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An AI-supported modeling approach for teaching metal bonding: design and implementation of a teacher education program integrating model-based learning and the 5E learning cycle

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This study presents the design and implementation of an AI-supported modeling-based teacher education program integrating Model-Based Learning (MBL) with the 5E learning cycle. The program was implemented with 14 in-service chemistry teachers over 24 lessons and consisted of pre-interviews, three modeling cycles, and post-interviews. During the modeling process, teachers developed dynamic models through dialogic interactions with generative AI (Claude). Metamodeling knowledge levels were explored using seven questions across six domains: nature of models, purpose of models, modeling processes, variability, diversity, and evaluation criteria. Responses were analyzed from objectivist and subjectivist understandings. Teachers identified limitations of the electron sea model in explaining luster (n = 14), thermal conductivity (n = 7), malleability and ductility (n = 6), and electrical conductivity (n = 3). To address these, teachers developed educational models incorporating the wave nature of electrons, lattice vibrations (phonons), and redistribution of electron clouds. Analysis revealed a shift from predominantly objectivist understandings of models in the pre-assessment toward more subjectivist understandings of models in the post-assessment. Notable improvements were observed in modeling processes, variability, and diversity of models. These changes were observed in the context of modeling activities that involved recognizing model limitations and developing educational models, within which generative AI served as an interactive element supporting dialogic interaction and iterative revision as part of the broader instructional program. Teachers came to understand models not as fixed knowledge but as tentative and revisable inquiry tools. These findings provide direction for teacher education focused on strengthening modeling knowledge in science education.

1. Introduction

Modeling serves as a core practice in science. Scientists use models to simplify natural phenomena, make predictions, provide explanations (Gobert and Buckley, 2000; Gilbert, 2004; Passmore *et al.*, 2014; Park and Paik, 2025). Models used in science are designed to simplify natural phenomena and therefore inevitably have limited explanatory scopes; from a pluralistic perspective, science consists of multiple models with different scopes and limitations rather than a single, complete truth – that is, 'where no single model can provide it everywhere' (Chang, 2012, p. 273). In this regard, models should be evaluated not against an absolute standard of truth, but in terms of their adequacy for purpose – that is, whether a model is sufficiently adequate for the specific goals it is intended to serve (Parker, 2020). In this context, ignorance refers to aspects intentionally omitted or simplified in models. From an epistemological perspective, such simplifications can be understood as felicitous falsehoods—representations that are not literally true yet contribute meaningfully to understanding by serving the explanatory purposes for which they are constructed (Elgin, 2017). Scientific Progress is driven not only by established knowledge but also by recognizing what remains unknown (Firestein, 2012). Accordingly, recognizing model ignorance during modeling processes is essential for fostering metamodeling knowledge, as such awareness supports understanding how science works and how scientific knowledge is constructed (Schwarz *et al.*, 2009; Al-Balushi, 2011; Abd-El-Khalick, 2013; Chiu and Lin, 2019).

Metamodeling knowledge represents the foundation of modeling education. Learners develop understanding of model nature, purposes, and processes through metamodeling knowledge (Schwarz *et al.*, 2009; Oh and Oh, 2011). Metamodeling knowledge was first introduced by Schwarz (2002) and later elaborated by Schwarz and White (2005) as learners'

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understanding of scientific models and the process of modeling. Specifically, metamodeling knowledge refers to what scientific models are, how and why they are constructed and used, and what their strengths and limitations are.

Learners with strong metamodeling knowledge can evaluate model limitations and utility, and they can apply appropriate models to new situations (Oh and Oh, 2011). However, many science teachers and students lack this understanding (Justi and Gilbert, 2002; Krell *et al.*, 2015). Previous studies have reported that students often describe models as miniature replicas or simple pictures (Harrison and Treagust, 2000; Justi and Gilbert, 2002; Seo *et al.*, 2024).

Teachers' also play an important role in shaping students' metamodeling knowledge. However, prior studies indicate that the lack of sufficient metamodeling knowledge among in-service science teachers is a major factor that hinders the effective implementation of modeling-based instruction (Oh and Oh, 2011; Russ, 2018; Lowell *et al.*, 2022). Research has further demonstrated that students' development of model understanding depends heavily on teachers' metamodeling perspectives (van Driel and Verloop, 1999; Treagust *et al.*, 2002; Schwarz and White, 2005). For example, Bamberger and Davis (2013) found that teachers can strengthen their metamodeling knowledge through direct experiences of developing and evaluating educational models (Rost and Knuuttila, 2022). Therefore, it is essential to provide teachers with both theoretical understanding and practical opportunities to engage with models in science education.

2. Theoretical background

2.1. The electron sea model and its limitations

In most educational contexts, the electron sea model is introduced at the upper secondary level as an introductory framework for explaining metallic bonding and related properties. For example, in South Korea, this model is presented in the national high school Chemistry I curriculum, which is usually taken by students around the age of 17. At this stage, the electron sea model serves as an initial explanatory model through which students are expected to understand why characteristic metallic properties arise from metallic bonding. The electron sea model, a representative model for describing metallic bonding, depicts a structure in which metal cations are regularly arranged within a 'sea' of delocalized electrons (Taylor and Coll, 2002; Cheng and Gilbert, 2014; van Dulmen *et al.*, 2023; Kaldaras *et al.*, 2024). While widely adopted in textbooks, this model oversimplifies metallic bonding and does not adequately capture the complex electrostatic interactions or the quantum-mechanical behaviour of electrons. Consequently, students may develop alternative conceptions or partial understandings (Taylor and Coll, 2002), which can lead to various misconceptions (Taber, 2003).

Chemical bonding is one of the most difficult abstract concepts for students. Metallic bonding is also difficult for students, and research has reported that students generate models by mixing chemical bonding concepts (Özmen, 2004; Dhindsa and Treagust, 2014). Some students believed that molecules exist in metals or understood that ionic bonds form between metal atoms (Taber, 1998; Taber, 2003; Ünal *et al.*, 2006). These alternative conceptions can be interpreted as results from the electron sea model oversimplifying metallic bonding (Cheng and Gilbert, 2014; Park and Paik, 2025). These misconceptions arise because the electron sea model provides only a superficial explanation of metallic properties (Nicoll, 2001; Taber, 2003; Cheng and Gilbert, 2014).

For instance, Cheng and Gilbert (2014) observed that the model fails to emphasise the electrostatic interactions between delocalised electrons and metal cations, leading students to struggle in explaining malleability and ductility. Similarly, Park and Paik (2025) noted that the model does not sufficiently explain metallic luster as well as malleability and ductility of metals. Such limitations point to the need for educational models that can offer a more comprehensive and scientifically accurate representation of metallic bonding (Özmen, 2004; Levy Nahum *et al.*, 2010).

In other chemistry topics, such as acid–base chemistry, various models such as the Arrhenius, Brønsted–Lowry, and Lewis models coexist. Through this diversity, students can naturally recognize the scope, limitations, and developmental progression of each model (Taber, 2002; Levy Nahum *et al.*, 2010). In contrast, metallic bonding is typically presented almost exclusively through the electron sea model in textbooks, with little attention to the diversity or limitations of competing models (Taylor and Coll, 2002; Cheng and Gilbert, 2014; Park and Paik, 2025). This lack of model diversity restricts both teachers and students from experiencing the diversity, variability, and tentativeness of scientific models, thereby constraining the development of their metamodeling knowledge (Schwarz *et al.*, 2009; Chiu & Lin, 2019).

To overcome the limitations of the electron sea model, developing various models that can explain metallic bonding properties is necessary.

To address this lack of model diversity as a learning opportunity, engages teachers in developing, evaluating, and revising multiple models of metallic bonding. This approach is not intended to replace the electron sea model, but to counter the tendency for teachers to understand it as a fixed and authoritative account of metallic bonding and to promote their metamodeling knowledge of model diversity, variability, and tentativeness.

2.2. Model-based learning (MBL)

Model-based learning (MBL) is an instructional framework that supports learners in developing a deeper understanding of scientific concepts by engaging them in the processes of generating, evaluating, revising, and applying models to explain and predict scientific phenomena (Justi & Gilbert, 2002; Schwarz *et al.*, 2009).

Previous studies have shown that MBL provides learners with opportunities to experience the tentative and revisable nature of models, as well as the possibility that multiple models

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can be constructed to explain the same phenomenon (Schwarz *et al.*, 2009; Louca & Zacharia, 2012). In particular, engaging learners in evaluating the adequacy of models and revising them in response to conceptual or explanatory limitations has been identified as a key instructional mechanism for fostering higher-level metamodeling knowledge (Clement, 2000; Louca & Zacharia, 2012; Campbell *et al.*, 2015). Therefore, MBL has been regarded as a theoretically grounded approach for supporting both conceptual understanding and reflective understanding of models in science.

However, recent research suggests that alone does not automatically lead to the development of metamodeling knowledge. Studies indicate that modeling activities need to be accompanied by explicitly supported reflective and metacognitive engagement, and that instructional design plays a critical role in creating conditions under which model use can extend toward deeper epistemic understanding (Chang, 2022; Carroll & Park, 2024). These findings imply that the effectiveness of MBL depends not only on iterative modeling cycles but also reflects how model assumptions, scope, and limitations is structurally supported within instruction.

In response to these considerations, the present study integrates structured instructional support based on the 5E instructional model with AI-supported dialogic revision processes. The 5E framework provides a coherent sequence for eliciting prior conceptions, guiding model construction, and promoting evaluation and refinement (Bybee, 1997; Bybee *et al.*, 2006). At the same time, generative AI supports iterative dialogue that encourages learners to reconsider model assumptions and explanatory scope. Through this design, the study aims to create instructional conditions that facilitate reflective engagement within modeling activities.

2.3. Generative AI-supported modeling activities

In the context of model development discussed above, recent advances in generative AI technology are opening new possibilities in education. Generative AI tools have the potential to support modeling activities by facilitating interactive dialogue and providing feedback that learners can use to reflect on and refine their models (Holmes *et al.*, 2019; Verma *et al.*, 2023; El Fathi *et al.*, 2025; Lee *et al.*, 2025). In the specific context of modeling activities, generative AI can help learners visualise complex mechanisms in real time through interactive dialogue (El Fathi *et al.*, 2025; Lee *et al.*, 2025). Several recent studies have explored how AI-supported learning activities can contribute to learners' construction and evaluation of their own representations or tentative solutions during problem-solving processes. For instance, Zhu *et al.* (2025) reported that real-time feedback provided by AI can facilitate iterative revision processes by prompting learners to reconsider their initial hypotheses, while Borchers *et al.* (2024) presented cases in which AI-based systems promoted conceptual change by diagnosing learners' misconceptions and suggesting alternative explanatory pathways. Additionally, Lee *et al.* (2023) found that dialogic interactions with AI can support metacognitive reflection by encouraging learners to explicitly articulate their reasoning processes. Collectively, these studies suggest that AI-supported activities facilitate the iterative cycle of construction–evaluation–revision, and that these effects become more pronounced when the activities are designed to engage learners in active construction and evaluation of representations (Liu *et al.*, 2025; Wan *et al.*, 2025; Yıldızhan Bora and Kölemen (2025)). Notably, El Fathi *et al.* (2025) reported that preservice teachers came to explicitly examine the explanatory power and limitations of scientific models by using AI to analyze students' misconceptions, thereby adding the development of instructional strategies. Similarly, Lee *et al.* (2025) found that teachers came to recognize the scope and constraints of model applicability by applying their explanatory models to various contexts through interactions with AI. These studies suggest that when interactions with AI are structured to require learners to articulate model assumptions or justify the validity of explanations, they can more effectively develop metamodeling knowledge – that is, understanding of the purposes, limitations, and conditions of applicability of models as tools for scientific inquiry and reasoning.

3. Research purpose and research questions

Most previous research focuses on students' understanding of models or learning effects (Justi and Gilbert, 2002; Gouvea and Passmore, 2017). In contrast, relatively little work has examined how in-service teachers engage in AI-supported modeling and how such engagement influences their metamodeling knowledge. Addressing this gap, this study was designed to enable chemistry teachers to experience the process of developing, evaluating, and revising new educational models of metallic bonding based on generative AI to overcome the limitations of the electron sea model and to help students understand metallic bonding concepts correctly. This study explores how teachers' metamodeling knowledge evolved through their participation in this process.

The study focuses on three research questions:

3.1. How do teachers understand the limitations of the electron sea model in explaining different metallic properties?

3.2. How do teachers design and revise alternative models of metallic bonding to address the identified limitations through AI-supported modeling activities?

3.3. How does a teachers' metamodeling knowledge develop after participating in AI-supported modeling activities?

4. Methods

4.1. Participants

This study was conducted with 14 in-service chemistry teachers who participated in the TPACK competency development program at K Graduate School of Education. The participants consisted of six male teachers and eight female teachers with teaching experience ranging from 1 to 15 years. All participants had prior experience using models to teach chemical concepts

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Table 1 Information on the participants

Experience teaching the electron sea model	Number of teachers
Yes	11 (T2, T3, T6, T7.T8, T9, T10, T11, T12, T13, T14)
NO	3 (T1, T4, T5)

in their classrooms. Although some teachers had not directly taught the electron sea model to students, all participants had previously been taught the electron sea model during their undergraduate coursework or teacher education programs. The teachers worked in various regions across South Korea. This study was approved by the Institutional Review Board of Korea National University of Education (IRB No. KNUE-202507-BMSB-0475-01), and all participants provided informed consent prior to participation. Information about the research participants is presented in Table 1.

4.2. Procedure

This study was designed based on previous research on scientific modeling, metamodeling knowledge, and ignorance analysis of the electron sea model (Kim *et al.*, 2019; Park and Paik, 2025). In a previous study, Park and Paik (2025) analyzed the ignorance of the electron sea model presented in textbooks and identified several explanatory limitations. Building on these findings, the present study aims to explore the process by which chemistry teachers develop models to explain metallic properties that are difficult to explain using the electron sea model. Open-ended questions and analytical frameworks used in previous studies were employed for this purpose (Kim *et al.*, 2019; Seo *et al.*, 2024). A teacher education program was therefore developed and implemented at K Graduate School of Education, a teacher training university, to provide in-service chemistry teachers with opportunities to engage in successive modeling activities through which their metamodeling understandings could develop implicitly.

The research procedure consisted of three stages: pre-interview, modeling activity, and post-interview. In the pre-interview, teachers' initial levels of metamodeling knowledge were examined. After the pre-interview, during the instructional sessions, teachers engaged in a classroom-based modeling activity in which they explained the electrical conductivity, thermal conductivity, malleability, ductility, and luster of metals using the textbook electron sea model.

The teacher education program was pre-designed before data collection and implementation. It was grounded in Model-based learning (MBL) as its theoretical foundation and used the 5E learning cycle model (Engage–Explore–Explain–Elaborate–Evaluate) as its procedural framework (Bybee, 1997; Bybee *et al.*, 2006). The program consisted of three model development cycles. This integrated design was intentional: the MBL framework provided the theoretical logic for engaging teachers in successive cycles of model generation, evaluation, and revision, while the 5E cycle operationalized these processes

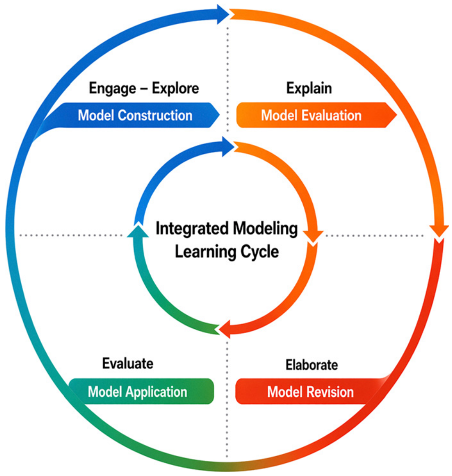

Fig. 1 The integrated modeling learning cycle: integration of model-based learning and the 5E learning cycle (Bybee, 1997; Justi & Gilbert, 2002; Bybee *et al.*, 2006; Schwarz *et al.*, 2009).

as structured instructional stages. Specifically, the Engage–Explore stages were designed to establish teachers' recognition of the electron sea model's limitations to promote model development. The Explain and Elaborate stages incorporated peer discourse and iterative refinement to develop teachers' understanding of models as purpose-dependent and revisable tools; while the Evaluate stage was designed to deepen teachers' recognition of model tentativeness through application and reflection. In this study, this pre-designed instructional structure, which integrates the theoretical principles of MBL with the operational stages of the 5E learning cycle based on previous research program (Bybee, 1997; Justi & Gilbert, 2002; Bybee *et al.*, 2006; Schwarz *et al.*, 2009), is referred to as the integrated modeling learning cycle, as illustrated in Fig. 1.

In the first modeling cycle, Teachers recognized the limitations of the electron sea model and visually constructed and presented their own metallic bonding models to explain metallic properties that could not be explained by this model. In the second modeling cycle, teachers explored ideas for developing models through conversational interaction with Claude, reflecting on evaluation and discourse of the first model. Teachers developed improved models using HTML and JavaScript through interaction with generative AI. In the third modeling cycle, teachers finalized their models through conversational interaction with Claude and reflection on the evaluation and discourse of the second model. Teachers developed metamodeling knowledge by critically examining models and exploring new alternatives rather than passively accepting models presented in textbooks.

The post-interview employed the same set of open-ended questions as the pre-interview. The seven open-ended questions were designed to examine teachers' metamodeling knowledge across six components: nature of models, purpose of models, modeling processes, variability, diversity, and evaluation criteria. The components and corresponding questions are presented in Table 2.

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Table 2 Metamodeling knowledge components and open-ended questions

No.	Component of metamodeling knowledge	Open-ended questions
1	Nature of model	What is a model? Please provide examples and explain why you think they qualify as models
2		When developing a model, how closely should it resemble a real phenomena? Please explain why you think it should be the same, or why it could be different
3	Purpose of models	What is the purpose of a model? Please explain your answer
4	Process of modeling	When constructing a model, what factors must be considered? Please explain your answer
5	Evaluating models	What criteria should scientists use when evaluating these models? Please explain your answer
6	Variability of model	Can a scientist revise or modify a model? Please explain your answer
7	Diversity of model	Can scientists construct more than one model for the same phenomenon? Please explain your answer

Changes in teachers' metamodeling knowledge were examined by comparing teachers' responses across the pre- and post-interviews.

The teacher education program consisted of 24 sessions, and the program structure is shown in Table 3.

4.2.1. Engage–explore stage (sessions 1–4). This stage corresponds to the 'Generate' process in MBL. Teachers were asked to explain the electrical conductivity, thermal conductivity, malleability, ductility, and luster of metals using the electron sea model from textbooks. Through this, teachers critically recognized the limitations of the model. Teachers then developed their first model to address the limitations of the electron sea model in explaining metallic properties.

4.2.2. Explain stage (sessions 5–8). This stage corresponds to the 'Evaluate' process in MBL. Peer evaluation and discourse were conducted based on the first model presentations.

4.2.3. Elaborate stage (sessions 9–20). This stage corresponds to the 'Modify' phase of MBL, during which the model was systematically revised and elaborated. In the second modeling cycle, conversational interaction with Claude was incorporated as an interactive resource within the instructional environment to support idea generation and refinement. Teachers were provided with opportunities to construct models using HTML and JavaScript with the support of generative AI, and to articulate their model development intentions and explanatory rationales. Rather than being provided with a fixed prompt template, teachers were free to initiate and sustain conversations with the AI at their own discretion, exploring whether a chosen scientific concept was capable of explaining the targeted metallic property. For example, a teacher might begin by asking, "Can the wave nature of electrons explain metallic luster?" and iteratively continue the dialogue until convinced that the concept provided a satisfactory explanation. Once a teacher judged that the scientific concept was explanatorily sufficient, they requested that the AI use JavaScript and HTML to generate a model that embodied that concept. This cycle of generation, evaluation, and revision was repeated across multiple modeling cycles until the model was deemed satisfactory. Subsequently, iterative model revision activities were structured to incorporate peer feedback, discourse, and further interaction with Claude. As part of these activities, teachers were asked to submit presentation materials documenting revision intentions, code

Table 3 Configuration of the teacher education program

Sessions	MBL step	5E step	Activities and data
1–4	Model sonstruction	Engage–explore	Explain metallic properties by using the electron sea model; recognize limitations; present hand-drawn models; pre-interview; first model outputs
5–8	Model evaluation	Explain	Peer evaluation and discussion of first models; Presentation materials
9–20	Model revision	Elaborate	Dialogic interaction with Claude to refine ideas; develop educational models using HTML/JavaScript; reflect feedback; second and third model outputs; presentation data
21–24	Model application	Evaluate	Apply final models to explain metallic properties; post-interview; final model outputs

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modifications, and design rationales (Louca and Zacharia, 2012).

4.2.4. Evaluate stage (sessions 21–24). This stage corresponds to the 'Use' process in MBL. Teachers explained metallic properties by applying their developed third models. Post-interviews explored changes in teachers' metamodeling knowledge levels compared to the pre-stage (Justi and Gilbert, 2002; Schwarz *et al.*, 2009).

4.3. Data collection

In this study, surveys were conducted to explore changes in chemistry teachers' metamodeling knowledge levels and to confirm educational effects.

Crawford and Cullin (2004) developed survey items to explore prospective secondary science teachers' conceptions of models and modelling; focusing on their understanding of the roles and purposes of a model's design, construction, development and evaluation. Scientific metamodeling knowledge has been conceptualised in diverse ways depending on theoretical perspectives (Grosslight *et al.*, 1991; Justi and Gilbert, 2002; Treagust *et al.*, 2002; Justi and Gilbert, 2003; Crawford and Cullin, 2005; Schwarz and White, 2005; Schwarz *et al.*, 2009; Sins *et al.*, 2009; Gobert *et al.*, 2011; Oh and Oh, 2011; Krell *et al.*, 2012; Grünkorn *et al.*, 2014; Krell *et al.*, 2014). A synthesis of these studies indicates that scientific metamodeling knowledge generally converges on six core components: the nature of models, the purpose of models, the process of modeling, the variability of models, the diversity of models, and the evaluation and modification of models. In this study, survey items were based on the instrument proposed by Crawford and Cullin (2004), with the addition of one item explicitly addressing the nature of scientific models following Seo *et al.* (2024), resulting in a total of seven open-ended survey questions. To more clearly distinguish the developmental levels of teachers' knowledge about models and modeling, open-ended questions were designed to require participants to provide not only their understanding but also concrete examples and explanations for their reasoning. The metamodeling knowledge components and corresponding open-ended questions are presented in Table 2.

4.3.1. Quality criteria for interpreting open-ended responses. Question 1 confirms understanding of the 'Nature of model' through definitions and examples of models. Question 2 addresses the 'Nature of model' by examining how closely a model should resemble real phenomena. Question 3 asks about the 'Purpose of models' to identify the functions and roles that models perform. Question 4 is questions about the 'Process of modelling' that ask about factors to consider when developing models. Question 5 is a question about 'Evaluating the model' that ask teachers about criteria for evaluating models, designed to explore teachers' capacity to critically evaluate models. Question 6 asks about the 'Variability of modes' which addresses whether a models can be revised or changed. Question 7 is a question about the 'Diversity of models' to confirm whether teachers recognize that multiple models are possible for the same phenomenon.

4.4. Analysis framework

In this study, we adapted an analytical framework proposed in previous research that conceptualizes the development of scientific metamodeling knowledge (Kim *et al.*, 2019; Seo *et al.*, 2024) to examine changes in chemistry teachers' understanding of models and modeling. The revised framework is presented in Table 4. Using this framework, pre- and post-survey responses were categorized into two epistemic understandings of models: an objectivist understanding and a subjectivist understanding. Rather than emphasizing fine-grained distinctions among multiple levels, the analysis focused on how teachers' understanding of models shifted from an objectivist understanding toward a subjectivist understanding (Grosslight *et al.*, 1991; Schwarz and White, 2005; Schwarz *et al.*, 2009; Oh & Oh, 2011).

This study focused on examining whether and how teachers' understanding of metamodeling shifted from an objectivist perspective to a subjectivist perspective through participation in the modeling activities designed in this study, as reflected across the set of metamodeling-related questions.

Responses were classified as reflecting an objectivist understanding when teachers perceived models as direct representations of natural phenomena or as tools for explaining objective knowledge or established theories. In contrast, responses were either classified as reflecting a subjectivist understanding when teachers understood models as inquiry tools, evaluated models based on whether they functioned as intended by a modeler or adequately explained specific phenomena, or explicitly recognized the tentativeness and limitations of models.

This categorization highlights the central analytical focus of the study: the epistemic transition from understanding models as objective representations to understanding them as tentative, purpose-dependent tools for scientific inquiry.

To ensure the trustworthiness of the qualitative analysis, several strategies were employed. First, a multiple-analyst approach was adopted. One chemistry education expert, three doctoral researchers, and two in-service chemistry teachers

Table 4 Framework for understanding metamodeling knowledge

Understanding of models	Metamodeling knowledge in science
Subjectivity	Tentativeness of the model; various perspectives; recognizing the limitations of the model; inquiry tool; models working as intended by the modeler
Objectivity	Tools for explanation; objective knowledge and theories; thumbnail of nature; representing the phenomenon as it is

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independently analyzed all interview transcripts and related artifacts. The analysis results were then compared and discrepancies were resolved through in-depth discussion until a consensus was reached. More specifically, based on the revised analytical framework presented in Table 4, this study did not assign a level based on a single item response. Instead, response patterns across each teacher's entire interview were examined holistically. When an understanding of models appeared relatively consistently across the interview, the teacher was interpreted overall as showing either an objectivist understanding or a subjectivist understanding. When features of both perspectives were mixed across different components, the classification was based on the following procedure. Each teacher's responses were analyzed independently according to the four metamodeling dimensions presented in Table 4. When the distribution of responses across dimensions was unequal, the predominant perspective was assigned. Analysts evaluated which perspective was cognitively central using the following criteria: (a) Explicit reasoning: did responses demonstrate specialized terminology, mechanistic explanations, or conceptual integration? (b) Conceptual consistency: were responses within the dimension logically integrated without internal contradictions? (c) Integration: did responses demonstrate connectivity across multiple sub-questions within the dimension? The perspective from the cognitively central dimension determined the overall classification. Such cases were discussed repeatedly among all analysts until consensus was reached. Second, to enhance analytic validity, participants' verbatim statements were directly quoted in the Results section to provide transparent evidence supporting the researchers' interpretations.

5. Results and discussion

5.1. Teachers' recognition of the electron sea model's limitations

During the Engage–Explore phase, teachers were asked to explain metallic properties (electrical conductivity, thermal conductivity, malleability and ductility, and luster) using the electron sea model presented in textbooks. This explanatory activity was designed to encourage teachers to apply the electron sea model to explain natural phenomena, thereby prompting them to recognize the tentative nature and explanatory limitations of the model.

Prior to this activity, teachers generally regarded the electron sea model as established knowledge and believed that it could sufficiently explain all metallic properties. However, when they attempted to explain each property using the model, difficulties in providing coherent explanations emerged. Through this experience, teachers came to recognize the limitations of the electron sea model. The results are shown in Table 5.

When multiple responses were allowed, all teachers identified luster as a metallic property that is difficult to explain using the electron sea model. In addition, seven teachers identified thermal conductivity, six teachers identified malleability and ductility, and three teachers identified electrical conductivity as limitations.

Table 5 Metallic properties identified as difficult to explain using the electron sea model

Metallic property	Number of teachers	Teachers
Electrical conductivity	3	T2, T7, T14
Thermal conductivity	7	T2, T3, T4, T5, T6, T7, T14
Malleability and ductility	6	T2, T3, T6, T7, T9, T14
Luster	14	T1–T14 (all)

These results indicate that the electron sea model has several explanatory limitations. Consequently, teachers encountered difficulties when attempting to explain certain metallic properties using this model. Such challenges suggest that directly confronting the explanatory limitations of a model can serve as an important – and productive – starting point for model evaluation. From the perspective MBL, recognizing such limitations may provide opportunities for learners to critically examine existing models and engage in metamodeling practices involving model evaluation and revision.

5.2. Teachers' design and revision of metallic bonding models through AI-supported modeling activities

Building on teachers' recognition of these limitations (Table 5), teachers subsequently developed educational models to address these limitations during the Explain and Evaluate stages. Representative cases for each property are provided below.

5.2.1. Electrical conductivity. The electron sea model assumes that free electrons behave as simple particles (Drude, 1900). This assumption fails to explain the rapid movement of electrons in metals or differences in electrical conductivity among metals.

As teachers recognized these limitations, they developed various explanatory models that can be grouped into two distinct conceptual types. Table 6 summarizes the types of models developed by teachers for explaining electrical conductivity. As shown in Table 5, only three teachers (T2, T7, T14) identified electrical conductivity as a property that the electron sea model fails to explain adequately; accordingly, only these teachers developed alternative educational models for this property.

T2 developed a model that reflects the wave nature of electrons. Electrons move collectively in response to an external electric fields and are highly sensitive to small perturbations arising from the wave superposition. T7 attempted to reflect the wave nature of electrons through interactions with Claude. The

Table 6 Types of models developed by teachers for electrical conductivity

Type	Teachers
Wave-based	T2, T7, T14
Wave-based + electron cloud	T14

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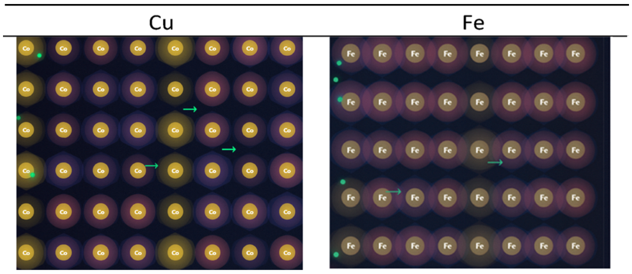

Fig. 2 T14's modeling results.

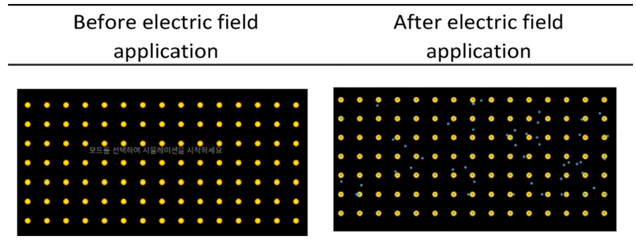

Fig. 3 T4's modeling results.

final model had low completeness due to implementation limitations. T14 represented electrons as a delocalized electron cloud distributed throughout the metal. T14 explained electrical conductivity of metals by reflecting the wave nature of electrons and interactions between charges. Fig. 2 presents T14's model as a representative case.

"*Although the electron sea model explains electrical conductivity of metals qualitatively, the model has limitations in explaining conductivity differences between metals or why electrons move freely without being trapped by metal cations. I represented electrons as a delocalized electron cloud throughout the metal to address these limitations. I visualized continuous distribution and superposition by representing electron density through variations in color intensity. This representation emphasizes that the wave nature of electrons spreads throughout the lattice and responds immediately to external electric fields. This approach can explain why different metals have different conductivities through electron density differences*." (T14)

T14 reflected the continuity of electron density and wave superposition in the model by depicting electrons as a delocalized electron cloud. This representation explained the collective and immediate response of electrons to external electric fields. In this model, electrons are represented as green points, arrows indicate the direction of electron motion under an external electric field, and differences in electron density distribution are used to explain conductivity differences between metals, with color intensity employed to visualize electron density, becoming progressively lighter as the distance from atomic centers increases. This approach specifies the microscopic mechanism of electrical conductivity that the electron sea model fails to present.

5.2.2. Thermal conductivity. Teachers recognized that the electron sea model fails to explain how thermal energy is rapidly transferred inside metals. Based on this understanding, teachers developed various models that can be grouped into four distinct conceptual types. Table 7 summarizes the types of models developed by teachers for explaining thermal conductivity. As shown in Table 5, seven teachers (T2, T3, T4, T5, T6, T7, T14) identified thermal conductivity as a property that the electron sea model fails to explain adequately. According to these results, only some teachers developed alternative educational models for this property.

Table 7 Types of models developed by teachers for thermal conductivity

Type	Teachers
Wave-based	T2, T6, T7, T14
Wave-based + band theory	T3
Free electron movement + lattice vibration	T4
Free electron movement	T5

T6 developed a model centered on the wave nature of electrons. Energy is transmitted in a wave-like manner when the wave functions of free electrons overlap and their distribution changes upon heating. T3 reflected the process of heat transfer by integrating the concepts of wave superposition and band theory, rather than relying on the simple particle collision concepts. T4 emphasized that both free electron movement and lattice vibrations (phonons) contribute to thermal conductivity. T4 integrated both mechanisms. T2, T7, and T14 developed models that reflect the wave nature of electrons. T5 developed a model that simplified free electron movement.

Fig. 3 presents T4's model as a representative case.

"*The electron sea model explains thermal conductivity of metals only through free electron movement. Metal cation lattice vibrations also play an important role in thermal conductivity of metals. Considering only electrons makes it difficult to explain why metals have high thermal conductivity and why it decreases as temperature increases. I reflected both free electron movement and lattice vibrations in my model. Free electrons transfer energy at high speed. Lattice vibrations transfer energy between adjacent cations. I represented the process where thermal conductivity decreases as temperature increases because lattice vibrations increase and electron scattering increases. This representation can explain thermal conductivity of metals more realistically and address limitations of the electron sea model*." (T4)

By considering both free electrons and lattice vibrations, T4 modeled the high thermal conductivity of metals and its decreased thermal conductivity with increasing temperature. This representation specifies the contribution of lattice vibrations and temperature dependence that the electron sea model fails to reflect.

5.2.3. Ductility and malleability. The electron sea model fails to show how bonding is maintained when the lattice structure deforms. Teachers recognized this limitation and presented various models that can be grouped into three distinct conceptual types. Table 8 summarizes the types of models developed by teachers for explaining ductility and malleability. As shown in Table 5, six teachers (T2, T3, T6, T7, T9, T14) identified malleability and ductility as properties that

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Table 8 Types of models developed by teachers for ductility and malleability

Type	Teachers
Electron cloud deformation	T9
Electron movement	T2, T6, T7, T14
Spin-based	T3

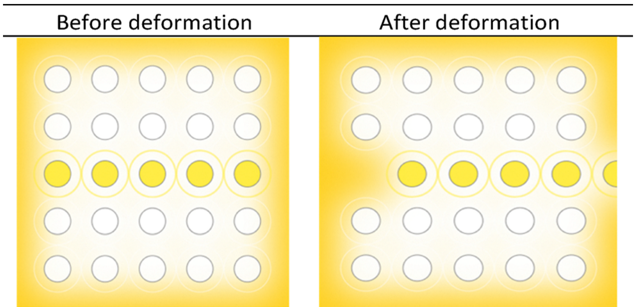

Fig. 4 T9's modeling results.

the electron sea model fails to explain adequately. These results show how only some teachers developed alternative educational models for these properties.

T9 developed a model illustrating that electron cloud distribution deforms in response to the movement of metal cation position, thereby maintaining metallic bonding. T2, T6, T7, and T14 represented that metals can stretch or spread without breaking through collective electron movement and charge redistribution during lattice structure deformation. T3 explained metallic properties by emphasizing electron spin. Fig. 4 presents T9's model as a representative case.

"*The electron sea model explains that free electrons reduce repulsion between cations so bonding is maintained even when metals deform. The model fails to show how electrons respond when the lattice deforms. The explanation that free electrons exist makes it difficult to understand the dynamic process of bonding maintenance. I modeled the process by representing electrons as an electron cloud, in which electron density deforms and redistributes together as atomic nuclei move, thereby maintaining metallic bonding. I intended to explain why metals can stretch or spread thin without breaking when subjected to external forces.*" (T9)

By representing electrons as an electron cloud density distribution, T9 implemented a model where electron density deforms and redistributes together when metal cations deform by external forces. This representation specifically explains the dynamic mechanism involved in maintaining metallic bonding, which the electron sea model fails to capture.

5.2.4. Luster. The electron sea model shows the existence and mobility of free electrons but fails to explain wave interactions between light and electrons. Teachers recognized this limitation and developed models in different ways that can be grouped into nine distinct conceptual types. Table 9 summarizes the types of models developed by teachers for explaining metallic luster. As shown in Table 5, all fourteen teachers

Table 9 Types of models developed by teachers for metallic luster

Type	Teachers
Wave-based	T2, T6, T7, T12, T14
Electron density	T9
Spin-based	T13
Wave overlap	T3
Particle-based	T5
Electron cloud-based	T10
Phase-synchronized free electron vibration	T1
Color-dependent	T11
Electron vibration and re-emission	T8

(T1–T14) identified luster as a property that the electron sea model fails to explain adequately. These results show how all participating teachers were able to develop alternative educational models for this property.

T2, T6, T7, T12, and T14 developed models based on the wave nature of electrons, in which incident light induces synchronized oscillations of the electron ensemble, resulting in the reflection of light that produces metallic luster. T3, T5, T9, and T13 approached by extending existing models. They explained luster through electron density redistribution (T9), electron spin emphasis (T13), wave overlap concepts (T3), and reflection by simple free electron movement (T5). T4 visualized free electron vibration and reflection processes. T10 described diffuse reflection of silver-white luster through representation of electrons as an electron cloud. T1 modeled the physical mechanism of specular reflection employing phase-synchronized vibration of free electrons. T11 attempted to explain variation in reflected colors among metals. T8 explained silver-white luster through collective vibration of free electrons and re-emission processes at the same wavelength. Fig. 5 presents T10's model as a representative case.

"*The electron sea model only shows that free electrons fill the entire metal. The model fails to explain why metals have luster. Metals have luster because light interacts with electrons and re-emits light at the same wavelength as incident light. The electron sea model does not reveal this process. I represented electrons as a probabilistic electron cloud and reflected the wave nature of electrons. I implemented a model where electron density vibrates collectively when light is incident, and phase superposition occurs to produce reflection. This representation can explain why metals have silver-white luster.*" (T10)

T10 modeled light–electron interactions by representing electrons in terms of both an electron cloud and wave nature.

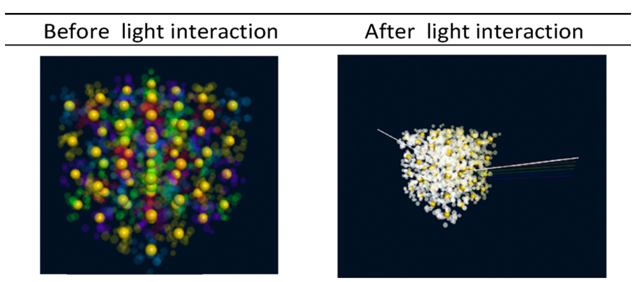

Fig. 5 T10's modeling results.

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Before light interaction, the model showed stable lattice and electron distribution. After light interaction, the model visualised the process of reflection arising from collective oscillations of electron density and phase superposition induced by light–electron interaction. This representation specifies the microscopic mechanism of metallic luster from a wave optics perspective that the electron sea model fails to present.

As illustrated by the cases presented above, teachers developed models to explain metallic properties by incorporating various scientific concepts, including the wave nature of electrons, electron density distributions, lattice vibrations, and light–electron interactions. During this process, teachers repeatedly revised their models through interactions with generative AI tools and reflective discussions. From a metamodeling perspective, these experiences provided opportunities for teachers to reflect on which concepts should be included in a model and which aspects may be intentionally simplified or excluded depending on the explanatory purpose. This generative AI-supported iterative modeling process helped teachers recognize that models are not direct representations of natural phenomena but selectively constructed representations shaped by specific assumptions and explanatory goals.

5.3. Changes in teachers' understanding of scientific models (pre- and post-analysis)

During the participation–exploration phase, teachers responded to seven open-ended questions related to metamodeling knowledge through pre-interviews. Subsequently, they engaged in model development activities during the explanation and elaboration phases and responded to the same questions again through post-interviews conducted during the evaluation phase. Changes in teachers' understanding of models from pre- to post-interviews were analyzed based on the analytical framework presented in Table 4 and are summarized in Table 10.

The results of this study should be interpreted as reflecting teachers' metamodeling-related understandings as elicited through responses to these open-ended questions. These observed changes emerged implicitly through teachers' engagement in successive modeling activities, including model construction, evaluation, revision, and discourse supported by generative AI.

Although all 14 teachers reported having experience using models in science instruction, their responses in the pre-interviews reflected an objectivist understanding of models, in which models were understood as fixed tools for directly representing natural phenomena or explaining objective scientific knowledge. Through the modeling activities in which they attempted to explain metallic properties using the electron sea model, they came to recognize that the model could not adequately account for all phenomena, leading them to recognize the limitations of the model in relation to its explanatory purpose. Building on this understanding, teachers engaged in developing and evaluating educational models, resulting in an overall change in their mentality, as expressed in the post-interviews. As a representative example of response change, T5's responses to Question 4 (When constructing a model, what factors must be considered? Please explain your answer.) are presented below.

In the pre-interviews, T5 responded to Question 4 by stating that "When constructing a model, the theory should be represented accurately and clearly so that the model can be useful." This response indicates that T5 regarded accurate representation of established theory as a primary consideration in model construction and reflected an objectivist understanding of models, in which models are understood as fixed tools for representing objective scientific knowledge.

Afterwards, T5 participated in AI-supported modeling activities in which educational models of metallic bonding were repeatedly revised and implemented using generative AI tools (Claude). As summarized in Table 5, T5 recognized that the electron sea model was insufficient for explaining thermal conductivity and metallic luster, although it appeared relatively adequate for other metallic properties. Building on this recognition, T5 attempted to develop alternative educational models incorporating concepts such as the wave nature of electrons, the distinction between valence and conduction bands, and energy levels. However, during the model implementation process, persistent coding errors and representational failures occurred. For example, attempts to visualize electron wave behavior through color and animation were repeatedly revised but did not operate as intended. Similarly, educational models designed to account for both thermal conductivity and metallic luster revealed limitations arising from tensions between explanatory scope and representational form.

Reflecting on this process, T5 explained that "I repeatedly discussed with the AI which concepts were necessary for the model, what its limitations and unexplainable aspects were, and how to balance implementability with scientific validity."

Through these repeated experiences of failure and revision, T5 came to understand that incorporating more concepts does not necessarily result in a better model. Instead, T5 developed an understanding that constructing educational models requires making deliberate decisions about which concepts must be included and which aspects must be left unexplained, depending on the explanatory purpose of the model.

After participating in the AI-supported modeling activities, T5 responded to Question 4 by stating that "When developing a model, it is necessary to clearly distinguish between the concepts that must be included and the ignorance of the model. I

Table 10 Changes in teachers' understanding of models in pre- and post-interviews

	Pre		Post	
Question	Obj (n)	Subj (n)	Obj (n)	Subj (s)
1	10	4	8(∇2)	6(Δ2)
2	10	4	5(∇5)	9(Δ5)
3	10	4	6(∇4)	8(Δ4)
4	11	3	3(∇8)	11(8)
5	9	5	3(∇6)	11(Δ6)
6	9	5	2(∇7)	12(Δ7)
7	8	6	1(∇7)	13(Δ7)

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do not think it is possible to represent and explain everything.'' In contrast to the pre-interview response, this statement reflected a subjectivist understanding of models, in which model construction involves purposeful selection of concepts and explicit recognition of what the model does not aim to explain, rather than a sole emphasis on theoretical accuracy.

When put together, these findings suggest that teachers' understanding of models shifted from an objectivist perspective toward a more subjectivist perspective. In the pre-interviews, teachers tended to understand models primarily as fixed representations of established scientific knowledge. However, through repeated cycles of model construction, evaluation, and revision supported by generative AI interactions and reflective discussions, teachers began to reconsider the role and nature of models in scientific inquiry. These experiences encouraged teachers to recognize that models are constructed based on particular assumptions, operate within specific conditions, and may coexist with alternative models that explain different aspects of the same phenomenon. From a metamodeling perspective, such experiences appear to have supported the development of more sophisticated understandings of the purposes and limitations of models.

In addition, T7's responses to Question 5 (Scientists evaluate models. What criteria should be used for this evaluation? Please explain your answer.) are presented below as another illustrative case of response change. In the pre-interview, T7 evaluated models mainly in terms of how accurately they represented actual phenomena. T7 stated that a scientific model should explain the target phenomenon ''without misconceptions and clearly,'' emphasizing that the key criterion for evaluation was whether the model corresponded closely enough to avoid distortion. This response reflects an objectivist understanding of models, in which models are treated primarily as accurate representations of natural phenomena and are judged by the degree to which they faithfully reproduce established scientific knowledge. Afterwards, T7 participated in AI-supported modeling activities in which educational models of metallic bonding were repeatedly generated, tested, and revised through interactions with generative AI. During this process, T7 became concerned that representing free electrons only as particles could reinforce misconceptions in students' thinking. In the presentation, T7 explained that if conductivity were represented solely as the movement of a fixed number of particles, students might conclude that ''electrons simply accumulate on one side and are no longer present on the other side'' when an electric field is applied. To address this, T7 submitted the prompt ''Please visualize electrical conductivity not as the movement of a fixed number of particles, but as a bias in the wave'' to the AI search engine. This prompt explored whether electrical conductivity could be expressed as a directional shift in a wave-like distribution rather than as the linear displacement of discrete particles. T7 also asked the AI to represent thermal conductivity by submitting the prompt ''Please visualize the process so that when heating starts, the wave becomes denser from the left side and propagates to the right, showing the movement of a higher-energy wave state,'' requesting that the propagation of a higher-energy wave state from one side of the metal to the other be visualized.

Through these repeated interactions with AI-generated outputs, T7 did not merely seek a more realistic representation. Rather, T7 evaluated alternative models not simply by how closely they resembled reality, but in relation to whether each model was adequate for its explanatory purpose, pedagogically useful, and free from unintended implications. The AI-supported process provided multiple provisional representations that T7 could compare, apply new concepts to, and revise in light of the intended instructional goal.

Following participation in the program designed in this study, T7's responses showed a broader view of model evaluation. In the post-interview, T7 stated that model evaluation should consider not only whether a model explains phenomena clearly and supports prediction, but also whether it is understandable for learners and appropriate for the intended purpose. Compared with the pre-interview, this response reflects a more subjectivist understanding of models, in which models are not judged solely by their resemblance to reality, but by their adequacy for explanation, use, and communication under particular conditions.

6. Conclusions

This study examined changes in teachers' understandings by applying the metamodeling knowledge progression framework proposed in prior research (Kim *et al.*, 2019; Seo *et al.*, 2024) through a framework-based qualitative content analysis (Schreier, 2012; Mayring, 2014). The analysis focused on three dimensions: the limitations teachers recognized in the electron sea model, the conceptual elements they emphasized in developing educational models to address these limitations, and whether their metamodeling understandings shifted from an objectivist toward a subjectivist orientation through modeling activities. Thus, this study can be regarded as an educational investigation demonstrating that teacher participation in modeling activities can enhance metamodeling knowledge and strengthen instructional contexts. This study suggests that the very process of recognizing the limitations of models and striving to improve them constitutes an essential learning opportunity in itself. This implies that going beyond focusing solely on the 'usefulness' of models, critically reflecting on and improving model limitations is itself a practice for understanding the nature of scientific modeling.

The main conclusions revealed through this study are as follows.

First, teachers recognized limitations of the electron sea model in explaining metallic properties. For electrical conductivity, teachers pointed out that simple movement of free electron cannot sufficiently explain the energy transfer process. Regarding thermal conductivity, teachers noted that particle movement alone is insufficient to explain the efficiency of thermal energy transfer. In the case of malleability and ductility, teachers indicated that it is difficult to explain the deformation of atomic arrangement without considering electrostatic repulsion between cations. For luster, teachers

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highlighted that wave properties are necessary for light-electron interactions. Based on this recognition, teachers developed models that integrate both particle and wave nature of electrons, as well as models that consider electrical interactions between electrons and metal cations. Some models also expressed electron cloud distribution and redistribution potential. These results demonstrate that the teacher education program designed in this study was effective not only in enabling teachers to supplement existing models but also in cultivating modeling knowledge to analyze models.

Second, teachers participating in this study demonstrated an overall development of metamodeling knowledge, as reflected in a shift from an objectivist to a subjectivist understanding of models through repeated modeling cycles. After engaging in the modeling activities, teachers increasingly understood models not as fixed or objective representations of natural phenomena, but as purpose-driven, tentative, and revisable tools for inquiry (Table 10). Changes were observed across teachers' understandings of the nature and purpose of models, the processes of modeling, the variability and diversity of models, as well as the practices of evaluating models.

Through iterative model construction, interaction with generative AI, and reflective discussion, teachers came to recognize that models are shaped by underlying assumptions, operate within specific conditions and scopes, and may coexist with alternative models that explain different aspects of the same phenomenon. These experiences supported a transition away from understanding models primarily as miniature representations or explanatory devices for objective knowledge, toward understanding models as tentative, purpose-dependent tools shaped by underlying assumptions and contextual constraints.

Two analytically distinct but interrelated forms of knowledge were observed to develop through this program. First, content knowledge of metallic bonding properties – such as electrical conductivity and thermal conductivity – served as the empirical foundation that enabled teachers to identify the explanatory limitations of the electron sea model. Second, modeling knowledge was developed through iterative practices of model construction, revision, and application. However, the central focus of this study is the development of metamodeling knowledge – that is, teachers' epistemological understanding of what models are, why they are constructed, and what their limitations are (Schwarz and White, 2005; Schwarz *et al.*, 2009). The observed shift from an objectivist to a subjectivist understanding of models reflects this metamodeling dimension, rather than content mastery or modeling proficiency alone. These three forms of knowledge were mutually complementary within this program: content knowledge of metallic bonding properties served as the empirical grounding that enabled teachers to identify the explanatory limitations of the electron sea model, modeling practices offered the procedural context for engagement, and explicit reflection on modeling processes fostered metamodeling understanding. Thus, effective model-based teacher education must integrate rigorous conceptual understanding with metacognitive engagement in modeling activities through explicit reflection.

These findings suggest that, within this specific program context, the iterative modeling activities (including generative AI interaction and peer reflective discussion) integrated with the cyclical MBL-5E processes were associated with teachers' metamodeling knowledge development – specifically, a shift from objectivist to subjectivist understandings of models.

7. Implications

The implications derived from this study can be categorized into three main areas: for expanding research participants/comparative research across educational levels/developing supplementary teacher education programs.

7.1. Implications for expanding research participants

As noted in the introduction of this study, developing students' modeling competencies is a central goal of science education, and teachers play a critical mediating role in achieving this goal by facilitating students' engagement in modeling practices (van Driel and Verloop, 1999; Justi and Gilbert, 2002). The present study suggests that iterative modeling activities integrated with the cyclical MBL-5E processes were associated with in-service chemistry teachers' metamodeling knowledge development, within this specific program context. These activities – including generative AI interaction and peer reflective discussion – were specifically associated with a shift from objectivist to subjectivist understandings of models. Given that teachers' metamodeling perspectives are recognized as a key variable shaping students' understanding of models (Schwarz and White, 2005), the modeling cycle structure employed in this study holds potential for adaptation within student learning contexts as well. In particular, the limitations of the electron sea model that teachers identified in this study emerged through the process of explaining various metallic properties. Engaging students in recognizing the limitations of existing models and developing revised models would provide opportunities that extend beyond conceptual understanding alone, fostering the development of metamodeling knowledge and scientific inquiry competencies (Schwarz *et al.*, 2009). Future research should therefore investigate whether and how the application of this program to student populations supports the development of students' metamodeling knowledge, thereby extending the educational implications of the present findings from teacher education to science learning more broadly.

7.2. Implications for comparative research across educational levels

This study focused on in-service teacher populations, so research is needed to apply the same education program to preservice teachers or students and conduct comparative analysis of results. Comparing the degree of metamodeling knowledge development across groups will provide insights into developmental differences and trajectories by educational level. For example, when the program is applied to secondary

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students, comparing and analyzing student metamodeling knowledge level development patterns with teachers will reveal differences and developmental trends by educational stage.

7.3. Implications for AI-supported teacher education programs

This study suggests several implications for the design of supplementary teacher education programs intended to support teachers' metamodeling knowledge through AI-supported modeling activities. Within the present program, teachers engaged in repeated cycles of constructing, evaluating, revising, and discussing educational models while participating in a broader instructional sequence that integrated Model-Based Learning with the 5E learning cycle. As illustrated in the teacher cases presented in the Results and Discussion section, generative AI was used in specific ways during these activities: teachers asked AI tools to visualize model ideas, modify representations, generate HTML or JavaScript code for dynamic models, evaluate whether a model matched an intended explanation, and suggest possible revisions when a model failed to explain a targeted property. These interactions formed one part of the overall program environment in which teachers reflected on explanatory scope, assumptions, limitations, and purposes of models.

The findings indicate that teachers' opportunities to revise their models were often shaped by moments in which their intended explanations did not align with the representations they had produced, or in which one model could not adequately account for multiple metallic properties at the same time. In these situations, interaction with generative AI provided occasions for teachers to restate their intentions, compare alternative representations, and reconsider which aspects of a phenomenon should be emphasized, simplified, or left unexplained. At the same time, these experiences were embedded in the larger teacher education program, including peer discussion, instructor feedback, and repeated modeling cycles. Accordingly, it is difficult to distinguish the contribution of generative AI from that of the broader instructional design, and the present findings should therefore be interpreted as reflecting the combined effect of the AI-supported modeling environment rather than the isolated effect of AI itself.

Overall, these findings suggest that AI-supported modeling activities in teacher education should be designed not simply to produce technically elaborate models, but to support repeated opportunities for explanation, critique, revision, and explicit reflection on the assumptions and limitations of models. More specifically, productive use of AI in such contexts may depend on structuring activities so that teachers are expected to compare representations, articulate why a model succeeds or fails for a particular explanatory purpose, and revise their models in response to those judgments.

8. Limitations

8.1. Limitations related to participants and sampling

This study was conducted with 14 in-service chemistry teachers, which entails certain limitations in terms of sample size and sampling scope. The participating teachers voluntarily enrolled in a teacher education program and may therefore have had relatively high interest and motivation toward modeling practices or professional development in science education. Due to this, caution is required when generalizing the observed changes in metamodeling knowledge to the broader population of in-service chemistry teachers.

8.2. Limitations related to the transfer to classroom practice

Another limitation of this study is that it did not examine how teachers' participation in AI-supported modeling activities and the observed changes in their metamodeling knowledge were enacted in subsequent classroom teaching practices. Although the findings indicate changes in teachers' understanding of models and modeling within the context of the teacher education program, the study did not investigate how this enhanced understanding influenced teachers' instructional practices in actual science classrooms.

Specifically, this study did not examine whether and how teachers' instructional approaches changed after the program, including their ways of organizing instruction, explaining and using models during lessons, and supporting students' engagement in modeling activities. In addition, the study did not investigate how students' understanding of models developed in response to possible changes in teachers' instructional practices, nor whether teachers' enhanced metamodeling knowledge was applied beyond the electron sea model to other models used in chemistry instruction. Future research should therefore examine classroom-level implementation to explore how teachers' developed metamodeling knowledge is reflected in instructional practices and in students' understanding of models across diverse scientific contexts.

8.3. Limitations related to the two-category analytical classification

Another limitation of this study concerns the analytical procedure used to classify teachers' metamodeling understanding into two broad categories: objectivist and subjectivist. This two-category classification was useful for identifying the overall direction of change across the pre- and post-interviews; however, teachers' responses were not always fully consistent across all metamodeling components addressed in the analytical framework. In some interviews, features associated with objectivist and subjectivist understandings coexisted across different components, indicating that teachers' metamodeling understanding was not necessarily uniform across dimensions.

Accordingly, the final classification required interpretive judgment based on the predominant response pattern across each teacher's interview as a whole. Although this process was carried out through repeated discussion among multiple analysts to enhance trustworthiness and intersubjective comprehensibility, it inevitably involved some degree of uncertainty. Therefore, the two-category classification should be understood as an analytical simplification that captures the overall tendency of teachers' responses, rather than as a precise representation of their level in each metamodeling dimension.

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Future research could address this limitation by adopting more fine-grained analytical approaches that examine teachers' understandings separately across different metamodeling components, thereby providing a more differentiated account of consistency, variation, and transition in teachers' metamodeling knowledge.

8.4. Limitations related to the isolation of the AI-supported component

A further limitation of this study concerns the difficulty of isolating the specific contribution of generative AI from the effects of the broader teacher education program. The program designed in this study constituted a complex instructional environment integrating MBL, the 5E learning cycle, and dialogic interactions with generative AI (Claude). Consequently, it is not possible within the current research design to causally disentangle whether the observed changes in teachers' metamodeling knowledge were attributable to their interactions with generative AI, to the iterative modeling cycle activities themselves, or to the collaborative discussions and reflective practices conducted among participating teachers.

This limitation suggests that generative AI is more appropriately understood as one component of the overall instructional environment rather than as an isolated causal mechanism driving changes in metamodeling knowledge. Future research should seek to more rigorously examine the distinct effects of generative AI by employing comparative designs that include AI-supported and non-AI-supported conditions, or quasi-experimental designs in which the AI interaction component is systematically controlled across instructional phases.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting the findings of this study are not publicly available due to privacy regulations protecting participants' personal information. However, anonymized data are available from the corresponding author upon reasonable request, in accordance with institutional ethical approval (IRB No. KNUE-202507-BMSB-0475-01).

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