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An integrated professional framework for experimental chemistry teaching

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ABSTRACT

Experiment-based teaching is a core feature of school chemistry education. However, existing accounts of teachers' competence often treat laboratory techniques, pedagogical skills, and professional reflection as separate domains, leading to a fragmented understanding. The novelty of this study lies in establishing a unified, process-oriented competence framework that connects five components of experimental chemistry teaching and operationalizes them through 23 Delphi-validated manifestations. A mixed-methods framework-development design was employed, using a two-round Delphi method to establish consensus. The panel comprised 16 experts in chemistry education and teacher training. The final framework connects five components: cognition of experimental use, conducting experiments, designing learning activities, organizing classroom instruction, and evaluation and adjustment. All manifestations achieved strong expert consensus (Mdn=4.00-5.00; interquartile range (IQR)≤1.00) and high item-level content validity index (I-CVI=0.88-1.00). In conclusion, shifting from isolated skill lists to a process-oriented structure provides a coherent basis for chemistry teacher education, professional development (PD), and future research.

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1. INTRODUCTION

Experiments have long been considered a central component of chemistry teaching [1]. In educational contexts, they provide opportunities for students to observe chemical phenomena, manipulate apparatus, and engage in scientific practices [2]. Thus, experiments are widely regarded as an important means of supporting conceptual understanding and developing scientific competencies, such as evidence-based reasoning and inquiry-oriented learning [1], [3]–[5]. This role is increasingly emphasized in international trends toward competence-based and inquiry-oriented science education, as well as in Vietnam's 2018 General Education Curriculum [6], which promotes active learning, practical competence, and meaningful integration of experiments.

However, the educational value of experiments does not automatically arise from simply organizing practical activities. In many cases, experiments are implemented procedurally, with students mainly following predetermined steps and having limited involvement in scientific reasoning [1]. Under such conditions, experimental activities may become isolated technical operations that do not lead to meaningful understanding of scientific concepts [7]. Therefore, effective experiment-based teaching depends not merely on the presence of experiments, but on how teachers design, implement, and use them pedagogically to support meaningful learning.

In classroom practice, organizing such instruction places complex demands on teachers [8]. To transform experimental procedures into meaningful learning experiences, teachers must integrate disciplinary knowledge in chemistry, pedagogical knowledge about teaching and learning, and knowledge of the classroom context when planning and implementing instruction [9]. This means that experimental teaching competence should not be understood as a set of isolated technical skills, but as an integrated professional capacity connecting experimental work, instructional design, classroom interaction, and reflective practice [3]–[5].

This complexity has led researchers to identify the competencies required for teachers to effectively use experimental activities. Previous studies have addressed various aspects of this competence, such as laboratory manipulation skills, safety practices, and instructional design [3], [10]. While providing important insights, these approaches often emphasize specific and isolated aspects of teaching practice. As a result, experimental teaching competence has not yet been consistently defined across the literature. The professional relationships among teachers' disciplinary understanding, pedagogical actions in the classroom, and processes of professional reflection have not been sufficiently articulated within a coherent structure. This gap is practically important because chemistry teacher education and curriculum implementation need a clear framework to support teachers in organizing experiment-based learning in both reform-oriented Vietnamese classrooms and comparable global contexts. To address this need, this study establishes an integrated, process-oriented competence framework for experimental teaching. The framework articulates relationships among its components and operationalizes them through empirically validated manifestations, thereby providing a coherent basis for chemistry teacher education, professional development (PD), and curriculum implementation.

2. LITERATURE REVIEW

2.1. Experiment-based learning in chemistry education

In science education research, laboratory activities are often viewed as a distinctive learning environment in which students engage with scientific phenomena through observation and experimentation. They can support conceptual understanding and scientific competencies by enabling students to collect data, analyze results, and construct evidence-based explanations [2], [3], [11], [12]. In contemporary science education, these activities are often associated with inquiry-based approaches, where students actively engage in exploring and explaining natural phenomena [1], [13]–[15].

However, empirical research in science education has shown that the implementation of laboratory activities in classrooms does not always lead to the intended learning outcomes. Abrahams [4] emphasized the need to distinguish between doing experiments and learning from experiments. In many cases, students may correctly follow the procedural steps of an experiment yet still struggle to connect their empirical observations with the underlying scientific concepts. This problem is especially evident when practical work emphasizes procedural execution rather than interpretation and explanation.

Recent studies have also highlighted that the effectiveness of experimental activities depends on how they are integrated into teaching. When experiments are designed as part of learning tasks that encourage students to ask questions, discuss observations, and interpret results, they can support conceptual understanding and scientific reasoning [3], [11], [16]. In contrast, when experiments are used merely as demonstrations or technical procedures, their potential to promote meaningful learning may be limited.

These analyses highlight the crucial role of teachers in shaping how students engage with experimental activities. Teachers are responsible not only for organizing the practical conditions of laboratory work but also for supporting students in interpreting their observations and linking them to relevant scientific ideas. Consequently, examining the competencies required for teachers to use experiments effectively has become an important issue in chemistry education research.

2.2. The complexity of experimental teaching

Research in science education suggests that the use of experiments in the classroom involves more than organizing practical activities; it is also closely related to how teachers guide students' learning processes throughout the experimental experience. Hofstein and Lunetta [3] argue that the role of teachers in laboratory activities extends beyond preparing equipment and explaining experimental procedures. Teachers must also help students observe phenomena, interpret results, and connect empirical observations with scientific concepts. From this perspective, experimental activities acquire educational value only when they are integrated into teaching through pedagogical actions that support students' understanding.

In many studies, experiment-based teaching is viewed as a form of pedagogical practice in which elements of scientific practice and instructional activity are closely interconnected. Teachers are responsible not only for organizing the practical conditions of experimentation but also for designing learning tasks that enable students to observe, analyze, and explain the phenomena occurring during experiments. Accordingly, teachers need to coordinate practical work, observation, discussion, and conclusion-making during experimental activities [11]. Consequently, the use of experiments in teaching should not be regarded merely as a technical operation but rather as an integral component of the teaching-learning process.

From this perspective, experiment-based teaching can be understood as a complex professional activity of teachers. When organizing experimental activities, teachers must mobilize and integrate different forms of professional knowledge [9]. These include disciplinary and pedagogical knowledge, the ability to design experiment-based learning tasks, classroom management and interaction, and reflective adjustment based on students' learning processes. These requirements indicate that organizing experiment-based teaching involves the integration of disciplinary knowledge, pedagogical knowledge, and reflective practice in teaching.

Some studies in science education also emphasize that the effective use of experimental activities depends largely on teachers' ability to transform experimental procedures into meaningful learning opportunities for students [17], [18]. Such transformation requires teachers to identify key experimental features, guide observation, and support interpretation in relation to scientific concepts. When these pedagogical processes are effectively organized, experiments can serve as powerful tools for helping students construct scientific understanding by connecting empirical observations with theoretical ideas.

Recognition of the complexity of experiment-based teaching has led to research efforts aimed at identifying the competencies required for teachers to effectively organize and use experimental activities in instruction [3], [10]. These studies have proposed various approaches to describing teachers' experimental teaching competence. However, these approaches often emphasize different aspects of instructional practice, resulting in diverse ways of conceptualizing and structuring this competence in the literature. The following section therefore examines the main approaches used in research on experimental teaching competence.

2.3. Approaches to experimental teaching competence in previous studies

The recognition of the complexity of experiment-based teaching has encouraged many researchers to identify the competencies required for teachers to effectively use experiments in science instruction. In these studies, experimental teaching competence has been described in different ways, reflecting diverse perspectives on the nature of experiment-based teaching. Three main approaches can be identified: the laboratory practice-based approach, the teaching process-based approach, and approaches emphasizing integrated professional practice.

2.3.1. The laboratory practice–based approach

Some studies approach experimental teaching competence primarily from the perspective of laboratory practice. In these studies, teachers' competence is often described in terms of the skills and activities associated with preparing, organizing, and conducting experiments in the laboratory [19], [20]. For example, Yalcin-Celik *et al.* [21] identified challenges faced by pre-service chemistry teachers in laboratory teaching, particularly in experiment selection and design, management of experimental processes, and laboratory safety. Similarly, Imaduddin and Hidayah [22], in their study of laboratory activities for pre-service chemistry teachers, emphasized competencies in planning inquiry-based experiments and managing laboratory activities, including designing practical activities, identifying equipment and material needs, and preparing tools and materials before implementation.

Other studies also emphasize the teacher's role in ensuring the technical and safety conditions of laboratory activities. For instance, Copriady [10] identified competence components related to experiment preparation, experiment implementation, and the management of practical laboratory activities. These studies have made important contributions to clarifying the technical requirements involved in organizing experimental activities in science teaching. However, when the focus is placed primarily on laboratory operations and technical conditions, these studies tend to pay less attention to the pedagogical aspects of using experiments in the teaching process. As a result, this approach often understands experimental teaching competence mainly as the ability to conduct experiments, leaving the pedagogical design and organization of experiment-based learning less fully addressed.

2.3.2. The teaching process–based approach

Another approach conceptualizes experimental teaching competence through the stages of the teaching process. In these studies, teachers' competence is often described in terms of activities related to designing, implementing, and evaluating experiment-based learning activities. For example, Bae *et al.* [23] developed a field-based chemistry experiment teaching model that emphasizes designing experimental activities, organizing practical work, and discussing experimental results.

Similarly, several studies in teacher education have approached experimental competence through instructional models based on experiential learning or scientific inquiry. For instance, inquiry-based learning models or the conceive–design–implement–operate (CDIO) framework often describe experiment-based teaching through stages such as identifying a problem, designing experiments, conducting experiments, and evaluating results [24]. These models help clarify how experiment-based learning activities can be organized within the teaching process and highlight the teacher's role in guiding students to participate in scientific inquiry processes. However, these approaches often focus on the structure of instructional activities rather than on the structure of teachers' competence. Thus, although they describe the stages of experiment-based teaching, they do not clearly specify the competence components teachers need to implement these activities effectively.

2.3.3. Approaches emphasizing the integrated nature of professional practice

In recent years, several studies have begun to emphasize that experimental teaching competence should be understood as an integrated form of teachers' professional practice. From this perspective, the use of experiments in teaching involves not only technical skills or the stages of instructional processes but also the integration of disciplinary knowledge, pedagogical action, and reflective practice in teaching. For example, Hofstein and Lunetta [3] argue that effective laboratory organization requires teachers to connect scientific practices with instructional strategies so that students can construct understanding from experimental results.

Some studies in teacher education also highlight that experimental teaching competence should be considered in relation to teachers' professional competence. Research on teacher competence often defines teaching competence as the integration of disciplinary knowledge, pedagogical knowledge, and classroom enactment [25]. From this perspective, experiment-based teaching can be understood as a professional activity in which teachers integrate scientific practice with pedagogical actions to support students' construction of scientific understanding.

Although studies adopting this perspective emphasize the integrated nature of experimental teaching competence, its structure remains inconsistent. Many studies refer to the combination of different aspects of teaching practice, yet they do not clearly identify the competence components or the relationships among them within a coherent competence framework. Therefore, further research is needed to clarify the structure of experimental teaching competence in the context of teacher education and science teaching practice.

2.4. Teacher competence as an integrated professional process

In research on teacher competence, many scholars argue that teachers' professional competence should not be understood merely as a collection of discrete skills but rather as an integrated process that brings together multiple elements of professional practice. Contemporary competence models often emphasize that teaching competence develops through the integration of disciplinary knowledge, pedagogical knowledge, and the ability to apply these forms of knowledge in specific instructional contexts. Thus, teacher competence is reflected not only in what teachers know, but also in how they mobilize that knowledge in classroom situations [25], [26].

Several studies have proposed theoretical models to describe the structure of teachers' professional competence. For example, Blömeke *et al.* [27] conceptualize teacher competence as a continuous process in which teachers' personal resources–such as knowledge, beliefs, and professional motivation–are activated to perform pedagogical actions in classroom contexts. In this model, competence involves transforming internal resources into observable teaching practices. Similarly, Mulder [28] argues that professional competence should be understood as the ability to mobilize knowledge, skills, and attitudes in an integrated manner to effectively perform professional tasks in real-world contexts.

In the context of science teaching, this integrated perspective is particularly relevant when examining the use of experiments in instruction. As discussed, organizing experimental activities in the classroom requires teachers to connect elements of scientific practice with pedagogical activities. This includes understanding the scientific principles underlying experiments, designing experiment-based learning activities, guiding students in observing and interpreting experimental results, and reflecting on the effectiveness of the instructional activities. Accordingly, experimental teaching competence can be viewed as a form of professional competence requiring teachers to mobilize disciplinary knowledge, pedagogical action, and reflective practice simultaneously.

This approach makes it possible to conceptualize experimental teaching competence not simply as a set of technical skills or stages of instructional procedures, but as an integrated professional practice enacted by teachers in classroom contexts. Identifying its structure therefore requires examining the relationships among cognitive, practical, and reflective dimensions of teaching practice. However, although theoretical models of teacher competence provide important insights, their application to experimental teaching competence remains limited.

2.5. Research gap, research aim, and research questions

A review of previous studies shows that experiment-based teaching has become an important area of research in science education. These studies highlight both its potential for supporting students' scientific understanding and the professional demands it places on teachers. They also show that the effective use of experimental activities depends largely on how teachers design and organize experiment-based learning activities.

However, when examining research on teachers' experimental teaching competence, it becomes apparent that existing approaches remain fragmented and lack conceptual consistency. Some studies focus on the skills and activities related to organizing and conducting laboratory experiments, while others describe experimental teaching competence through the stages of instructional processes or through models for organizing experiment-based learning activities. Although these approaches provide valuable insights, they often emphasize specific elements of practice, such as technical skills or stages of the teaching process.

In addition, recent studies have begun to emphasize that experimental teaching competence should be understood as an integrated form of teachers' professional practice. However, although these studies have acknowledged the interplay between disciplinary knowledge, pedagogical action, and professional reflection in the teaching process, the structure of experimental teaching competence has not yet been clearly articulated within a unified competence framework. In particular, the relationships among competence components and their mobilization in actual teaching practice remain insufficiently clarified. Thus, there remains a need to clarify the structure of experimental teaching competence as an integrated professional competence and to describe the relationships among its components in teacher education and science teaching practice.

Based on this research gap, the present study aims to develop and determine the structure of a competence framework for experimental teaching among chemistry teachers. The study conceptualizes experimental teaching competence as an integrated professional practice in which teachers mobilize disciplinary knowledge, pedagogical action, and reflective practice simultaneously in the teaching process. To achieve this objective, the study employs the Delphi method to collect and synthesize expert opinions from specialists in chemistry education and teacher education in order to identify the components and manifestations of experimental teaching competence. Accordingly, the study aims to address the following research questions:

- What core components constitute experimental teaching competence in secondary chemistry education, and how can these components be organized within an integrated competence framework? (RQ1)
- What specific manifestations describe the components of experimental teaching competence in the proposed competence framework? (RQ2)
- To what extent do experts reach consensus regarding the components and manifestations of the proposed experimental teaching competence framework? (RQ3)

3. METHOD

3.1. Research design

The aim of this study was to develop an integrated framework of experimental teaching competence in teacher education. Addressing this aim requires clarifying the structure of a competence that is complex, context-dependent, and not directly observable. In such cases, research designs that rely on systematic expert judgment are considered appropriate, as they allow professional knowledge to be articulated and refined through structured consensus-building processes [29], [30].

Based on this consideration, the study employed a modified Delphi approach as the main methodological strategy. Delphi methods support convergence of expert opinion through multiple rounds of structured feedback while maintaining anonymity and reducing the influence of individual dominance [29]. This makes them suitable for research that seeks to clarify conceptual structures rather than to measure outcomes. Specifically, the Delphi method is particularly suitable for developing competence frameworks because competence is often a complex, multifaceted construct that cannot be easily measured by traditional empirical tests. By employing iterative rounds of anonymous expert feedback, the Delphi approach systematically builds consensus and operationalizes abstract professional requirements into validated, concrete manifestations.

Within this methodological choice, the study was designed as an exploratory framework development study. The research did not aim to evaluate teaching effectiveness or individual performance. Rather, it identified, refined, and stabilized the core components of experimental teaching competence and clarified the logical relationships among them. Figure 1 summarizes the three-stage research process used in this study.

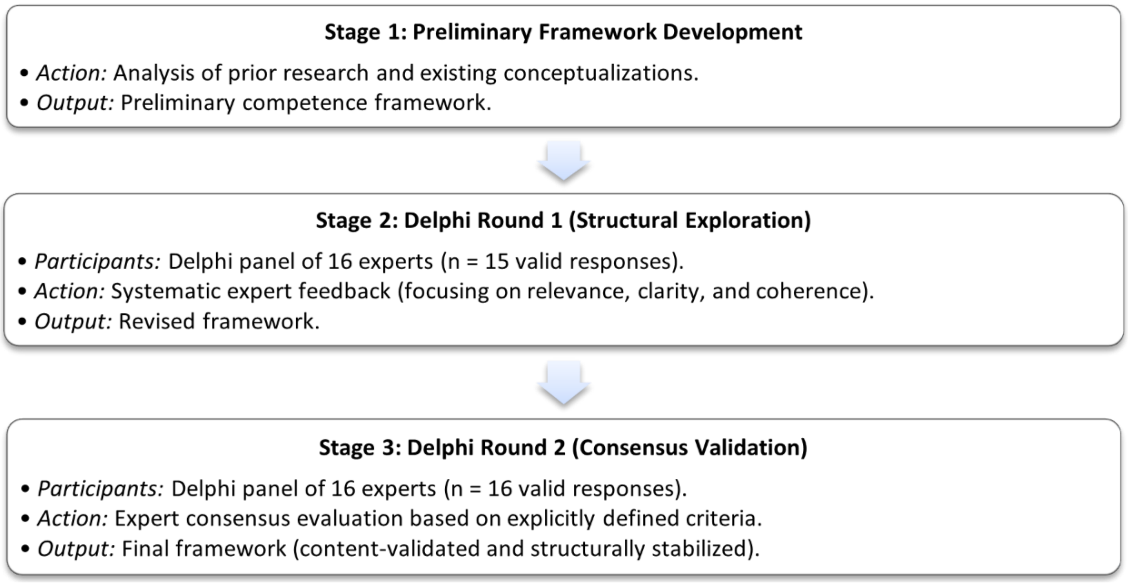

Figure 1. Overview of the three-stage research process using the modified Delphi method

First, a preliminary competence framework was developed based on prior research and existing conceptualizations of experimental teaching. Second, this framework was examined and refined through systematic expert feedback, with attention to the relevance, clarity, and coherence of its components. Third, the revised framework was subjected to expert consensus to stabilize its structure. If consensus had not been sufficiently achieved after round 2, additional Delphi rounds would have been conducted. The validation plan consisted of two stages: i) qualitative refinement of the framework through expert feedback in Delphi round 1 and ii) quantitative consensus validation and content validity assessment in Delphi round 2 using predefined criteria. Throughout the Delphi process, expert responses were collected and analyzed anonymously, and aggregated feedback was shared without identifying individual participants, thereby supporting the independence of expert judgments and minimizing the influence of dominant individuals. All procedures involving expert participants were conducted in accordance with ethical guidelines, including informed consent, voluntary participation, and confidentiality of responses.

In line with methodological recommendations for Delphi studies, the study defined explicit criteria for consensus in advance, rather than assuming that agreement would naturally emerge through iteration [31]. Expert consensus was therefore treated as an analytically defined outcome used to support framework stabilization, rather than as an implicit or informal judgment. This design ensured that the final framework was grounded in scholarship, informed by professional expertise, and developed transparently.

Experts were selected using purposive sampling to ensure disciplinary authority and alignment with the study objective. The inclusion criteria required that participants hold a doctoral degree in chemistry or chemistry education, have at least 10 years of experience in teaching and/or research in relevant fields, and be actively engaged in chemistry teaching, teacher education, or laboratory-based instruction. The Delphi panel consisted of 16 experts who met these criteria. This panel size falls within the range commonly recommended for Delphi studies (10–30 experts) [29]. The panel comprised university lecturers, chemistry education researchers, and teacher educators affiliated with universities of education and educational research institutes across Vietnam. Most experts had over 20 years of professional experience, while the remainder had between 11 and 20 years of experience, and the panel included 5 male and 11 female experts. Panel stability across the two Delphi rounds exceeded 90%. A total of 16 experts participated; however, one response in round 1 was invalid, resulting in 15 valid responses in round 1 and 16 in round 2. This indicates strong engagement and consistency of expert participation.

3.2. Development of the preliminary framework

The first stage focused on constructing a preliminary framework of experimental teaching competence to serve as the basis for subsequent expert consultation. This stage aimed to articulate an initial structural representation of the competence grounded in prior research and theoretical considerations. The development process involved a systematic analysis of existing literature on experimental teaching, laboratory practice in science education, and professional competence frameworks. Particular attention was given to conceptualizations that addressed the cognitive, practical, pedagogical, and reflective dimensions of teaching with experiments. The objective was not to compile isolated skills, but to identify structural components reflecting the professional logic of experimental teaching practice. Based on this analysis, a preliminary framework consisting of four core components was formulated: i) cognition of experimental use in teaching; ii) conducting experiments; iii) organizing teaching with experiments; and iv) assessment and adjustment.

Each component was accompanied by a concise descriptive statement clarifying its professional scope and function within experimental teaching. The descriptions were designed to differentiate the components conceptually while preserving their interrelated nature within instructional practice. At this stage, the framework was presented as a theoretically informed proposal rather than a validated model. It did not yet include detailed operationalized manifestations or empirical justification. This preliminary structure was to provide a clearly articulated reference framework to be examined and refined through the first Delphi round.

3.3. Delphi round 1: structural exploration

The preliminary four-component framework developed in stage 1 was subjected to expert consultation through the first Delphi round. This round was exploratory, examining not only the adequacy of the proposed components but also the theoretical grounding and internal logic of the framework. This exploratory step was necessary to identify possible overlaps, missing elements, and conceptual ambiguities before conducting formal consensus validation.

Experts received a structured questionnaire presenting the preliminary framework, including four components and their descriptive definitions. The instrument was designed to elicit feedback across several dimensions. First, experts were invited to evaluate the overall structure of the framework, including the relevance and clarity of each component. They were asked whether the proposed components sufficiently captured experimental teaching competence and whether any should be merged, separated, or supplemented. Second, the questionnaire explicitly requested expert input on the theoretical basis of the framework. Experts were encouraged to indicate theoretical models or conceptual approaches that they considered relevant and to suggest alternative structuring principles if appropriate. This element ensured that the framework was grounded not only in literature analysis but also in informed professional and theoretical perspectives.

Third, experts were asked to comment on the logical relationships among components. This included examining whether the components represented hierarchical levels, functional phases, or interrelated domains within a professional cycle. This question was intended to clarify the internal coherence of the framework and to avoid treating components as isolated categories.

Fourth, experts were invited to propose specific manifestations for each component. These proposals were intended to operationalize the conceptual domains and to prepare for the structured evaluation conducted in round 2. Additional questions addressed contextual and practical considerations affecting experimental teaching, ensuring that the framework would remain applicable within real instructional settings.

Round 1 generated primarily qualitative data. Responses were analyzed thematically to identify recurrent suggestions for structural revision, clarifications of theoretical positioning, proposed reconfigurations of component relationships, and lists of potential professional manifestations for subsequent validation. The purpose of this analysis was to refine the conceptual structure and strengthen the theoretical coherence of the framework before proceeding to formal consensus evaluation. No statistical measures of agreement were calculated at this stage. The revised framework derived from this analysis served as the basis for the round 2 instrument. Following this exploratory refinement, the revised framework was subjected to a second Delphi round aimed at assessing expert consensus and examining content validity.

3.4. Delphi round 2: consensus validation

Unlike round 1, which emphasized exploratory feedback and structural revision, round 2 focused on the evaluation of the revised framework. Specifically, it examined the appropriateness and clarity of each manifestation, assessed whether the set adequately represented each competence component, and provided structured judgments for consensus determination. To serve this evaluative purpose, the round 2 instrument was constructed based on the round 1-revised framework. The updated structure consisted of five competence components and 23 specific manifestations, organized according to a logical progression from cognition to implementation and reflection.

Experts were provided with a brief summary explaining that the framework was developed based on round 1 feedback and literature comparison. They also received the five components with definitions, a list of 23 specific manifestations distributed across the five components, and a structured rating scale for evaluating their appropriateness. Each manifestation was evaluated using a 5-point Likert scale ranging from 1 (completely inappropriate) to 5 (completely appropriate). Experts were also invited to provide written comments or recommendations after each manifestation and at the end of each component section. The data obtained from round 2 served as the basis for quantitative consensus analysis and content validity assessment, conducted according to predefined criteria.

3.5. Data analysis

Data analysis was conducted separately for each Delphi round in accordance with their distinct objectives. Importantly, criteria for determining consensus in round 2 were defined a priori, following methodological recommendations for Delphi reporting [31]. This approach ensured consistency and transparency in the analysis across the two rounds.

Round 1 generated primarily qualitative data through open-ended responses. These responses were subjected to thematic analysis to identify recurring suggestions concerning structural revision, theoretical clarification, and proposed manifestations for each competence component. Similar responses were grouped and synthesized to inform refinement of component definitions and restructuring of the framework. As round 1 served an exploratory and developmental purpose, no statistical indicators of agreement were calculated at this stage.

Round 2 generated quantitative data through expert evaluations of each manifestation using a 5-point Likert scale. Qualitative comments were also collected to support interpretation and wording refinement. Descriptive statistics were calculated for each manifestation, including the median as a measure of central tendency and the proportion of experts assigning high-level ratings (levels 4 or 5). The use of the median is widely recommended in Delphi studies due to the ordinal nature of Likert-scale data and the typically limited panel size [32].

In addition, dispersion of responses was examined using the interquartile range (IQR), as suggested in Delphi methodological literature [33]. Lower dispersion values were interpreted as indicating stronger convergence of expert opinion. The consensus criteria were defined a priori in accordance with established reporting guidelines [31], [34]. Given the 5-point Likert scale employed in this study, a manifestation was considered to have reached consensus if it met the following conditions: a median rating of ≥ 4, and an item-level content validity index (I-CVI) of ≥ 0.78.

I-CVIs were calculated following Lynn [35] and subsequent clarification by Polit and Beck [36]. An I-CVI threshold of≥ 0.78 was considered indicative of acceptable content validity. Given the panel size of 16 experts in the present study, the likelihood of chance agreement was reduced, thereby strengthening the robustness of the content validity assessment. Manifestations were evaluated against these predefined criteria. Items not fully meeting the criteria were reviewed in light of both quantitative indicators and qualitative feedback before final decisions were made.

4. RESULTS AND DISCUSSION

4.1. Evolution of the competence framework

The preliminary framework developed in stage 1 consisted of four components: cognition of experimental use in teaching, conducting experiments, organizing teaching with experiments, and assessment and adjustment. This structure reflected a literature-based attempt to conceptualize experimental teaching competence as a coherent professional process from understanding to enactment and improvement. At this stage, the framework functioned as a theoretically grounded proposal and had not yet been empirically examined or operationalized through specific manifestations. Table 1 summarizes the subsequent evolution of the competence framework across the Delphi rounds.

Round 1 expert consultation refined both the conceptual structure and the internal logic of the framework. Experts affirmed the relevance of the four domains but emphasized that their relationships required clearer articulation. Rather than viewing the components as independent categories, many experts interpreted them as elements within a professional process. Several described the sequence from cognition to implementation and evaluation as a logical progression in teaching practice. At the same time, feedback highlighted the cyclical character of experimental teaching, in which reflection and adjustment feed back into subsequent cognitive and instructional decisions. A smaller number of responses pointed to overlapping boundaries, particularly between conducting experiments and organizing teaching with experiments, indicating that further differentiation was needed to avoid conceptual ambiguity.

Round 1 also provided important clarification regarding the theoretical grounding of the framework. Experts explicitly referred to several established conceptual perspectives when evaluating the structure. Some interpreted the sequence of components in relation to pedagogical content knowledge (PCK), emphasizing the transformation of subject-specific experimental knowledge into teachable instructional action. Others described the framework using a logic comparable to a plan–do–check–act (PDCA) cycle, highlighting the iterative movement from planning and implementation to evaluation and subsequent adjustment. References were also made to national professional standards for teachers and broader competence frameworks, which reinforced the need for alignment between experimental practice and pedagogical responsibility. These theoretical references did not replace the original structure but served to clarify and justify the internal logic connecting cognition, action, and reflection.

Table 1. Evolution of the experimental teaching competence framework across Delphi rounds

Stage	Structural components	Key modifications	Role of expert feedback
Preliminary framework (before Delphi)	4 components: cognition; conducting experiments; organizing teaching; assessment and adjustment	Literature-based structure; components conceptually defined but not operationalized	Not yet validated; theoretical proposal derived from literature
After Delphi round 1	5 components (addition of planning/design stage); initial set of manifestations developed	Clearer differentiation between conducting experiments and pedagogical planning; articulation of logical relationships (sequential, cyclical, interactive); operationalization through synthesized manifestations	Experts clarified theoretical grounding, refined component boundaries, proposed structural revision, and generated candidate manifestations
After Delphi round 2 (final framework)	5 components + 23 manifestations	Framework stabilized; manifestations validated and wording refined; no further structural changes required	Expert consensus confirmed relevance and coherence of components and manifestations

In addition to validating and clarifying the structure, experts proposed concrete revisions. The most influential suggestion concerned the absence of an explicit planning or design stage. Several experts argued that experimental teaching competence should not move directly from conducting experiments to organizing instruction, but should include a distinct phase in which teachers design instructional plans that integrate experiments pedagogically. This proposal was conceptually significant because it captured the transformation from technical laboratory competence to pedagogical implementation. Other suggestions, such as separating laboratory safety into an independent component or introducing innovation as a distinct domain, were discussed but did not receive sufficient convergence to justify structural expansion at that level. Instead, these aspects were integrated within relevant components.

Based on the synthesis of round 1 feedback, the framework was revised from four to five components. The revised structure adopted a clearer process orientation, distinguishing between conducting experiments and designing experimental teaching plans, and articulating assessment and adjustment as a reflective dimension within a dynamic professional cycle. This restructuring enhanced the internal coherence of the model and made explicit the developmental and functional relationships among components.

Round 1 feedback also contributed to operationalization. Experts proposed specific professional actions and manifestations associated with each component. These suggestions were analyzed, consolidated, and reorganized to form a structured set of manifestations aligned with the revised five-component framework. This revised framework was then submitted to round 2 for formal consensus evaluation.

In round 2, experts evaluated the appropriateness of the proposed manifestations using a 5-point Likert scale. The results indicated strong convergence in expert judgments, with the majority of manifestations reaching high levels of agreement. Only minor wording adjustments were required, with no further structural reconfiguration. The outcome of this process was a stabilized competence framework consisting of five components and their associated manifestations.

4.2. Consensus results and validation of the final framework

Delphi round 2 was conducted to evaluate the appropriateness of the 23 manifestations distributed across the revised five-component framework. Expert judgments were analyzed in accordance with the predefined consensus criteria. Table 2 presents the final framework and the consensus indicators obtained from Delphi round 2. As shown in Table 2, descriptive statistics indicated a high level of agreement across all manifestations. The median values for all 23 manifestations were equal to or greater than 4 on the 5-point Likert scale, satisfying the predefined criterion for central tendency. Dispersion of expert ratings, examined using the IQR, showed limited variability across items, indicating convergence of expert opinion. No manifestation demonstrated substantial disagreement requiring structural reconsideration. I-CVI were calculated for all manifestations. Each item achieved an I-CVI value equal to or exceeding the predefined threshold ($\geq$0.78), supporting the relevance and representativeness of the manifestations within their respective components.

Because all manifestations met the predefined criteria for central tendency and content validity, no manifestation was removed at this stage. Minor revisions were made to wording in several items to improve clarity and precision based on expert comments; however, these refinements did not alter the conceptual structure of the framework. The final competence framework therefore consists of five interrelated components supported by 23 validated manifestations. The stability of the structure between round 1 revision and round 2 validation indicates strong expert convergence regarding both the conceptual configuration and its operational expressions. Because all predefined consensus criteria were fully satisfied in round 2, no additional Delphi rounds were required.

Table 2. Final experimental teaching competence framework and consensus indicators (round 2)

Component and description	Manifestation (final wording)	Median	IQR	I-CVI
1. Cognition of experimental use in teaching: the theoretical foundation and professional understanding of the use of experiments in teaching, including pedagogical role, scientific basis, methods of implementation, and safety regulations to meaningfully integrate experiments into learning.	1.1. Present safety regulations and proper procedures for storing and handling chemicals before, during, and after conducting experiments.	5	1	0.94
	1.2. Describe how to use common laboratory equipment and perform basic experimental techniques.	5	1	0.94
	1.3. Explain the role and significance of experiments in chemistry teaching for developing students' competencies and character.	5	1	1.00
	1.4. Explain the scientific basis and related knowledge underlying experiments.	5	1	0.94
	1.5. Present forms and methods of using experiments in chemistry teaching.	4	0.25	0.94
2. Conducting experiments: the ability to prepare, conduct, and manage chemistry experiments accurately, scientifically, and safely, including planning, observation, data collection, and problem handling.	2.1. Identify the scientific purpose of an experiment.	4.5	1	1.00
	2.2. Develop an appropriate plan for conducting an experiment.	5	1	1.00
	2.3. Prepare the required chemicals, apparatus, and equipment according to the established experimental plan.	5	0.25	1.00
	2.4. Carry out experimental procedures in a safe, accurate, and scientifically sound manner according to the planned sequence.	5	0.25	1.00
	2.5. Observe, record, collect experimental data, analyze results, and draw conclusions.	5	0.25	1.00
	2.6. Handle unexpected situations during experimentation and collect and dispose of experimental waste in accordance with regulations.	5	1	1.00
3. Designing experimental teaching activities: the pedagogical ability to plan learning activities incorporating experiments, including defining objectives, selecting approaches, designing assessment tools, and preparing alternatives.	3.1. Define the objectives of experiment-based teaching activities.	5	1	1.00
	3.2. Select appropriate forms and methods of using experiments in alignment with instructional objectives and contextual conditions.	5	1	0.94
	3.3. Select or design suitable assessment tools for experiment-based teaching activities.	5	1	0.88
	3.4. Design detailed instructional content for experiment-based teaching activities.	5	1	1.00
	3.5. Select appropriate alternative media (experimental videos, virtual experiments, simulations) and determine suitable ways to use them when real experiments cannot be conducted.	4.5	1	1.00
4. Organizing experimental teaching: the ability to manage and facilitate experiment-based learning activities in the classroom, ensuring safety, clarity of tasks, student guidance, discussion, and feedback.	4.1. Arrange the learning environment appropriately for experiment-based instruction.	5	1	1.00
	4.2. Assign experimental tasks effectively, including clear guidance on safety measures.	5	1	1.00
	4.3. Support, guide, and manage students during experiment-based teaching activities.	5	1	0.94
	4.4. Organize students' reporting, discussion, and formulation of conclusions related to experiments.	5	1	1.00
	4.5. Provide timely assessment and feedback during experiment-based teaching activities.	5	1	1.00
5. Evaluation and adjustment: the ability to critically reflect on and improve the use of experiments in teaching, ensuring continuous enhancement of instructional quality.	5.1. Analyze strengths and limitations after organizing experiment-based learning activities.	5	1	0.94
	5.2. Propose improvements to experiment-based teaching activities (including experimental procedures and instructional organization plans).	4	1	1.00

4.3. Relationships and professional logic among components

Beyond statistical validation, analysis of expert feedback across the two Delphi rounds revealed increasing structural coherence in the final framework. The five-component model reflects not merely a categorical classification of competences but a structured professional configuration linking cognition, disciplinary action, pedagogical design, classroom enactment, and reflective adjustment [27], [28]. Figure 2 illustrates this integrated framework as a cyclical professional process.

As shown in Figure 2, the first component, cognition of experimental use in teaching, functions as the conceptual foundation of the framework. Expert feedback consistently emphasized that understanding the pedagogical role and scientific basis of experiments precedes and informs subsequent professional actions. This foundational dimension supports the transition from theoretical awareness to practical implementation. The second component, conducting experiments, represents disciplinary and procedural competence.

It operationalizes the teacher's ability to plan, prepare, and carry out experiments in a scientifically sound and safe manner. However, expert commentary in round 1 indicated that this capacity alone does not constitute experimental teaching competence unless it is connected to pedagogical planning and instructional purposes. The third and fourth components–designing experimental teaching activities and organizing experimental teaching–clarify this progression. Designing involves translating experimental procedures into structured learning activities aligned with instructional objectives and assessment strategies. Organizing refers to the enactment of those plans within classroom contexts, including task assignment, student guidance, management of learning interactions, and formative feedback. The fifth component, evaluation and adjustment, completes the structure by incorporating reflective practice. Experts highlighted that experimental teaching competence must include the ability to analyze instructional effectiveness and refine both experimental procedures and teaching strategies. This dimension introduces a recursive element into the framework, linking evaluation to future planning and instructional decisions.

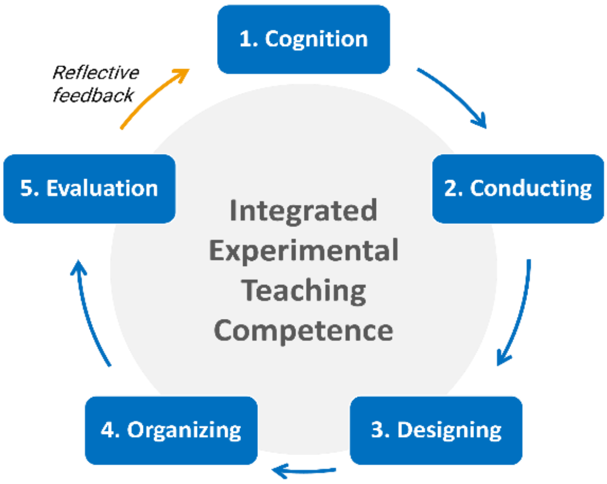

Figure 2. Integrated framework of experimental teaching competence as a cyclical professional process

Together, the five components form a coherent structure in which each dimension performs a distinct yet interrelated function. The convergence of expert evaluations and qualitative feedback across Delphi rounds indicates that the final framework demonstrates internal consistency and professional relevance as a representation of experimental teaching competence. In addition to sequential progression, expert feedback highlighted the integrative nature of the framework. The five components are not conceived as isolated competences to be developed independently; rather, they operate in coordinated interaction within authentic teaching situations. For instance, designing experimental teaching requires simultaneous mobilization of disciplinary understanding (cognition), practical feasibility considerations (conducting experiments), and anticipation of classroom implementation (organizing teaching). Similarly, evaluation and adjustment are not positioned as an external add-on but function as a mechanism that informs and reshapes both conceptual understanding and subsequent instructional planning. This integrative structure reflects the expectation that experimental teaching competence involves the coordinated activation of knowledge, skills, and pedagogical judgment in context, rather than the mechanical accumulation of discrete abilities.

To enhance the practical interpretability of the framework, the validated manifestations may be understood as observable expressions of competence in teaching practice. For example, cognition may be evidenced through teachers' explanations, lesson plans, and pedagogical justifications for the use of experiments; conducting experiments through direct observation of preparation, procedural accuracy, safety compliance, and data handling; designing through the alignment of objectives, experimental tasks, and assessment strategies in instructional plans; organizing through classroom enactment, including task assignment, student guidance, discussion facilitation, and formative feedback; and evaluation-adjustment through post-lesson reflection, professional dialogue, or documented instructional revisions. While the present study focuses on framework development rather than instrument construction, these manifestations not only provide a structured basis for future development of observation protocols, performance rubrics, and assessment tools, but also offer an initial reference for interpreting and assessing teachers' experimental teaching competence in practice.

4.4. From fragmented skill lists to an integrated, process-oriented framework

These findings suggest a shift in how experimental teaching competence can be conceptualized within teacher education. Previous research has frequently approached this competence through discrete skill categories–such as laboratory techniques, safety management, or instructional strategies–often treated as parallel or loosely connected domains [19], [20], [37], [38]. While such categorizations provide practical clarity, they may risk fragmenting competence into isolated elements without sufficiently articulating their interrelationships [27], [28].

The final framework developed in this study offers an alternative structural configuration. Rather than presenting experimental teaching competence as a checklist of technical and pedagogical abilities, the five-component model organizes these dimensions into a coherent professional process. Cognition of experimental use in teaching provides the conceptual grounding; conducting experiments represents disciplinary enactment; designing and organizing experimental teaching articulates the pedagogical transformation and classroom realization of that knowledge; and evaluation and adjustment introduce a recursive mechanism for professional learning and refinement.

This configuration responds directly to concerns regarding the lack of a process-oriented perspective in prior models [27]. By positioning reflection not as an external evaluative step but as an integral component that informs future planning and instructional decisions, the framework foregrounds the dynamic nature of professional competence [39]. Competence is thus understood not as a static possession of knowledge and skills, but as an ongoing capacity to mobilize, integrate, and refine these resources in response to instructional contexts [27], [28].

The framework is integrative not only because it includes multiple dimensions, but because these dimensions are structurally connected. Designing experimental teaching activities, for instance, requires the coordination of disciplinary understanding, awareness of pedagogical goals, and anticipation of classroom implementation. Similarly, evaluation and adjustment are inseparable from both conceptual understanding and subsequent instructional design. In this sense, the framework conceptualizes competence as a coordinated professional capacity rather than a mechanical aggregation of discrete skills. By making explicit the structural relationships among cognition, action, and reflection, the study contributes to a more integrated understanding of experimental teaching competence in teacher education. This integrated, process-oriented orientation provides a foundation for both curriculum design and PD that moves beyond fragmented skill training toward coherent professional formation.

4.5. Clarifying the transformation from scientific practice to pedagogical action

A second contribution is clarifying the distinction and relationship between conducting experiments and teaching with experiments. Prior research has frequently acknowledged the importance of both disciplinary laboratory competence and pedagogical competence. However, these dimensions have often been treated as parallel capacities rather than as structurally connected processes [11], [17].

The findings of the present study make explicit the transformation that occurs between these two domains. Conducting experiments reflects the teacher's ability to perform scientific procedures accurately, safely, and systematically. It demonstrates disciplinary and procedural proficiency, or the capacity to "do" the experiment successfully. However, the ability to do an experiment does not automatically entail the ability to organize meaningful learning experiences around that experiment.

The inclusion of a distinct component–designing experimental teaching activities–emerged as a critical structural refinement in the Delphi process. Expert feedback indicated that pedagogical planning constitutes a mediating stage between scientific performance and classroom enactment. This stage involves translating experimental procedures into instructional objectives, selecting appropriate forms of experimental use (demonstration, inquiry-based investigation), anticipating students' difficulties, and aligning assessment strategies with learning goals. In this respect, the framework operationalizes the idea that effective teaching requires transformation of disciplinary knowledge into pedagogically powerful representations, a process central to PCK [18], [40], [41].

Furthermore, organizing experimental teaching represents the enactment of this transformation within authentic classroom contexts. It encompasses not only task assignment and safety management but also the orchestration of student interaction, discussion, interpretation of results, and formative feedback. In doing so, it highlights that experimental teaching competence involves guiding others to engage in scientific reasoning rather than merely demonstrating scientific procedures. By distinguishing between conducting, designing, and organizing, the framework avoids conflating laboratory expertise with pedagogical expertise. Instead, it makes visible the intermediate professional work required to transform scientific practice into structured learning experiences. This structural clarification contributes to a more precise understanding of how experimental competence operates within teacher education and provides a basis for designing training programs that explicitly address the transition from "doing science" to "teaching science".

4.6. Implications for teacher education and professional development

The integrated structure of the proposed framework has several critical implications for teacher education and educational practice. These implications highlight how the framework can inform concrete decisions in curriculum design, teacher training, and instructional support. To enhance its practical applicability, these implications are discussed across four interrelated domains: teacher education curricula, PD, school leadership, and educational policy.

Teacher education curricula: first, it demonstrates that traditional, fragmented approaches to science teacher education, which often isolate laboratory training from pedagogical methodology, may be insufficient. Instead, training should be organized around coherent professional processes that connect conceptual understanding, experimental execution, pedagogical planning, classroom enactment, and reflective evaluation. Teacher education programs can operationalize this integration by embedding experiment-based lesson design tasks within methods courses, rather than treating laboratory skills as isolated elements of competence. For example, pre-service teachers may be required to redesign a standard experimental procedure into a student-centered inquiry activity aligned with curriculum objectives and student characteristics. Such an approach encourages future teachers to view experimentation not merely as a technical task, but as a pedagogical resource embedded within broader instructional goals.

For in-service PD, the framework provides a structured diagnostic tool for identifying strengths and areas for improvement across different components of competence. Such diagnostic potential can be applied in PD programs by aligning training activities with specific components of the framework. For instance, teachers who demonstrate strong laboratory execution skills but encounter difficulties in facilitating student discussion may participate in targeted workshops focused on classroom organization and discourse facilitation. Conversely, teachers who effectively manage classroom interaction but lack confidence in experimental design may benefit from activities that strengthen disciplinary reasoning and instructional planning. By distinguishing among yet integrating these components, the framework supports more differentiated and coherent PD pathways. Moreover, the inclusion of evaluation and adjustment as a core component highlights the importance of reflective practice in teacher education and PD. The evaluation component can be operationalized through structured activities such as post-lesson analysis, peer feedback, and video-based reflection on experimental teaching practices.

At the level of school leadership and instructional mentoring, the framework can be used as a reference tool to support classroom observation and feedback. School leaders and mentors may use the five components to structure observation protocols and provide focused feedback on specific aspects of experimental teaching. For example, a lesson observation may explicitly examine how a teacher organizes student activities during an experiment or facilitates reflective discussion after the activity. By providing a granular, process-oriented map of competence, the framework enables targeted and coherent instructional support and may support teacher evaluation and educational reform efforts.

At the system level, the validated manifestations can support the development or refinement of teacher professional standards, accreditation criteria, and school-based expectations for laboratory instruction. Policy makers may use the framework to align competence standards with competence-based education reforms, particularly by emphasizing the integration of disciplinary knowledge, instructional practice, and reflective processes in teaching. In contexts where laboratory resources are limited, the framework also supports the use of alternative media (videos and virtual experiments) as pedagogically meaningful substitutes, rather than purely technical replacements. This provides a policy-relevant basis for strengthening resource-sensitive laboratory instruction.

Taken together, these implications suggest that teacher education programs and educational policies may benefit from shifting from fragmented competence training toward integrated professional formation. By supporting curriculum design, targeted PD, structured instructional supervision, and policy alignment, the framework provides a practical basis for improving experiment-based teaching in science education. This contribution reinforces the role of the framework as a coherent reference for guiding teaching improvement across multiple educational contexts.

4.7. Limitations and directions for future research

Despite its contributions, this study has several limitations that should be acknowledged to provide proper context for these results. First, the framework was developed and validated through expert consensus rather than empirical classroom implementation. Although the Delphi process supported content validity and structural coherence, it represents a theoretical construct at this stage and has not yet been tested in classroom settings. Therefore, a next step is the empirical validation of these 23 manifestations through real-world classroom observations and the development of performance rubrics in diverse educational contexts. This can be achieved through systematic classroom-based studies in which the manifestations are operationalized as observable indicators, followed by the development and validation of analytic rubrics to assess teachers' experimental teaching competence. In addition, large-scale survey studies and confirmatory factor analysis can be conducted to examine the structural validity of the proposed framework.

Second, the expert panel, although composed of experienced professionals in science education and teacher training, was limited to a specific educational context. The interpretation of experimental teaching competence may vary across national curricula, institutional settings, and levels of schooling. A further line of inquiry involves replicating the framework in different educational systems and comparing results across contexts to evaluate its transferability and contextual sensitivity.

Third, while the framework conceptualizes competence as an integrated and process-oriented capacity, the current study focused primarily on structural clarification rather than measurement development. Subsequent studies can build on the identified components and manifestations to develop standardized assessment instruments and pilot them in teacher education programs. Longitudinal research designs can be used to examine how experimental teaching competence develops over time in both pre-service and in-service teachers. Finally, the study conceptualizes competence at the level of professional structure rather than individual psychological processes. Another important direction is to incorporate qualitative approaches, such as interviews or classroom observations, to explore how teachers' beliefs, motivations, and contextual constraints influence the enactment of the identified components in practice.

5. CONCLUSION

This study developed and content-validated an integrated competence framework for experimental chemistry teaching using a modified two-round Delphi process. The resulting framework comprises five interrelated components: teachers' cognition of experimental use, conducting experiments, designing experimental teaching activities, organizing experimental teaching, and evaluation and adjustment, operationalized through validated manifestations. It conceptualizes experimental teaching competence as a coherent professional practice that integrates disciplinary understanding, instructional design, classroom enactment, and reflective improvement.

The framework provides a structured reference for aligning teacher education, PD, and policy expectations in experiment-based instruction. It can inform teacher professional standards, accreditation criteria, and competence-based appraisal by specifying observable expectations for teaching practice. In doing so, it supports the integration of laboratory skills with pedagogical design, classroom facilitation, and reflective evaluation. Further research is needed to empirically validate and operationalize the framework in classroom contexts. This includes developing observation or performance rubrics, conducting multi-site lesson studies, and testing reliability and validity across diverse school contexts. Such efforts will help establish the robustness and practical applicability of the framework across different teaching contexts.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This study complied with relevant national regulations and institutional guidelines for research involving human participants and was conducted in accordance with the ethical principles of the Declaration of Helsinki. Prior to participation, all experts were provided with information about the study objectives and procedures via the survey form. Completion of the questionnaire was taken as informed consent to participate in the study. Participation was voluntary, and participants could withdraw at any time without consequence. All data were anonymized, securely stored, and used solely for research purposes.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [PTB], upon reasonable request.

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