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High school students' use of epistemic knowledge in understanding atomic models

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Understanding Chemistry requires not only learning scientific concepts but also developing epistemic knowledge about how chemical knowledge is constructed, evaluated, and validated. Explicitly addressing epistemic aspects in chemistry lessons is essential for enhancing students' understanding and their performances. In this sense, this study examined how secondary school students employed epistemic knowledge involved in the scientific practice of modelling when analysing different atomic models. A qualitative design was adopted to examine in detail how participants engaged with some epistemic aspects of modelling. The participants were seventeen 15–16-year-old students enrolled in a Physics and Chemistry course at a rural public school in Spain. The intervention was conducted in the middle of semester over four 50 minute-sessions and consisted of a teaching unit on atomic models. It began with a questionnaire aimed at identifying students' initial ideas about the atomic structure of matter with an epistemic focus, followed by several teaching activities addressing the different atomic models, with emphasis on their scientific development and historical context. At the end of the unit, an application activity was conducted to assess students' ability to apply their epistemic and scientific knowledge of the different atomic models. The data, consisting of individual written responses, were analysed through qualitative content analysis focusing on disciplinary epistemic knowledge (recognising representational plurality, model tentativeness, and explanatory scope) and social epistemic practices (model comparison). The main findings reveal persistent challenges in students' performances, especially in identifying the cumulative explanatory power of atomic models and in connecting phenomena with supporting evidence to each atomic model. The results suggest the need of new instructional experiences as well as strategies to explicitly incorporate epistemic aspects in Chemistry lessons together with content knowledge.

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Introduction

Learning Chemistry involves relating the macroscopic world with a submicroscopic world based on atoms and molecules that cannot be perceived (Deboer, 2000) and also with the symbol system that is needed for its representation (Salazar *et al.*, 2019). Establishing and coordinating relationships among these three levels of representation is particularly challenging for students and constitutes a major source of difficulty in learning chemistry. Modelling addresses this challenge by providing explicit representational tools that allow students to visualize, connect, and reason across the macroscopic, submicroscopic, and symbolic levels, thereby supporting their understanding of chemical phenomena.

The scientific practice of modelling involves constructing and using models, as well as evaluating and revising them (Schwarz *et al.*, 2009; NRC, 2013). This practice is particularly relevant in the teaching of chemistry, a discipline dominated by the use of models. For instance, understanding macroscopic phenomena almost invariably requires the use of submicroscopic representations or models (Oversby, 2000). Models are employed to represent a system under study or parts of it, to support the development of questions and explanations, to generate data that can be used to make predictions, and to communicate ideas (NRC, 2013).

Scientific models are useful to communicate, explain phenomena or set solutions found at a particular time in history (Salazar *et al.*, 2019). Therefore, involving learners in modelling practices can help them build subject matter expertise and epistemological understanding (Schwarz *et al.*, 2009). However, their use in the classroom entails challenges for students due to their unfamiliarity with scientific models and their limitations (Duit, 1991; Harrison and Treagust, 2000). More specifically, several studies reported students' difficulties when engaging in modelling practices such as connecting multiple representations, building causal/mechanistic explanations, and using

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models as epistemic tools (Lehrer and Schauble, 2006), connecting multiple representations of the model (Chittleborough and Treagust, 2009) or weak understanding of the purpose of models and its limitations (Schwarz *et al.*, 2009).

In this sense, addressing epistemic knowledge involved in this practice can enhance students' performances since it helps them not only do science, but also understand how scientific knowledge is constructed, justified, and validated (Berland *et al.*, 2016; Crujeiras-Pérez and Brocos, 2021).

In science lessons, models play a crucial role in fostering epistemological understanding of the nature of science (Tasquier, Levrini and Dillon, 2016) as well as in developing epistemic skills (Pluta *et al.*, 2011).

In the literature, numerous terms are used to refer to the epistemic aspects of science, such as epistemic knowledge, epistemological beliefs, personal epistemologies or epistemic practices. A construct that would encompass all of these is epistemic cognition, understood as an array of understanding, practices and motivations related to topics such as what counts as knowledge and how knowledge claims are justified (Chinn *et al.*, 2014). Extensive research has been conducted on epistemic cognition, addressing topics such as students' understanding of scientific epistemic knowledge (Yang *et al.*, 2016, 2018), their personal epistemologies (Hammer and Elby, 2003; Sandoval, 2005), the application of epistemic criteria (Sandoval and Çam, 2011), and engagement in epistemic practices (Kelly and Takao, 2002; Sandoval and Reiser, 2004; Christodoulou and Osborne, 2014).

In this study we focus on students' application of epistemic knowledge, which means the comprehension of the role of specific constructs and the essential characteristics of the processes involved in the construction of scientific knowledge (Duschl, 2008). Within scientific practices and particularly in relation to the practice of modelling, epistemic knowledge is necessary to understand both the use and the limitations of models. Thus, the use of epistemic criteria enables students to more appropriately evaluate scientific models (Pluta *et al.*, 2011).

In science education, epistemic knowledge can be approached from three distinct perspectives: disciplinary, social, and personal (Kelly *et al.*, 2012). In this study, we focus on the disciplinary and social epistemic dimensions. The disciplinary aspect, referred to here as disciplinary knowledge, encompasses all elements related to how knowledge is used within the scientific community and its main characteristics (Duschl, 1990; Kelly, 2008). The social aspect, referred to as practice, is characterized by the specific ways in which members of a community propose, justify, evaluate, and legitimize knowledge claims within a disciplinary framework (Kelly, 2008). The personal perspective, although it is not addressed in this study, focuses on how individual learners understand knowledge and how these personal views influence their learning (Hofer, 2001; Kelly *et al.*, 2012). The difference between these two aspects lies in their nature: disciplinary aspects refer to theoretical knowledge, whereas social aspects correspond to actions. For example, in the context of modelling, the scientific practice analysed in this study, a disciplinary epistemic aspect would be recognizing that ''different models can be used to represent the same phenomenon'' (Crawford and Cullin, 2004), while an epistemic practice would be ''comparing models to identify common features and differences'' (NRC, 2013). Epistemic knowledge associated to modelling has been an understudied issue, both theoretical and empirical, that has been emphasised in the last decades, especially since the emergence of the scientific practices approach. In this sense, Oh and Oh (2011) characterised the nature of models and their uses in the classroom in terms of the meanings of a model, the purposes of modelling, multiplicity of scientific models and change in scientific models.

The empirical studies have examined both students' epistemic beliefs and epistemic performances related to scientific models. Students' epistemic beliefs about the nature of models have been widely investigated across different contexts using the Students Understanding of models in Science instrument (SUM) (Treagust *et al.*, 2002), such as high school Chemistry (Liu, 2006; Park *et al.*, 2017), high school Biology (Burgin *et al.*, 2018), pre-service teacher education (Muñoz-Campos *et al.*, 2016; Derman and Kayacan, 2017) or undergraduate students (Lazenby and Becker, 2021). These studies combine this diagnostic instrument with different instructional interventions such as using computational or conceptual models and have substantially contributed to understanding students' epistemic knowledge about models, particularly through dimension-based approaches that examine beliefs about the nature and purposes of models. However, they mainly capture what students know or believe about models, providing limited insight into how such epistemic knowledge is enacted in practice during modelling activities.

In contrast, research focusing on epistemic performances addresses this limitation by examining how students apply epistemic knowledge in authentic modelling contexts. For instance, Pluta *et al.* (2011) examined the epistemic criteria for good models developed by middle-school students after instruction and experience with model-based reasoning practices. Their findings suggest that with explicit instruction about the nature of models, students begin to apply more epistemically grounded criteria. Ryu *et al.* (2015) investigated how students' epistemic understanding about the nature, purpose and justification of scientific knowledge and models developed together when engaging in modelling practices using mobile devices. Their results reported improvements in students' epistemic reasoning, particularly regarding model limitations and of how evidence supports or conflicts with a model.

Those studies have provided important insights into students' modelling practices as well as their meta-modelling knowledge about the nature and purposes of scientific models. However, fewer studies have examined how students' epistemic knowledge about models is mobilised when they participate in modelling activities. In this study we address this issue by distinguishing between disciplinary epistemic knowledge, referring to students' understanding of key epistemic features of scientific models and social epistemic practices, referring to the ways in which such knowledge is enacted through activities such as comparing models or identifying similarities and differences (NRC, 2013). By connecting these two dimensions, this framework extends existing modelling research by enabling the examination of the relationship between students' epistemic understanding of models and how this understanding is enacted in modelling practices.

Building on this perspective, the present study examines both students' disciplinary epistemic knowledge about scientific modelling and how this knowledge is enacted when students justify and evaluate different atomic models. This approach allows us to examine not only whether students recognise key epistemic features of models, such as the idea that multiple models can represent the same phenomenon, but also whether and how they use such knowledge in practice, for example when comparing models or justifying model choices. In this sense this study provides an analytical perspective for examining potential alignments or tensions between what students know about the epistemic nature of models and how they use that knowledge in modelling tasks in chemistry.

This epistemic approach is examined in the context of atomic models, which are fundamental to chemistry education because they provide a conceptual framework for explaining the structure and behaviour of matter. The particulate nature of matter is recognised as a challenging topic in Science Education (Park and Light, 2009; Treagust *et al.*, 2010), due, in part, to its abstract nature and also due to students' misconceptions about the atom, such as considering it as the smallest building block of matter (Kaya, 2023), attributing macroscopic characteristics to the atom such as physical state or colour (Griffiths and Preston, 1992; Adbo and Taber, 2009), lack of distinction between the atom and other submicroscopic particles (Cokelez and Dumon, 2005) or even anthropomorphic conceptions, confusing atoms with cells (Harrison and Treagust, 1996). These misconceptions could be attributed to ideas that do not reflect the facts in the historical development of scientific concepts, commonly addressed in elementary education (Griffiths and Preston, 1992; Kaya, 2023).

In this sense, Taber (2003) argued that the atom is frequently introduced in educational curricula as both a historical construct and a foundational scientific concept and stated that presenting these models as absolute truths rather than as conceptual tools can lead to epistemological difficulties for students.

Moreover, a correct understanding of atomic models supports further learning, since many higher-level chemical ideas (such as bonding, molecular geometry, periodic trends, reactivity) depend on an accurate submicroscopic view (Lateef *et al.*, 2026). In fact, by linking microscopic structures to macroscopic phenomena, students are able to develop scientific reasoning skills and to apply chemical knowledge effectively in real-world contexts (Taber, 2003, Kelly *et al.*, 2021).

Given the relevance of this topic, the particulate nature of matter has been extensively investigated in Chemistry Education, with plenty of studies reporting students' difficulties in understanding the nature of matter and particle models (*e.g.* Griffiths and Preston, 1992; Harrison and Treagust, 1996; Adbo and Taber, 2009; Samarapungavan *et al.*, 2017).

Regarding atomic models specifically, Harrison and Treagust (1996) examined learners' mental models of the concepts of atom and molecule and found that students often confuse ideas such as the nucleus and electron shells. Many tended to merge features from different models, for instance, combining elements of Bohr's model with aspects of earlier models, analogies, or incorrect interpretations, to construct their own understanding. In a similar sense, Adbo and Taber (2009) investigated high school students' mental models of matter at the particulate level, concluding that the teaching model of the atom derived from Bohr's model gives the students an image of a disproportionately large and immobile nucleus, emphasises a planetary model of the atom, among other aspects. In another sense, Souza, Justi and Ferreira (2006) studied how students understand Thomson and Bohr atomic models when using analogies. The findings evidenced that most students do not understand the analogies, as well as the atomic models to which they are associated.

Students' mental models are still explored nowadays due to their relevance for students' comprehension of atomic structure. Recent studies examined high school students' mental models about quantum mechanical model of the atom (Zarkadis *et al.*, 2017) or more specifically about the concept of electron cloud (Çalis, 2024) identifying the influence of Bohr model in students' mental models or the existence of a hybrid model between the Bohr and quantum mechanical ones.

In addition to exploring students' conceptions and models, some teaching strategies have examined, such as the historical approach addressing the evolution of atomic models from early Greek atomism to contemporary theories. This approach helps students trace how philosophers and scientists developed their ideas, promoting comprehension of matter's particulate nature and the dynamics of scientific advancement (Vienner, 2020), as well as nature of science aspects such as tentativeness, empirically based or social and cultural embeddedness (Lederman, 2007).

Building on this perspective, the present study examines how secondary school students use epistemic knowledge involved in the scientific practice of modelling when analysing different atomic models. It forms part of a broader investigation into students' epistemic cognition during their engagement in scientific practices.

The research questions that guide the investigation are:

RQ1. How do students use disciplinary epistemic knowledge about the representational, provisional and explanatory nature of scientific models in an intervention about atomic models?

RQ2. What are students' performances in comparing different atomic models in order to identify the phenomena they explain and the scientific evidence that supports their validity?

Theoretical framework

This study conceptualizes models as epistemic artefacts designed to explain phenomena, test ideas, and support scientific reasoning and argumentation (Campbell and Oh, 2015).

Consequently, learning science through models requires not only conceptual understanding, but also epistemic awareness of how models function within the knowledge-building practices of science.

This study focuses on both disciplinary and social epistemic dimensions, addressing disciplinary aspects such as ''different models can be developed to explain the same phenomenon'' (Crawford and Cullin 2004) or social practices such as comparing models to identify common features and differences (NRC, 2013). Both dimensions are interdependent and essential for meaningful engagement in modelling activities. Empirical research has shown that when instruction explicitly addresses the epistemic nature of models, students develop more sophisticated criteria for evaluating and comparing them (Pluta *et al.*, 2011; Ryu *et al.*, 2015).

Atomic models provide a particularly suitable context for examining epistemic knowledge in modelling due to their historical development and conceptual complexity. The evolution of atomic models illustrates how scientific models change over time in response to empirical evidence and theoretical advances, while still retaining certain explanatory features.

By engaging students in a historically informed sequence on atomic models, this study positions model comparison as a central epistemic practice through which students can develop epistemic knowledge about modelling. Analysing how students compare atomic models allows for the examination of their disciplinary understanding of models and their participation in social epistemic practices. In this way, the framework adopted in this study conceptualises epistemic modelling performances as indicators of students' understanding of the nature of scientific knowledge and the role of models in Chemistry.

Methodology

This study adopts a qualitative research approach and consists of a case study (Swanborn, 2010) aimed at analysing in detail how participants use specific epistemic aspects involved in scientific modelling. The research draws from qualitative content analysis (Schreier, 2012), systematically describing the meaning of students' written productions by classifying them into categories within a defined coding framework.

Context and participants

The participants were 17 students (aged 15–16) in the fourth year of compulsory secondary education, enrolled in a Physics and Chemistry course at a rural public high school in Spain. All students in the class agreed to participate, as the study was conducted during regular lessons and did not require additional time beyond normal classroom activities. Students worked individually throughout the study. At the time of data collection, they had not yet been formally introduced to the scientific practice of modelling, as their regular instruction did not explicitly incorporate the use of models; instead, classroom activities had focused more on problem solving than on explaining and relating phenomena.

Intervention

The intervention was carried out in the middle of semester along four 50 minute-sessions, and it is summarised in Fig. 1. It started with a questionnaire aimed at identifying students' initial ideas about the atomic structure of matter, with an epistemic focus on several disciplinary aspects of modelling, which is reproduced in Fig. 2. After that, a teaching unit containing several activities addressing the different atomic models was implemented, highlighting the scientific development and historical context in which model emerged were carried out. These activities integrated theoretical explanations with illustrative examples and simulations of the key experiments that underpinned the formulation of each model, emphasising how experimental evidence and successive discoveries contributed to the evolution of atomic theory. At the end of the unit, an application activity was conducted to determine whether students were able to apply their knowledge of different atomic models, specifically how they related each model to the phenomena it explains, as illustrated in Fig. 3. Students were provided with a worksheet containing a series of phenomena and scientific evidence, which they had to

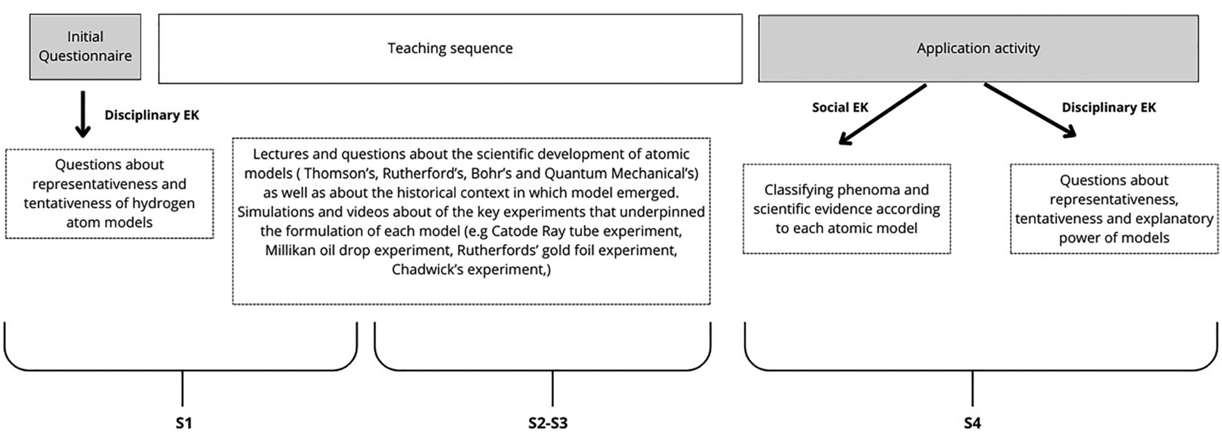

Fig. 1 Description of the intervention on atomic models and timeline.

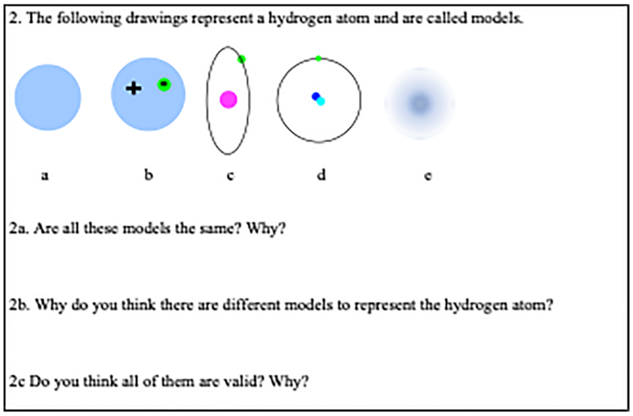

Fig. 2 Questions for identifying students' initial perceptions about the nature of models.

associate with the corresponding atomic models. After completing the classification task, students answered four questions designed to elicit their epistemic understanding of modelling.

It should be noted that, for the purposes of this study, we have analysed only the initial questionnaire and the final activity in order to address the research questions posed.

Data collection and analysis

Data collection consisted of individual written student responses related to the initial and final parts of the intervention. For data analysis, students' written responses to each question were examined using content analysis, based on the following epistemic aspects of scientific modelling:

(a) Disciplinary epistemic knowledge (RQ1):

– Different models can be used to represent the same phenomenon (Crawford and Cullin, 2004). To assess whether students recognize this aspect, they were provided with four different representations of the hydrogen atom and asked whether they considered them to represent the same model, as well as why they thought different models are used to represent the hydrogen atom (questions 2a/2b-Fig. 2).

– Models are provisional and are modified when they no longer fit observed data from the real world (Crawford and Cullin, 2004; Giere, 1990). To analyse this aspect, students were again shown different representations of the hydrogen atom and asked whether they believed all models were equally valid (question 2b/2c-Fig. 2).

– A model with explanatory purpose must be able to explain a wide range of phenomena (Ryu *et al.*, 2015) (question 5, Fig. 3).

(b) Social epistemic knowledge (epistemic practices) (RQ2):

– Comparing models to identify common features and differences (NRC, 2013) (Fig. 3).

The coding process was conducted inductively, following the principles of qualitative content analysis (Mayring, 2021) and using ATLAS. Ti software: first the data were read carefully several times to identify meaningful units of information. Subsequently, an inductive–deductive coding process was carried out based on the theoretical framework of epistemic knowledge in scientific modelling, resulting in a preliminary coding scheme. This coding was undertaken by the author and two members of the research team: the classroom teacher who implemented the instructional intervention and a second researcher who was not previously familiar with either the intervention or the research design. Then, inter-coder triangulation was performed through a joint review of code definitions, comparison of coded data segments, and discussion of discrepancies until consensus was reached, leading to refinement of the final category system.

The general categories resulting from the analysis of disciplinary epistemic knowledge correspond to students' perceptions

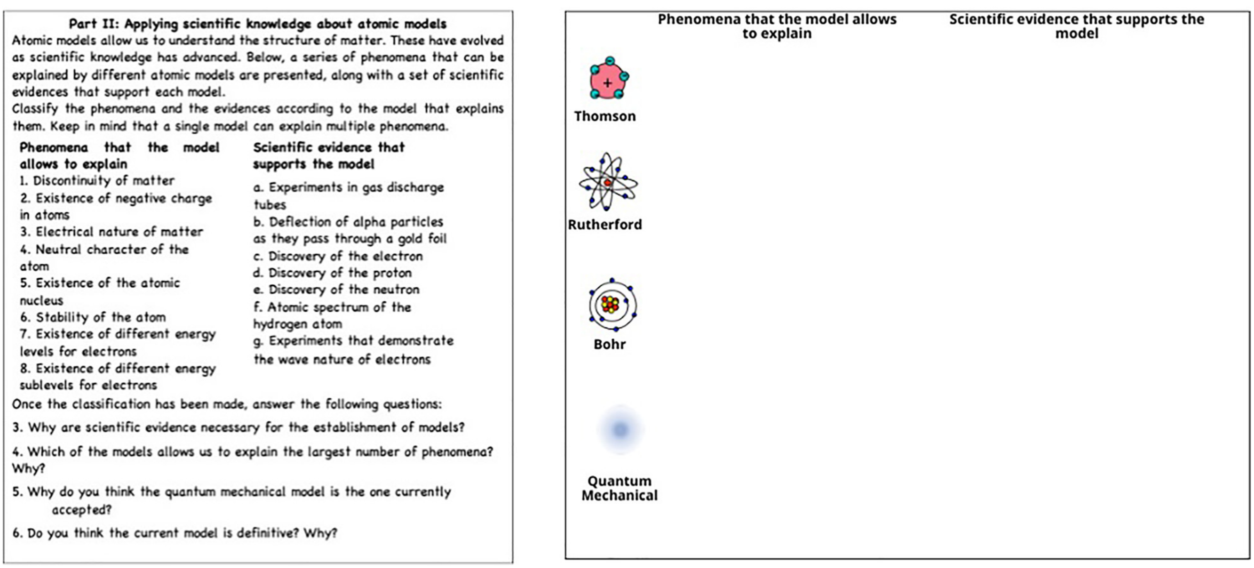

Fig. 3 Questions and worksheet for examining students' performances in comparing different atomic models in order to identify the phenomena they explain and the scientific evidence that supports their validity as well as students' perceptions about tentativeness.

of the representativeness, tentativeness and the explanatory power of scientific models. In contrast, the categories related to the epistemic practice correspond to students' identification of the phenomena explained by each model, as well as the evidence supporting each model. The final rubrics are presented within the results in the next section.

Ethical concerns in the research

The study was approved by the Ethical Committee of the university under code USC 106/2024. Participants were informed about the objectives, nature, and characteristics of the study, as well as the intended use of the data collected. Subsequently, all legal representatives of the participants included in the study voluntarily signed an informed consent form. To protect their privacy, all data were anonymized prior to analysis, and the authors identified participants using codes. The participation in the study was voluntary, and participants had the option to withdraw at any time.

Results

This section is organised into two subsections corresponding to the two research questions that guide this research. The results are presented in terms of epistemic sophistication, from highest to lowest. Although the study is qualitative, absolute frequencies are reported as descriptive indicators of dominant themes within the collected data (Creswell, 2005) and as a means of supporting the interpretation of the qualitative findings.

Students' use of disciplinary epistemic knowledge on the representativeness, tentativeness of and explanatory power of models

Regarding the representativeness dimension, the findings reported in Table 1 indicate that only six out of 17 students were able to recognise the representative function of atomic models, acknowledging that different models can be employed to represent the same phenomenon. There is also one student that did not respond to any question due to a lack of engagement in the lesson and also in the subject throughout the academic year.

According to the data in Table 1, students provided three different justifications for the representativeness of models. The first type referred to the evolution of scientific knowledge, as illustrated by student A13' response: "*They are not the same because each of these models represents the same thing, but over time new things were discovered, so the model changed by adding them*." This example shows a developing, but limited understanding of the representativeness of scientific models, in which the student perceived models as successive improvements in accuracy that reflected the accumulation of discoveries, but not yet as conceptual tools that can differ qualitatively in what aspects of reality, they represent or in the explanatory purposes they serve.

The second type of justification concerned the existence of multiple representations of a single phenomenon depending on the intended purpose of representation and was expressed by two students. For example, student A16 referred to the degree of precision in representation: "*Because each one represents the same as the others, but with more or less precision. I think that each one is used for something different depending on the degree of precision required*". In this example, the student demonstrated an understanding that different models can represent the same phenomenon, indicating an awareness of models as representations of reality. However, the student also showed a limited understanding of the distinct purposes of these representations, conflating precision with the different aspects that each model may emphasize. This interpretation may be influenced by the instructional context, particularly the focus on the historical development of atomic models.

And the third type of justification was related to a nominalist view of models, reflecting a lack of understanding of their representative function, expressed by only one student: "*because they have been studied by different scientists*". In this case, the student attributed the existence of different models solely to the contributions of different scientists, without acknowledging the representational, explanatory, and evolutionary nature of scientific models as theoretical constructs designed to account for the same phenomenon from diverse perspectives. Students who failed to identify this epistemic aspect tended to misinterpret the models as depictions of different atoms (N = 4), associated design differences with distinct models (N = 1), or provided no justification for their responses (N = 5). These patterns suggest a limited understanding of the representational nature of scientific models.

In relation to the tentativeness of scientific models, the results were even less satisfactory, as reproduced in Table 2.

According to Table 2, only three students demonstrated awareness of this epistemic dimension, referring either to the evolution of models in light of new knowledge (N = 1) or to the evolution of models without justification (N = 2). Student A13, for instance, explained: "*Because each model represented the idea*

Table 1 Students' perceptions about representativeness of scientific models in terms of frequency

Category	Justification	N
Recognizes that different models can be used to represent the same phenomenon	Evolution of scientific knowledge	3
	Existence of multiple representations of a single phenomenon depending on the intended purpose of representation	2
	Nominalistic view of models	1
Does not recognize that different models can be used to represent the same phenomenon	Models interpreted as different atoms	4
	Design differences interpreted as different models	1
	No justification	5

Table 2 Students' perceptions about tentativeness of scientific models

Category	Justification	*N*
Identifies the provisional nature of models	Refers to the evolution of models in light of new knowledge	1
	Refers to the evolution of models over time, but without justification	2
Not identifying the provisional nature of models	Considers all models valid without justification	5
	Relates model validity to precision without acknowledging tentativeness	2
	Does not consider all models valid without justification	2

that they [the scientists] had according to the times in which they lived. Ideas and discoveries were advancing, as was the model, which was renewed each time knowledge about the theory increased.'' In this example, the student acknowledged that scientific models are context-dependent representations shaped by the knowledge and ideas available at a given time, as well as that they are temporary and subject to change. This response therefore indicates a thoughtful grasp of the provisional character of scientific models.

The remaining fourteen students did not recognise the provisional status of models. Some considered all models valid without justification ($N = 5$), while others related model validity to precision without acknowledging tentativeness ($N = 2$), as illustrated by student A16's justification: *''I think they can be valid, although I see little use for a, b, and e due to their lack of precision*''. This response reflects an instrumental and static view of scientific models, centred on their precision and utility, but lacking a clear understanding of their provisional nature.

Other participants did not respond to the question ($n = 5$) or did not consider all models valid yet failed to justify their reasoning ($N = 2$), as illustrated by student A6's justification: *''No, because it [the atom] only has one form''*. This response reflects an absolutist view of scientific knowledge and suggests a confusion between the model and the real entity it represents.

It should be noted that these findings regarding tentativeness represent students' initial perceptions and were also examined at the end of the study (final activity, question 6). The results concerning students' final perceptions indicate an improvement in their conceptions, as ten out of 17 recognised the tentative nature of scientific models. One example is student *A13's response: ''No, because, surely, as time goes on, more and more things related to the models will be discovered, and they will have to create a new one based on this one''*.

Despite this improvement, a considerable number of students ($N = 6$) did not respond to the question, which may indicate persistent difficulties in understanding this epistemic aspect.

In relation to the explanatory power of models, the results summarised in Table 3 reveal a heterogeneous distribution of responses. Five students identified the explanatory power of the currently accepted model, demonstrating a basic understanding of the explanatory function of models in scientific knowledge. As an example, student A3 responded that ''*because the quantum mechanics model has the most evidence to explain all phenomena*''. This example reflects a perception that focuses on empirical adequacy and comprehensiveness of phenomena.

Additionally, one student explicitly referred to the empirical evidence that support the current model, indicating a limited appreciation of the role of empirical support in establishing explanatory power.

Table 3 Students' perceptions about the explanatory power of scientific models

Category	*N*
Identifies the explanatory power of the currently accepted model	5
Refers to the empirical evidence supporting the currently accepted model	1
Refers to the cumulative nature of the model in explaining phenomena	5
Refers to the absence of errors in the model	1
No response	5

Moreover, five students referred to the cumulative nature of scientific models, suggesting some awareness of the dynamic and evolving character of scientific knowledge, whereby models are refined and expanded to account for a wider range of phenomena. One example is student A5's response: ''*Because [the quantum mechanics model] is the last one and it incorporates all the previous theories''.* This response represents a hierarchical view of scientific models, interpreting the explanatory power as the ability to integrate earlier theories or data and adding a progressive dimension, in contrast to student A3's perception.

Furthermore, one student associated explanatory power with the absence of errors in the model, reflecting a naïve or absolutist view of scientific knowledge, perceiving science as a body of definitive truths rather than as a process of ongoing construction and revision.

Finally, a significant number of students ($N = 5$) did not provide a response to the question, which may be interpreted as a lack of understanding of the concept of explanatory power or as a difficulty in articulating it in epistemological terms.

Overall, the results suggest that, although some students recognised the explanatory and evolutionary nature of scientific models, their understanding remains partial and fragmented, with limited reference to the empirical and justificatory dimensions of scientific explanation. Rather than integrating multiple epistemic dimensions, such as explanatory scope and empirical support, students tended to rely on isolated criteria suggesting that their conceptions of the epistemic role of models in science remain only partially developed.

Students' performances in the epistemic practice of comparing models to identify common and distinct characteristics

In general, students' performances in this epistemic practice suggest considerable difficulty in engaging with the task, as

Table 4 Students' performances in identifying the phenomena explained by the atomic models

Subcategory	*N*
Relates all presented phenomena to the models that account for them and considers the cumulative explanatory power of the model	1
Identifies some phenomena that can be explained by each model and considers the cumulative explanatory power of the model	2
Identifies some phenomena that can be explained by each model, but does not consider the cumulative explanatory power of the model	5
Describes the characteristics of each model instead of the phenomena it explains	6
Confuses phenomena among models	2
No answer	1

reported in Table 4. Only one out of seventeen students successfully related all the phenomena to the corresponding explanatory models and identified the scientific evidence underpinning each model (reproduced in Fig. 4).

In Fig. 4, this student represented the cumulative explanatory power of atomic models, recognising that the quantum mechanics model explains all the phenomena discussed. The relevant evidence was also correctly associated with the corresponding model discoveries. This level of reasoning may indicate an integrated and hierarchical understanding of scientific models, in which each model is viewed not in isolation but as part of a progressive refinement of scientific explanation. This view was also shared by two other students, but they were not able to associate all the proposed phenomena with the corresponding atomic model. One example is student A14's classification, reproduced in Fig. 5, which illustrates a cumulative but incomplete understanding of the explanatory power of models, as well as difficulties in relating all the evidence supporting the interpretation of the associated phenomena, such as linking the discovery of the electron to the Thomson model or the discovery of the proton to the Rutherford's.

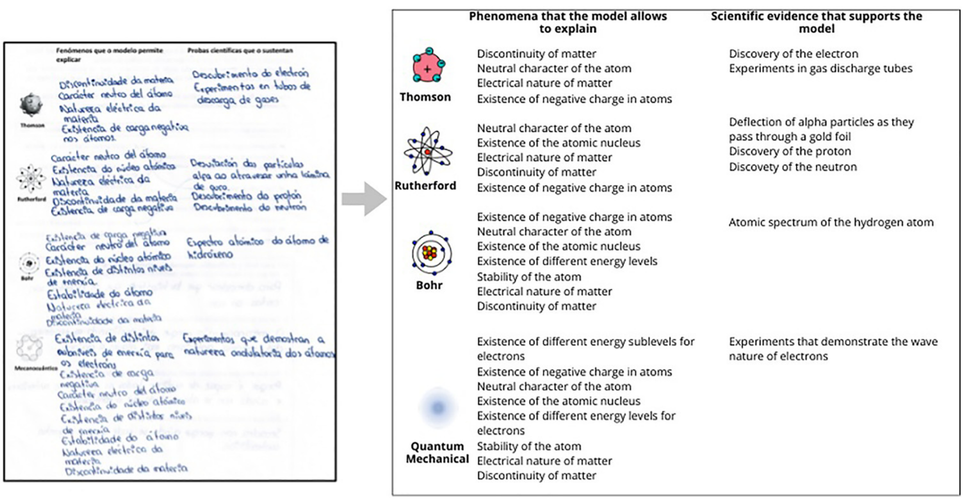

Fig. 4 Student's association of phenomena and evidence to each atomic model considering their cumulative scope.

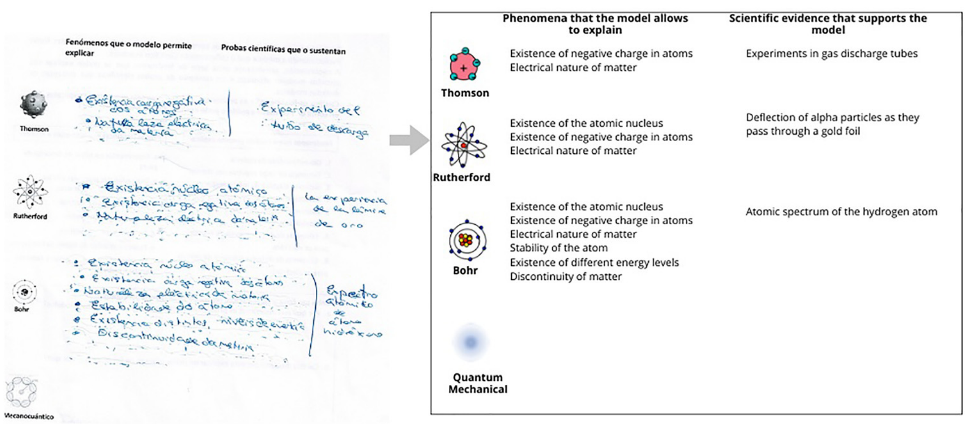

Fig. 5 Student's association of some phenomena and evidence to each atomic model considering their cumulative scope.

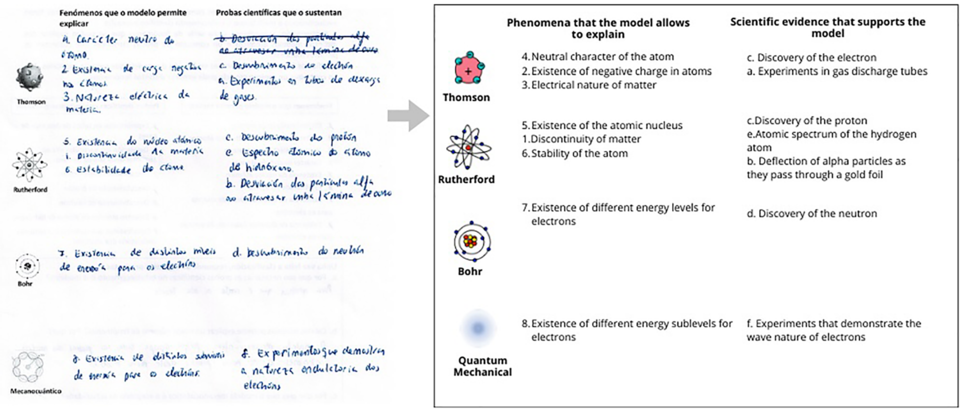

Fig. 6 Students' association of some phenomena with atomic models without considering the cumulative explanatory power of models.

In addition, five students correctly identified some phenomena explained by each model but failed to consider their cumulative explanatory scope, as illustrated by student A3's performance, reproduced in Fig. 6.

In contrast, the largest group (six students) instead of associating the proposed phenomena to models, merely described the characteristics of each model, which represents students' memorization of descriptive aspects of models rather than their understanding about their explanatory role. One example of this category is student A1's performance, reproduced in Fig. 7.

Of the remaining four students, two confused phenomena with evidence and *vice versa*, while the other did not answer the question, which may indicate the difficulty of the activity for them.

Concerning the identification of evidence supporting each model, although this was not an explicit research objective, only one student (A16) was able to identify all the evidence supporting each model, as reported in Fig. 4. In addition, half of the students were able to identify some pieces of evidence associated with each model, especially those related to Thomson and Rutherford models. In contrast, two students confused evidence across models, indicating difficulties in linking historical experiments to their corresponding models. Moreover, six students did not identify any evidence supporting the models, which may reflect a lack of understanding of atomic models or of the meaning of the evidence.

Discussion and conclusions

This study examined how secondary school students used disciplinary and social epistemic knowledge involved in the scientific practice of modelling in the context of atomic models. Although the study did not examine how students developed models, it addressed the epistemic knowledge involved in the practice of modelling which included other operations beyond model development, such as comparing models to identify common features and differences (NRC, 2013).

There is a huge number of studies that have been examined students' perceptions about models and modelling across grades by using standardised instruments such as SUMS (*e.g.* Treagust *et al.*, 2002; Liu, 2006; Chang and Chang, 2013; Park,

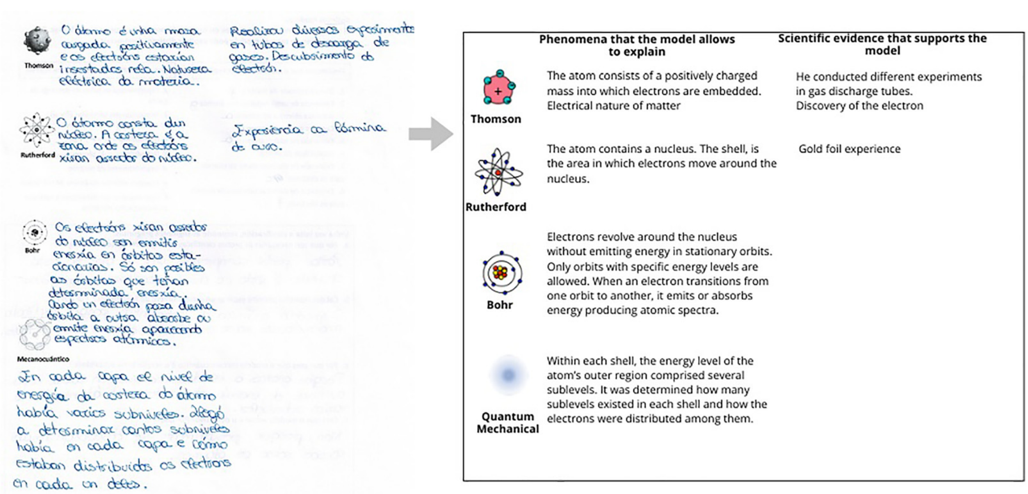

Fig. 7 Student description of each atomic model instead of associating them with the corresponding phenomena and evidence.

2013; Park *et al.*, 2017). However, in this study, student's epistemic ideas were examined in a natural school setting through an intervention about atomic models.

The first research question addressed students' use of disciplinary epistemic knowledge in terms of recognising the representative and tentative nature of scientific models as well as their explanatory power. The findings of this study suggest persistent challenges in students' use of disciplinary epistemic knowledge concerning the representativeness and tentativeness of scientific models as well as their explanatory function. Only the 35% appeared to recognise the representative function of atomic models, acknowledging that different models can be employed to represent the same phenomenon. Although some students were able to justify differences between models in terms of representational precision or the evolution of scientific knowledge, the majority tended to treat each model as a discrete and independent entity. This result aligns with findings from other studies such as Lateef's *et al.* (2026) who observed that students struggled to engage with the notion of scientific models due to their limited understanding of the epistemic nature of such models.

Moreover, some students also appeared to misinterpret models as depictions of different atoms, which is related to other naive ideas about modelling identified in studies such as considering models as toys or copies or scaled versions of reality (Grosslight *et al.*, 1991) or that multiple models of the same phenomenon could not exist (Schwarz and White, 2005).

Regarding students' perceptions about the tentative nature of scientific models, only a small number of participants showed awareness that models evolve in response to new knowledge, with one student explicitly recognising their historically situated and revisable character, an idea consistent with the provisional status of scientific knowledge according to Nature of Science (Lederman, 2007). Most students, however, did not recognise tentativeness of models, considering that all the provided examples representing the hydrogen atom were valid and not being able to explain why there are different models to represent the atom. Such responses may reflect absolutist conceptions of scientific models, where models were viewed as fixed depictions of reality rather than as interpretative constructs subject to refinement (Grosslight *et al.*, 1991; Schwarz and White, 2005).

Although students' conceptions improved by the end of the study, with the majority recognising that models may be replaced or modified as new discoveries emerge, a substantial proportion still provided no answer. This finding suggests that students' ideas about the tentativeness of scientific models may be context-dependent, since they may activate different epistemic resources depending on how the question is framed or what aspect of modelling is addressed. This aspect is in line with other studies that highlight the influence of context in modelling and meta-modelling practices (*e.g.* Schwarz *et al.*, 2016, 2022; Echeverri-Jimenez and Balabanoff, 2025).

Overall, the pattern suggests that while progress was made, the tentativeness of models remains a challenging epistemic dimension for many students.

In relation to students' perceptions of the explanatory power of models, some of them recognised key aspects, such as the importance of evidence or their evolving nature. These views align with previous research showing that high school students can begin to appreciate the developmental and explanatory roles of models, but this knowledge becomes more consistent in higher grades (Gogolin and Krüger, 2018). Nevertheless, the limited references to empirical evidence and the presence of absolutist reasoning suggest naïve conceptions of models, seen them as static or error-free representations (Grosslight *et al.*, 1991; Gilbert and Justi, 2016).

The second research objective examined students' ability to compare models to identify common and distinct characteristics (NRC, 2013) while relating scientific phenomena to the corresponding atomic models and recognising the scientific evidence that supports each of them. The main findings suggest that many students experienced difficulties in recognising the cumulative explanatory power of atomic models and in connecting scientific phenomena with the evidence supporting each model. While a small number appeared to demonstrate an integrated and hierarchical understanding aligned with more sophisticated forms of model-based reasoning, most students tended to focus on descriptive features, sometimes confusing evidence with phenomena, or did not provide a response.

Moreover, the high frequency of responses not associating empirical evidence to models (30%) may indicate limited confidence or awareness regarding how empirical evidence supports theoretical constructs. This finding highlights the need for pedagogical strategies that explicitly engage students in linking experimental data to model construction and evaluation, evidential support and the progressive refinement of scientific explanations.

Although an explicit comparison between students' disciplinary and social epistemic performances was not an aim of this study, it is important to note that some students who achieved the highest epistemic performance on the initial questionnaire were unable to apply this understanding in the final activity involving the classification of phenomena and evidence in relation of each atomic model. As an example, they did not take into account the explanatory power of models, as they did not recognise that the current model should be able to account for all the phenomena presented. Others focused on describing the characteristics of each model rather than classifying the provided phenomena and evidence or were not even able to carry out the classification task. These observations suggest that disciplinary epistemic knowledge about models should not be considered a robust indicator of students' epistemic understanding on its own, but rather should be examined in combination with its application in a specific context, that is, in its enactment, where the social perspective becomes relevant. This idea is supported by other studies such as Cheng and Lin's (2015), which combined theoretical and practical activities for investigating students' views and performances about models, identifying that not all the aspects addressed in the SUMS survey were positively correlated with students' developed models.

Overall, these results corresponding to the second objective, reinforce the importance of designing instruction that explicitly addresses discussions about epistemic ideas of modelling such as what counts as a model when engaging in modelling practices (Pluta *et al.*, 2011; Lazenby *et al.*, 2020). In addition, encouraging students to analyse the evidentiary reasoning that connects experiments, such as Thomson's cathode ray studies, Rutherford's scattering data, and Bohr's spectral analysis, to corresponding theoretical frameworks may help promote a deeper understanding of the nature of modelling and the empirical underpinnings of scientific knowledge. Furthermore, teaching interventions could incorporate tasks that explicitly encourage students to compare different models in terms of their explanatory scope, prompting them to consider which phenomena each model accounts for, which it does not, and the reasons for the development of subsequent models. Such approaches could foster a deeper understanding of the cumulative and revisable nature of scientific knowledge.

To sum up, the general findings of this study suggest that the use of epistemic knowledge remains a substantial challenge for students, particularly when engaging with abstract and conceptually complex topics such as atomic models. The analysed sequence demanded a high level of conceptual integration, especially in the final activity, where students were required to interpret multiple physical phenomena, associate them with the appropriate atomic models, and relate them to the scientific evidence that supports each. This level of reasoning presupposes an understanding of how scientific knowledge evolves and accumulates, perhaps too difficult for the students in this study (15–16 years old), since it was their first approach to atomic models, especially the Bohr and quantum mechanics models. In this context, it needs to be noted that the current chemistry curriculum in secondary education in Spain addresses epistemic knowledge mainly in terms of nature of science and scientific inquiry. Therefore, students are not expected to demonstrate a fully developed understanding of the nature of scientific modelling, but an emerging awareness of key aspects of the nature of models, such as their explanatory purpose and tentative character. In addition, the wide range of phenomena and content addressed in the atomic models unit might contribute to students' difficulties in appropriately applying scientific and epistemic knowledge when completing the final activity.

To foster improved outcomes in both the use of disciplinary epistemic knowledge and epistemic performance, it is proposed that instruction on atomic models should explicitly incorporate their historical development (Solbes, 2014). Additionally, the implementation of modelling-based activities that enable students to connect the underlying principles of each model, for example, the construction and application of simple atomic models derived from experimental data, as Talanquer (2020) proposes, could enhance conceptual understanding, aspect directly connected to epistemic knowledge development, as recognised in literature (*e.g.* Treagust *et al.*, 2002; Gobert and Pallant, 2004).

In short, the findings point to the importance of explicitly addressing epistemic knowledge in science classrooms. This involves exploring new instructional experiences and developing strategies to integrate this type of knowledge into chemistry lessons alongside content knowledge. Strengthening students' epistemic understanding is essential not only for improving their conceptual learning but also for fostering a deeper appreciation of how scientific knowledge is constructed and refined.

Implications for research and practice

The findings of this study have important implications for both research and classroom practice. From a research perspective, they highlight the need to examine students' epistemic understanding of models not only through self-reported views or isolated assessments, but also through their enactment in authentic modelling tasks. Future studies should therefore combine analyses of disciplinary epistemic knowledge with students' performance in context-specific modelling practices to better capture the complexity of epistemic reasoning. From a pedagogical perspective, the results indicate that instruction on atomic models should explicitly address key epistemic aspects of modelling, such as the representational, explanatory, and tentative nature of models, as well as the role of empirical evidence in model development. Designing learning activities that foreground model comparison, evidential reasoning, and the historical evolution of atomic models may support students in developing a more integrated and sophisticated understanding of scientific modelling.

Limitations

Several limitations should be acknowledged when interpreting the findings of this study. One of them is the small number of participants involved in the study, which does not enable the generalisation of results. However, this study was designed as a qualitative case study, where the primary aim was not statistical representativeness, but rather a detailed and contextualised exploration of students' epistemic engagement with scientific modelling. From this perspective, the findings provide analytically rich insights that may inform the design of future instructional interventions.

Moreover, the students' prior lack of familiarity with scientific modelling may have amplified some of the epistemic difficulties observed, meaning that the findings may not fully represent learners with more sustained exposure to modelling practices. Additionally, although qualitative content analysis enabled a detailed examination of students' written work, written responses alone may not fully capture students' reasoning processes; complementary data sources such as interviews or classroom observations could have provided a richer picture of their epistemic thinking. However, the results of this study provide an example of the difficulties that may encounter high school students when integrating disciplinary epistemic knowledge in abstract contexts such as atomic models and offers some insights of what needs to be consider from a design perspective prior to implement this type of activities in high school chemistry lessons.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data collected from human participants are not available for confidentiality reasons.

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