiments to structure investigations (reported by 12 teachers)
- Employing teacher-led questioning to support explanation building (reported by 10 teachers)
- Integrating basic mathematical reasoning, such as measurement and comparison, during investigations (reported by 7 teachers)

Representative excerpt: "I guide them step by step so they can explain what happened." These responses were coded under structured scaffolding and teacher-mediated explanation, indicating that teachers viewed scaffolding as essential for maintaining lesson flow and supporting student understanding.

### *Perceived opportunities*

Teachers reported that SEPs were more feasible when:

- Activities were already embedded within the Cambridge curriculum (11 teachers)
- Resources or digital tools were readily available (8 teachers
- Student abilities aligned with task expectations (9 teachers)

Conversely, practices requiring extended dialogue or open-ended inquiry were perceived as more difficult to sustain. Analytically, these responses formed a category of curriculum-aligned enactment, highlighting how teachers' perceived opportunities were shaped by structural conditions.

## RQ3. What Challenges Do Teachers Identify When Attempting to Integrate Inquiry-Based And SEP-Aligned Practices?

Three interconnected themes emerged consistently across participants.

### *Resource constraints*

Ten teachers described limited access to laboratory materials, modeling tools, or technological resources. Representative excerpt: "Not all schools have the tools needed for proper experiments." These responses were coded as material constraints influencing practice selection, particularly affecting modeling and extended investigations.

### *Time and curriculum pressures*

All 12 teachers emphasized that dense curricula and limited instructional time restricted opportunities for extended questioning or argumentation. Representative excerpt: "There isn't enough time to let students fully explore or debate ideas." This theme was categorized as curriculum pacing pressure, shaping teachers' prioritization of content coverage.

### *Student readiness*

Eight teachers expressed concerns about students' language skills, reasoning abilities, or mathematical readiness. Representative excerpt: "Some students struggle to explain their thinking, especially using data." These accounts were coded under perceived learner readiness, which teachers linked directly to their limited use of modeling and argumentation practices.

Across the three RQs, analytic conclusions regarding underrepresented practices are grounded in the relative absence of detailed conceptual or instructional descriptions within teachers' narratives rather than assumptions about classroom enactment. The findings, therefore reflect teachers' self-reported conceptualizations, strategies, and perceived constraints within their specific instructional contexts.

## DISCUSSION

The findings of this study illustrate how a small group of primary science teachers in Oman perceive and interpret their engagement with NGSS-aligned practices within their specific instructional contexts. Rather than providing evidence of classroom enactment or instructional quality, the results reflect teachers' self-reported understandings, professional reasoning, and perceived opportunities and constraints related to inquiry-oriented science teaching. Accordingly, the discussion is framed as an interpretation of context-specific teacher perspectives, situated within, but not generalized beyond, existing research on NGSS implementation and science teaching practices (Bybee, 2014; Osborne, 2014; Stroupe, 2015). The interpretations that follow are grounded in thematic categories derived from a deductive SEP-guided coding framework applied to teachers' narratives. Consistent with the structure of the results section, the discussion is organized around three analytic dimensions: teachers' conceptualizations of SEPs, their self-reported instructional strategies and perceived opportunities, and the challenges they identified when attempting to enact inquiry-oriented practices.

### Frequently Reported Practices

Patterns identified through deductive SEP coding indicated that practices such as *planning and carrying out investigations*, *analyzing and interpreting data*, and *obtaining, evaluating, and communicating information* were reported more consistently by participating teachers. One plausible explanation for this pattern is the structural alignment of these practices with existing curricula and instructional routines, particularly within the Cambridge curriculum used in Omani schools. Prior research suggests that teachers are more likely to enact science practices that can be embedded within familiar activity-based lessons and assessed through conventional classroom structures (Cherbow et al., 2020; Sandoval et al., 2016).

Another explanatory factor relates to the procedural nature of these practices as commonly interpreted by teachers. Investigations and data handling can be enacted through structured tasks that maintain teacher control over lesson flow and outcomes, reducing instructional risk and classroom management challenges. This finding aligns with research showing that teachers often adopt practices that emphasize activity completion rather than epistemic sense-making, especially when instructional time and resources are constrained (Berland et al., 2016; Miller et al., 2018).

From a cognitive engagement perspective, these practices may also be perceived as more feasible because they align with active but not necessarily constructive or interactive forms of engagement (Chi, 2009; Chi & Wylie, 2014). Teachers' descriptions suggest that while students were actively involved in tasks and discussions, opportunities for deeper epistemic interaction, such as generating explanations or evaluating evidence, were more limited.

### Moderately Reported Practices

Practices such as *using mathematics and computational thinking* and *constructing explanations* were reported with moderate consistency. Teachers' accounts suggest that these practices were contingent on student readiness and perceived ability, particularly in relation to mathematical reasoning, language proficiency, and abstract thinking. Research on student engagement and learning has consistently shown that variability in students' cognitive and self-regulatory capacities influences teachers' instructional decisions and the level of challenge they are willing to introduce (Fredricks et al., 2004; Guo et al., 2022; Zimmerman, 1990).

Teachers frequently described relying on scaffolding and guided questioning to support explanation-building, which may reflect attempts to balance inquiry-oriented goals with curriculum pacing demands. However, explanation construction requires students to engage in constructive and interactive cognitive processes, which are more time-intensive and difficult to sustain under tight curricular constraints (Chi & Wylie, 2014; Linnenbrink-Garcia et al., 2011). This may help explain why these practices were reported less consistently and at variable depths.

### Less Frequently Reported Practices

Practices requiring higher levels of epistemic agency, *asking questions*, *developing and using models*, and *engaging in argument from evidence*, were reported least frequently. Several interrelated factors may account for this pattern. Importantly, interpretations regarding the limited presence of modeling and argumentation practices were derived from the absence of detailed, practice-specific descriptions in teachers' narratives rather than from observational evidence of classroom enactment; participants' references to modeling were typically general or aspirational and were not accompanied by concrete examples of students constructing, revising, or using models during instruction. First, these practices demand a shift toward student-generated inquiry, epistemic uncertainty, and evaluative discourse, which may conflict with teachers' established instructional norms and assessment expectations. Previous studies have shown that teachers often struggle to operationalize modeling and argumentation without explicit pedagogical frameworks and sustained professional support (Berland et al., 2016; Choi et al., 2021; Jiménez-Aleixandre & Crujeiras, 2017).

Second, teachers' limited references to modeling and argumentation may reflect insufficient professional development focused on epistemic practices, rather than a lack of awareness of their importance. Research indicates that teachers' epistemic orientations and understanding of scientific practices strongly influence their classroom enactment (Park et al., 2022; Suh et al., 2022). When professional development emphasizes procedural inquiry over epistemic reasoning, practices such as modeling and argumentation are less likely to be enacted meaningfully (Kennedy, 2016; Yang et al., 2020).

Third, the limited reporting of these practices may be shaped by concerns related to classroom management, time efficiency, and student engagement. Argumentation and student-generated questioning introduce unpredictability and require extended discourse, which teachers may perceive as difficult to manage within examination-driven and time-constrained contexts. Similar tensions have been documented in studies examining teachers' beliefs and practices related to argumentation across different educational systems (Appiah-Odame & Frempong, 2025; Gutierez, 2024; Katsh-Singer et al., 2016).

Taken together, the findings suggest that, for this group of teachers, NGSS-aligned practices are perceived as more accessible when they align with structured, curriculum-supported activities and less accessible when they require sustained student agency, epistemic reasoning, and dialogic interaction. These patterns appear to be shaped by a combination of curricular alignment, perceived instructional feasibility, student readiness, and the nature of professional learning opportunities available to teachers.

Consistent with constructivist learning theory (Jonassen, 1991) and research on engagement and agency (Eccles, 2016; Skinner & Belmont, 1993), the selective uptake of NGSS practices observed in this study reflects teachers' efforts to negotiate inquiry-oriented reforms within local instructional realities. Given the qualitative design and limited sample size, these interpretations should be understood as plausible explanatory accounts grounded in teachers' perspectives, rather than definitive causal claims.

Nevertheless, the findings contribute to international discussions on NGSS implementation by illustrating how epistemically demanding practices, particularly modeling and argumentation, remain challenging to enact in non-NGSS-adopting, examination-oriented systems. In doing so, the study highlights the importance of professional development that explicitly targets epistemic practices and supports teachers in fostering deeper forms of student engagement and reasoning (Abou-Assali, 2014; Kennedy, 2016; Park et al., 2022).

## Challenges and Implications

The findings of this study illuminate how a group of primary science teachers in Oman perceive both progress and persistent challenges in their engagement with NGSS-aligned practices. From the perspectives of the participating teachers, practices such as *planning and carrying out investigations*, *analyzing and interpreting data*, and *obtaining, evaluating, and communicating information* were described as more readily integrated into classroom instruction, reflecting perceived alignment with inquiry-based approaches. In contrast, teachers reported greater difficulty engaging consistently with epistemically demanding practices such as *asking questions*, *developing and using models*, and *engaging in argument from evidence*. These perceptions resonate with patterns reported in prior NGSS-related research (Bybee, 2014), though the present findings should be understood as context-specific and limited to the accounts of the participating teachers, rather than indicative of broader instructional trends.

A recurring issue raised by teachers concerned perceived limitations in instructional resources, particularly in schools with fewer laboratory facilities or limited access to technological tools. Teachers reported that the absence of resources such as virtual labs, specialized equipment, and digital applications constrained their ability to support inquiry-oriented activities as they envisioned them. Similar constraints have been noted in previous studies (Appiah-Odame & Frempong, 2025; Chen & Terada, 2021; Sandoval et al., 2016); however, in this study, these challenges are reported as teachers' experiential interpretations of their instructional contexts, rather than as objective indicators of resource provision across schools.

Teachers also highlighted variation in students' readiness and skills, especially in relation to mathematical reasoning, questioning, and articulation of scientific ideas, as a factor shaping their instructional decisions. From teachers' perspectives, such variability complicated efforts to engage all students in higher-order practices and often led to increased reliance on scaffolding and teacher-directed support. While related challenges have been discussed in the literature (Park et al., 2022), the present findings reflect teachers' perceived constraints and adaptive responses within their classrooms, rather than measured differences in students' epistemic understanding.

Time constraints emerged as another salient theme in teachers' accounts. Participants described prioritizing curriculum coverage over extended engagement with practices such as modeling, questioning, and argumentation, particularly when instructional time was limited. These perceptions align with earlier research documenting tensions between curriculum demands and inquiry-oriented instruction (Appiah-Odame & Frempong, 2025; Berland et al., 2016; Windschitl et al., 2021). Within the context of this study, however, such constraints are interpreted as teachers' reported experiences, underscoring how curricular pacing and time pressures shape the feasibility of NGSS-aligned practices in everyday classroom settings.

Finally, teachers emphasized the need for instructional strategies that can accommodate diverse student abilities, particularly in relation to reasoning and conceptual understanding. Participants described using differentiated approaches, such as scaffolding, guided discussion, and peer-supported learning, to address these differences. These accounts suggest that, from teachers' perspectives, adapting instruction to students' varying needs is essential for supporting engagement with inquiry-oriented practices, though the effectiveness of such strategies was not examined directly in this study (Shahat & Al-Maamari, 2025).

## Implications for Addressing Challenges

To address these challenges, professional development programs are critical for equipping teachers with effective strategies to integrate NGSS practices. Based on teachers' reported challenges and perceived needs identified in the interview data, training in questioning techniques, iterative design processes, and argumentation frameworks can enhance teacher confidence and effectiveness in fostering higher-order thinking. Research supports the impact of professional learning opportunities that focus on these areas, showing improved teacher performance and student engagement (Kennedy, 2016; McNeill et al., 2015;

Schafer & Phillippi, 2025). For example, structured frameworks such as claim-evidence-reasoning (CER) can guide teachers in implementing evidence-based argumentation, a core element of NGSS practices (Berland et al., 2016).

Drawing on prior research, investments in technological resources, including virtual labs and simulation software, can also bridge resource gaps and enable inquiry-based learning. These tools allow for interactive and immersive experiences that engage students in scientific practices, as highlighted by Chen and Terada (2021) and Chi and Wylie (2014). Additionally, revising curriculum structures to balance content delivery with inquiry-based activities and extending instructional time for science lessons can create more opportunities for student-centered learning. Fostering a culture of inquiry and collaboration within classrooms is also essential, as it encourages students to actively engage with scientific phenomena and develop critical thinking skills (Shahat et al., 2017).

In sum, addressing these systemic challenges through targeted interventions, resource investments, and professional development is essential for advancing NGSS implementation in Omani classrooms. These implications should be interpreted as indicative rather than prescriptive, reflecting teachers' reported experiences complemented by established research rather than causal claims derived solely from the present dataset. Such efforts will not only enhance the quality of science education but also prepare students to meet the demands of a scientifically complex and rapidly evolving world. Aligning with international best practices will position Oman's education system as a forward-thinking model for fostering inquiry, collaboration, and critical engagement in science education (Bybee, 2014; NGSS Lead States, 2013).

## Recommendations for Improvement

The actionable recommendations provided by teachers during interviews highlighted the need for systemic changes to support NGSS implementation. Grounded in teachers' reported insights, and extended through alignment with the broader literature, this section outlines targeted improvements, professional development, enhanced resources, structured instructional frameworks, and curriculum restructuring.

Teachers emphasized the need for professional development programs designed to provide focused training on integrating NGSS practices, particularly in areas such as student questioning, argumentation, and modelling. This recommendation emerges directly from teachers' accounts of uneven engagement with epistemically demanding practices. These programs should include hands-on workshops and collaborative learning experiences to enable teachers to effectively foster higher-order thinking and critical reasoning in their classrooms. Additionally, training should emphasize the use of technology and innovative teaching strategies to bridge gaps in existing practices (Kennedy, 2016; Park et al., 2022).

As prior research has revealed, investments in resources are equally critical. Upgrading laboratory infrastructure and expanding access to virtual labs and technological tools will provide students with immersive and inquiry-based learning opportunities. Ensuring that schools in under-resourced areas receive equitable access to these tools is vital to creating a consistent educational standard across all institutions. Enhanced resources can support hands-on experiments and computational thinking, which are essential components of NGSS practices (Chen & Terada, 2021).

The implementation of structured instructional frameworks can significantly enhance student engagement and understanding. For example, frameworks such as CER can guide students in constructing evidence-based arguments, while templates for student questioning can encourage deeper inquiry and exploration. Although these approaches are not directly evaluated in the present study, they are included as literature-informed strategies that address challenges identified in the interview data. These structured approaches provide both teachers and students with a clear roadmap for engaging with complex scientific concepts, ultimately fostering critical thinking and problem-solving skills (Al-Hinai et al., 2026; McNeill et al., 2015; Shahat & Al-Maamari, 2025; Shahat et al., 2026).

Time management and curriculum restructuring are crucial components of improvement. Revisiting lesson structures to allocate more time for student-centered activities, such as investigations and modeling, can provide the space needed for deeper engagement. This recommendation aligns with teachers' reported constraints related to pacing and content coverage, while also reflecting broader findings in NGSS implementation research. Adjusting curriculum pacing to balance content delivery with skill development is critical for fostering inquiry-based learning. In addition, extending instructional time for science lessons where feasible can further enhance opportunities for meaningful student participation and exploration (Sun et al., 2022; Windschitl et al., 2021).

Taken together, these recommendations highlight the importance of systemic support at multiple levels, teacher training, resource provision, instructional design, and curriculum restructuring, to strengthen NGSS implementation in Omani classrooms. Collectively, they represent a synthesis of empirically grounded insights from this study and theoretically informed guidance from the existing literature.

## CONCLUSION AND LIMITATIONS

While the patterns identified in this study, particularly the limited engagement with modeling and argumentation, are consistent with prior NGSS-related research conducted in other national contexts (e.g., Berland et al., 2016; Jiménez-Aleixandre & Crujeiras, 2017), the contribution of the present study lies primarily in its contextual and comparative insights rather than in claims of instructional effectiveness or prevalence. By examining NGSS-aligned practices within the Omani primary science context, the study extends international understanding of how globally circulating reform frameworks are interpreted and recontextualized within centralized curricula, examination-driven systems, and resource-variable school environments. The findings illustrate how structural conditions, such as curriculum pacing, assessment priorities, and material constraints shape teachers' perceptions and selective uptake of NGSS practices in ways that parallel, yet are not identical to, those reported in Western education systems. In this sense, the study contributes to comparative science education scholarship by foregrounding context-specific mediating factors that influence how inquiry-oriented reforms are understood and negotiated at the classroom level.

The findings further indicate that some NGSS-aligned practices are perceived by participating teachers as more readily integrated into classroom instruction than others. Practices such as *planning and carrying out investigations*, *analyzing and interpreting data*, and *obtaining, evaluating, and communicating information* were reported as more frequently enacted, reflecting their perceived compatibility with existing curricular structures and instructional routines. In contrast, *asking questions*, *developing and using models*, and *engaging in argument from evidence* were described as less consistently enacted, suggesting areas where teachers perceive greater pedagogical, epistemic, and structural challenges. Importantly, because of the wide variation of these practices in terms of cognitive requirements and student engagement, these patterns should be interpreted as teachers' reported experiences and sense-making rather than as indicators of actual classroom enactment or comparative instructional quality.

Despite offering these insights, the study is subject to several important limitations that constrain the interpretation and transferability of its findings. First, the study relies exclusively on teachers' self-reported perceptions and interpretations of their instructional practices. Consequently, references to engagement with NGSS-aligned SEPs reflect perceived or reported enactment, not independently verified classroom behavior, instructional quality, or depth of epistemic engagement. The absence of classroom observations, instructional artefacts, or direct measures of student learning limits the extent to which conclusions can be drawn about how NGSS practices are enacted in practice or how they influence student outcomes. As a result, the findings should be understood as illuminating teachers' professional reasoning, epistemic orientations, and perceived instructional constraints, rather than as evaluative evidence of implementation fidelity.

Second, the study is based on a small, purposively selected sample of twelve teachers drawn from a limited number of schools. While this sampling strategy is appropriate for in-depth qualitative inquiry, it restricts the transferability of the findings beyond the participating teachers and contexts. The results should therefore not be interpreted as representative of science teaching practices across Oman or other educational systems. Instead, their relevance lies in their potential to inform analytical generalization, offering insights that may resonate with educators and researchers working in similarly centralized or examination-driven contexts.

Third, the study does not directly examine broader systemic influences such as curriculum policy design, assessment regimes, school leadership practices, or professional development structures. These factors likely play a critical role in shaping teachers' instructional choices and capacity to engage with epistemically demanding NGSS practices. The absence of data on these dimensions limits the study's ability to account for the interaction between classroom-level practices and system-level conditions and cautions against drawing conclusions about the effectiveness of specific policy or instructional interventions.

Taken together, these limitations suggest that the findings should be interpreted as exploratory and illustrative, offering a grounded account of how a small group of teachers perceives and navigates NGSS-aligned practices within their local instructional realities. While the study contributes to international discussions on the contextualization of NGSS principles, further research incorporating observational data, artefact analysis, larger and more diverse samples, and explicit examination of systemic factors is necessary to deepen understanding of how inquiry-oriented reforms are enacted and sustained across educational systems.

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## REFERENCES

Abou-Assali, M. (2014). The link between teacher professional development and student achievement: A critical view. *International Journal of Bilingual & Multilingual Teachers of English, 2*(1), 39–49. https://journal.uob.edu.bh/server/api/core/bitstreams/f695c3aa-ba7d-44da-9a42-1c3f2a33aa74/content

Al-Hinai, M., Shahat, M. A., Omara, E., Emam, M. M., Ismail, S. S., Alhabsi, N., Alhosni, K., Al-Amri, M., Al-Yahmedi, A., Fawzy, Y. M., & Al-Balushi, S. M. (2026). Exploring a STEM-integrated instructional approach and its preliminary contextual assessments of problem-solving and motivation in Oman. *European Journal of STEM Education, 11*(1), Article 3. https://doi.org/10.20897/ejsteme/17783

Appiah-Odame, E. K., & Frempong, G. (2025). The silent crisis of teacher burnout: Systemic challenges and coping mechanisms. *Educational Point, 2*(2), Article e136. https://doi.org/10.71176/edup/17638

Appleton, K. (2007). Elementary science teaching. In S. K. Abell, & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 493-535). Lawrence Erlbaum Associates. https://www.routledge.com/Handbook-of-Research-on-Science-Education/Abell-Lederman/p/book/9780805847147

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching, 53*(7), 1082-1112. https://doi.org/10.1002/tea.21257

Birt, L., Scott, S., Cavers, D., Campbell, C., & Walter, F. (2016). Member checking: A tool to enhance trustworthiness or merely a nod to validation? *Qualitative Health Research, 26*(13), 1802-1811. https://doi.org/10.1177/1049732316654870

Bybee, R. W. (2014). NGSS and the next generation of science teachers. *Journal of Science Teacher Education, 25*(2), 211-221. https://doi.org/10.1007/s10972-014-9381-4

Chen, Y.-C., & Terada, T. (2021). Development and validation of an observation-based protocol to measure the eight scientific practices of the next generation science standards in K-12 science classrooms. *Journal of Research in Science Teaching, 58*(10), 1489-1526. https://doi.org/10.1002/tea.21716

Cherbow, K., McKinley, M. T., McNeill, K. L., & Lowenhaupt, R. (2020). An analysis of science instruction for the science practices: Examining coherence across system levels and components in current systems of science education in K-8 schools. *Science Education, 104*(3), 446-478. https://doi.org/10.1002/sce.21573

Chi, M. T. H. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science, 1*(1), 73-105. https://doi.org/10.1111/j.1756-8765.2008.01005.x

Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*(4), 219-243. https://doi.org/10.1080/00461520.2014.965823

Choi, A., Seung, E., & Kim, D. (2021). Science teachers' views of argument in scientific inquiry and argument-based science instruction. *Research in Science Education, 51*(Suppl. 1), 251-268. https://doi.org/10.1007/s11165-019-9861-9

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement, 20*(1), 37-46. https://doi.org/10.1177/001316446002000104

Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry and research design: Choosing among five approaches* (4th ed.). SAGE Publications. https://collegepublishing.sagepub.com/products/qualitative-inquiry-and-research-design-4-246896

Eccles, J. S. (2016). Engagement: Where to next? *Learning and Instruction, 43*, 71-75. https://doi.org/10.1016/j.learninstruc.2016.02.003

Eshach, H., & Fried, M. N. (2005). Should science be taught in early childhood? *Journal of Science Education and Technology, 14*(3), 315-336. https://doi.org/10.1007/s10956-005-7198-9

Fredricks, J. A., Blumenfeld, P. C., & Paris, A. H. (2004). School engagement: Potential of the concept, state of the evidence. *Review of Educational Research, 74*(1), 59-109. https://doi.org/10.3102/00346543074001059

Guo, J.-P., Yang, L.-Y., Zhang, J., & Gan, Y.-J. (2022). Academic self-concept, perceptions of the learning environment, engagement, and learning outcomes of university students: Relationships and causal ordering. *Higher Education, 83*, 809-828. https://doi.org/10.1007/s10734-021-00705-8

Gutierez, S. B. (2024). 'Are they walking their talk?': Alignment of teachers' professed beliefs and enacted practices for teaching through dialogic argumentation. *Journal of Biological Education, 58*(5), 1329-1350. https://doi.org/10.1080/00219266.2023.2200800

Haverly, C., Lyle, A., Spillane, J. P., Davis, E. A., & Peurach, D. J. (2022). Leading instructional improvement in elementary science: State science coordinators' sensemaking about the next generation science standards. *Journal of Research in Science Teaching, 59*(9), 1575-1606. https://doi.org/10.1002/tea.21767

Jiménez-Aleixandre, M. P., & Crujeiras, B. (2017). Epistemic practices and scientific practices in science education. In K. S. Taber, & B. Akpan (Eds.), *Science education: An international course companion* (pp. 69-80). Sense Publishers. https://doi.org/10.1007/978-94-6300-749-8_5

Jonassen, D. H. (1991). Objectivism versus constructivism: Do we need a new philosophical paradigm? *Educational Technology Research and Development, 39*(3), 5-14. https://doi.org/10.1007/BF02296434

Katsh-Singer, R., McNeill, K. L., & Loper, S. (2016). Scientific argumentation for all? Comparing teacher beliefs about argumentation in high-, mid-, and low-socioeconomic status schools. *Science Education, 100*(3), 410-436. https://doi.org/10.1002/sce.21214

Kennedy, M. M. (2016). How does professional development improve teaching? *Review of Educational Research, 86*(4), 945-980. https://doi.org/10.3102/0034654315626800

Lincoln, Y. S., Guba, E. G., & Pilotta, J. J. (1985). Naturalistic inquiry: Beverly Hills, CA: Sage Publications, 1985, 416 pp. *International Journal of Intercultural Relations, 9*(4), 438–439. https://doi.org/10.1016/0147-1767(85)90062-8

Linnenbrink-Garcia, L., Rogat, T. K., & Koskey, K. L. K. (2011). Affect and engagement during small group instruction. *Contemporary Educational Psychology, 36*(1), 13-24. https://doi.org/10.1016/j.cedpsych.2010.09.001

McNeill, K. L., Katsh-Singer, R., & Pelletier, P. (2015). Assessing science practices: Moving your class along a continuum. *Science Scope, 39*(4), 21-28. https://doi.org/10.2505/4/ss15_039_04_21

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). SAGE Publications. https://unesdoc.unesco.org/ark:/48223/pf0000135289

Miller, E., Manz, E., Russ, R., Stroupe, D., & Berland, L. (2018). Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards. *Journal of Research in Science Teaching, 55*(7), 1053-1075. https://doi.org/10.1002/tea.21459

Mullis, I. V. S., Martin, M. O., & von Davier, M. (Eds.). (2021). TIMSS 2023 assessment frameworks. *TIMSS & PIRLS International Study Center, Boston College*. https://timssandpirls.bc.edu/timss2023/frameworks/

Mullis, I. V. S., Martin, M. O., Foy, P., Kelly, D. L., & Fishbein, B. (2020). TIMSS 2019 international results in mathematics and science. *TIMSS & PIRLS International Study Center, Boston College*. https://timssandpirls.bc.edu/timss2019/international-results/

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. The National Academies Press. https://doi.org/10.17226/18290

Nollmeyer, G. E., & Bangert, A. W. (2017). Measuring elementary teachers' understanding of the NGSS framework: An instrument for planning and assessing professional development. *Electronic Journal for Research in Science & Mathematics Education, 21*(8), 20-45. https://ejrsme.icrsme.com/article/view/17887

OECD. (2019). *PISA 2018 assessment and analytical framework*. OECD Publishing. https://doi.org/10.1787/b25efab8-en

OECD. (2023). *PISA 2022 results (volume I): The state of learning and equity in education*. OECD Publishing. https://doi.org/10.1787/53f23881-en

Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education, 25*(2), 177-196. https://doi.org/10.1007/s10972-014-9384-1

Park, S., Kite, V., Suh, J. K., Jung, J., & Rachmatullah, A. (2022). Investigation of the relationships among science teachers' epistemic orientations, epistemic understanding, and implementation of next generation science standards science practices. *Journal of Research in Science Teaching, 59*(4), 561-584. https://doi.org/10.1002/tea.21737

Sandoval, W. A., Kawasaki, J., Cournoyer, N., & Rodriguez, L. (2016). Secondary teachers' emergent understanding of teaching science practices. In C. K. Looi, J. L. Polman, U. Cress, & P. Reimann (Eds.), *Transforming learning, empowering learners: The International Conference of the Learning Sciences* (pp. 737-743). International Society of the Learning Sciences. https://repository.isls.org/handle/1/187

Schafer, R., & Phillippi, J. C. (2025). Updating and advancing member-checking methods: Use of video and asynchronous technology to optimize participant engagement. *International Journal of Qualitative Methods, 24*. https://doi.org/10.1177/16094069251315395

Shahat, M. A., & Al-Maamari, S. (2025). Cultural contexts and global challenges: Integrating science and social sciences in Omani teacher education. In J. Kreps Frisch, D. M. Alston, A. Feldman, R. Hagevik, & M. Schpakow (Eds.), *Wicked problems in PreK-12 science education* (pp. 147-156). Routledge. https://doi.org/10.4324/9781003508793-17

Shahat, M. A., Al-Balushi, S. M., Alawi, K. A., Bahri, K. A., & Seikkula-Leino, J. (2026). Fostering entrepreneurial mindsets and future skills: Innovative educational units for enhancing creative problem-solving in tenth-grade students. *Thinking Skills and Creativity, 60*, Article 102084. https://doi.org/10.1016/j.tsc.2025.102084

Shahat, M. A., Ohle, A., & Fischer, H. E. (2017). Evaluation of a teaching unit based on a problem-solving model for seventh-grade students. *Zeitschrift für Didaktik der Naturwissenschaften, 23*, 205-224. https://doi.org/10.1007/s40573-017-0068-1

Skinner, E. A., & Belmont, M. J. (1993). Motivation in the classroom: Reciprocal effects of teacher behavior and student engagement across the school year. *Journal of Educational Psychology, 85*(4), 571-581. https://doi.org/10.1037/0022-0663.85.4.571

Stroupe, D. (2015). Describing 'science practice' in learning settings. *Science Education, 99*(6), 1033-1040. https://doi.org/10.1002/sce.21191

Suh, J. K., Hwang, J., Park, S., & Hand, B. (2022). Epistemic orientation toward teaching science for knowledge generation: Conceptualization and validation of the construct. *Journal of Research in Science Teaching, 59*(9), 1651-1691. https://doi.org/10.1002/tea.21769

Sukor, R., Ayub, A. F. M., Ab Rashid, N. K. M., & Abdul Halim, F. (2021). Relationship between students' engagement with academic performance among non-food science students enrolled in food science course. *Journal of Turkish Science Education, 18*(4), 638-648. https://doi.org/10.36681/tused.2021.95

Sun, J., Anderson, R. C., Lin, T.-J., Morris, J. A., Miller, B. W., Ma, S., Nguyen-Jahiel, K. T., & Scott, T. (2022). Children's engagement during collaborative learning and direct instruction through the lens of participant structure. *Contemporary Educational Psychology, 69*, Article 102061. https://doi.org/10.1016/j.cedpsych.2022.102061

Wheeler, L. B., Navy, S. L., Maeng, J. L., & Whitworth, B. A. (2019). Development and validation of the classroom observation protocol for engineering design (COPED). *Journal of Research in Science Teaching, 56*(9), 1285-1305. https://doi.org/10.1002/tea.21557

Windschitl, M., Lohwasser, K., Tasker, T., Shim, S., & Long, C. (2021). Learning to teach science during the clinical experience: Agency, opportunity, and struggle. *Science Education, 105*(5), 961-988. https://doi.org/10.1002/sce.21667

Yang, Y., Liu, X., & Gardella, J. A. (2020). Effects of a professional development program on science teacher knowledge and practice, and student understanding of interdisciplinary science concepts. *Journal of Research in Science Teaching, 57*(7), 1028-1057. https://doi.org/10.1002/tea.21620

Zimmerman, B. J. (1990). Self-regulated learning and academic achievement: An overview. *Educational Psychologist, 25*(1), 3-17. https://doi.org/10.1207/s15326985ep2501_2

# APPENDIX A: INDIVIDUAL INTERVIEW QUESTIONS

## Observed Practices During the Lesson

Based on the data recorded in the classroom observation form, identify the NGSS practices to inquire about during the individual teacher interview.

## NGSS Practices

1. Asking questions
2. Developing models
3. Planning experiments
4. Analyzing data
5. Using mathematics
6. Constructing explanations
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

## Part 1. Understanding the Participant's Background

In the first part of the interview, focus on gathering information about the participant's background. Below are some guiding questions:

- What science subjects are you currently teaching? Have you taught other subjects in the past?
- What is your academic qualification and specialization?
- How many years of teaching experience do you have?
- Have you pursued any graduate studies or advanced courses in education?

## Part 2. General Questions on the Lesson and Inquiry Practices

- Can you describe your method of teaching science in today's class?
- How did you integrate inquiry-based teaching methods into today's lesson?
- What strategies did you use to encourage students to engage in exploration during today's lesson?

## Part 3. NGSS-Specific Questions

### *Practice 1. Asking questions*

**KER approach:** I noticed that during the lesson on (lesson title/date), you focused on developing the practice of asking questions.

1. Can you share examples of strategies or activities you used today to motivate students to ask questions?
2. What types of questions did students ask during the lesson? How do they compare to those typically asked in previous classes?
3. How did you utilize the questions posed by students? Can you describe instances where you incorporated their questions into the lesson content or activities?
4. Did you face any challenges in encouraging students to ask questions? If so, how did you address them?

### *Practice 2. Developing and using models to explain scientific phenomena*

**KER approach:** I observed that you emphasized developing and using models during the lesson on (lesson title/date).

1. Can you share examples of strategies or activities you used to encourage students to develop or use models?
2. Why did you choose this model for today's lesson? What other models have you used or developed in past lessons?
3. How do you help students understand diverse scientific models (e.g., physical, conceptual, mathematical) and create their own models?
4. Did you encounter any challenges in promoting this practice? If so, how did you handle them?

### *Practice 3. Planning and conducting investigations*

**KER approach:** During the lesson on (lesson title/date), you focused on planning and conducting investigations.

1. Can you provide examples of strategies or activities you used to motivate students to plan and conduct investigations?
2. How did you select the experiment for today? Do you follow the same process for selecting experiments in other lessons?
3. How do you enhance students' skills in planning and conducting investigations? Do you use technology or other resources to support this?
4. Did you face any challenges in fostering this practice? If so, how did you overcome them?

### *Practice 4. Analyzing and interpreting data*

**KER approach:** I noticed that during the lesson on (lesson title/date), you emphasized analyzing and interpreting data.

1. Can you share examples of strategies or activities you used to encourage students to analyze and represent data effectively?
2. What types of data did you ask students to collect and analyze today? Did you encourage discussions about their data findings?
3. How did you guide students to organize and represent their data effectively (e.g., tables, graphs)? Did you incorporate technology for data analysis?
4. Did you encounter any challenges in promoting data analysis? If so, how did you handle them?

### *Practice 5. Using mathematics and computational thinking*

**KER approach:** I observed that you focused on using mathematics and computational thinking during the lesson on (lesson title/date).

1. Can you share strategies or activities you used to encourage students to use mathematics and computational thinking?
2. What mathematical concepts or computational tools did you introduce today?
3. How did you help students see connections between mathematics and science in today's lesson?
4. Did you face any challenges in promoting this practice? If so, how did you address them?

### *Practice 6. Constructing explanations*

**KER approach:** I noticed that you focused on constructing explanations during the lesson on (lesson title/date).

1. Can you share strategies or activities you used to encourage students to construct explanations?
2. How did you encourage students to provide evidence-based explanations for scientific phenomena?
3. Did you encounter challenges in fostering this practice? If so, how did you overcome them?

### *Practice 7. Engaging in argument from evidence*

**KER approach:** I observed that during the lesson on (lesson title/date), you emphasized engaging students in argument from evidence.

1. How did you organize today's lesson to engage students in argumentation?
2. Can you describe your strategy for facilitating evidence-based arguments?
3. How did you encourage students to build and present evidence-based arguments?
4. Did you face any challenges in implementing this practice? If so, how did you handle them?

### *Practice 8. Obtaining, evaluating, and communicating information*

**KER approach:** I observed that you focused on obtaining, evaluating, and communicating information during the lesson on (lesson title/date).

1. Describe the strategies you used to engage students in obtaining and evaluating information.
2. How did you develop students' critical thinking skills to evaluate scientific information and sources?

3. How did you encourage students to communicate their findings? Did you incorporate technology (e.g., digital databases, online sources)?
4. Did you encounter challenges in promoting this practice? If so, how did you address them?