A SYSTEMATIC REVIEW OF THE EFFECTS OF MODELING IN SCIENCE EDUCATION

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ABSTRACT

This systematic review explores the role of modeling in science education, synthesizing findings from 31 research articles published between 2010 and 2022 and indexed in the Web of Science database. The selection process adhered to PRISMA guidelines, employing a comprehensive search strategy focused on modeling, science education, learning outcomes, and systems thinking. Thematic analysis of the selected studies revealed three principal dimensions: the direct impact of modeling on students' conceptual understanding and critical thinking; the socio-cultural factors influencing the effectiveness of modeling practices; and theoretical considerations regarding the integration of modeling into science curricula. Results indicate that modeling significantly enhances students' academic performance, promotes deeper engagement with scientific concepts, and fosters higher-order cognitive skills. Moreover, cultural and social contexts were found to play a vital role in shaping the success of modeling-based learning. These findings align with the broader educational reforms in Europe, emphasizing competency-based and active learning approaches.

Keywords: Model-based learning, systematic review, systems thinking, educational modeling, modeling strategies.

INTRODUCTION

To make challenging themes more understandable, educators commonly use models that illustrate how different parts are related and work together (Aseeva, 2021; Schwarz and Gwekwerere, 2007). To support the understanding of the cellular structure, instructors often use models such as animations or visual diagrams, allowing students to form clearer mental images. These tools also promote active participation, helping students become more immersed in the subject (Huber and Moore, 2001; Kolchin et al., 2022). The use of physical tools such as clay molecule models or representations on atom paper during chemistry instruction improves the students' understanding by involving them in active learning based on movement instead of passive reading only (Hofstein and Lunetta 2004).

Modeling usually begins with the construction of visual representations that represent certain characteristics of natural events or systems in fields such as biology. The diagrams are commonly used to help students see how the pieces relate and operate together, offering a clearer perspective than written descriptions alone. When improved with interactive tools such as animations, these models can significantly increase understanding by providing a deeper vision of the phenomenon studied.

Frederiksen et al. (1999) define modeling as the construction of mental models based on physical or theoretical systems to interpret better complex phenomena. They also argue that this strategy plays an important role in improving critical thinking and the transfer of knowledge of students within scientific education environments.

Ananishnev (2010) emphasizes that modeling allows researchers to replicate the object of study in their full form, including its structure and operations, and ensures that this coherence is preserved during all phases of the investigation. In addition, it points out that the significant measurement of the object characteristics depends on how the variables are embedded within a model that represents the object as a system.

López-Vargas et al. (2017) claimed that a model should not be known only as an instructional task but as a challenging human mental activity which contains such elements as conceptualization, representation, and simulation. This position echoes previous statements about the importance of modeling in learning environments, mostly in science disciplines like physics and chemistry. Furthermore, they discovered that these innovative teaching methods were powerful to awaken students' awareness of the learning process through direct interaction with materials, as opposed to just sitting and listening, which brings them higher levels of motivation. It has been a concept discussed in numerous studies in Russia, beginning with the work of López-Vargas et al. (2017). Chorosova et al. (2015), for instance, adopted cognitive modeling in identifying and evaluating teachers' digital competence. Their competency map is intended for developing innovative cognitive models and algorithms for the overall evaluation of teachers' digital skills. Likewise, Gilemkhanova et al. (2022) built a model of teachers' subjective well-being, taking into consideration socio-cultural expectations and risks pertaining to the teaching profession. In yet another study, Kasprzhak et al. (2022) researched and identified different models of instructional leadership.

Modeling sums up as an essential part of science education that allows students to envision abstract ideas and makes it more participative and engaging through interactivity and hands-on learning experiences. As Li et al. (2019) present, this instructional approach does well, aside from making it possible for students to understand; it also motivates and makes them have interest in STEM subjects.

Literature review

Battaglia et al. (2017) describe two different methods for analyzing clusters, associated variables, and parameters that should clarify what underlying information each method can produce. Overall, their clustering results from both methods are found to be strongly corresponding.

Pierson et al. (2020) further established that the social interaction patterns with which students originally came typically worked well as resources that enabled engagement with computational tools flexibly. Their findings show students presented participatory roles in computational models in three differentiated ways:

-as conversational peers,
-as co-producers of inquisitive pathways,
-as proffers of their empowerment and personal identity.

Furthermore, the students demonstrated flexibility in their approaches toward computational participants rather than rigidity.

According to Schademan (2015), it has been found that spades players consistently weigh in other variables and their mathematical relationships in their strategic decision making. The players predict their bids, which include the strength of their cards, the quantity of cards in each suit, individual bidding behaviors, the skill levels of participants, the game's current score, and the degree of trust in their partner.

Southern et al. (2016) posited that including science teachers in Research Experiences for Teachers (RET) programs undeniably impacted the manner and the beliefs with which these teachers taught. RET was made such that teachers would undergo experiences of real research environments and participate in coursework where the subject matter is personally relevant.

Despite all differences in academic background and the fact that the students had never programmed before, all the students got equal instructional hours, including the hours for programming learning. Wagh and Wilensky (2018) found that the students enrolled in EvoBuild had a more profound knowledge of the mechanisms of evolution than their peers.

Research works relevant to this study were done by Rates et al. (2022), who indicate that findings were from taking the actions and cognitive responses of the students under ontological conditions and tracking their pre-test and post-test progress. Despite progress in the understanding of causality, it seems to have come at the expense of understanding more about the consequences of actions. Besides, students in the ontology condition improved more than those in the self-monitoring conditions on the first and final assessments, and their more advanced understandings of sequence and structure are compared to those in the self-monitoring condition.

What Fuchs (2015) describes is that the figurative conceptual framework that came to being binds natural agents to both actors and recipients within the narrative worlds. The study draws parallels between modeling risks, simulations, and storytelling, suggesting essentially that these formal scientific models are narrative ones. This narrative relationship has found recent attention in research areas concerned with computational science and economics-related storytelling.

In their research, Bo et al. (2018) discovered that previous experiences for teachers in using simulation have mostly encompassed employing them as demonstration tools in teacher-centered instruction. Efforts to move toward student-centered usage of the simulation, where students would explore on their own, have not turned out so successfully.

According to Mierdel and Bogner (2019), model quality scores did not correlate with cognitive achievement in assessing students' creativity, while certain outcomes demonstrated a gender-specific pattern. Girls achieved far better in scores of model quality, where positive correlations could be traced for their short-term and medium-term retention of knowledge. Further, a noteworthy correlation was observed between the cognitive performance of girls and flow creativity. On the contrary, for boys, cognitive achievement did not seem to be influenced by either model quality or creativity. Both the girls and the boys tended to do similarly on average in basic modeling tasks, though those ratings did not correlate with knowledge retention over time.

As an example to showcase their suggested analytical framework, Danish and Enyedy (2015) conducted a case study that comprised six kindergarteners and freshmen who participated in a sort of improvised debate organized around three main questions: what is being negotiated, who or what serves as leverage in the negotiation, and how are actors positioned within emerging networks.

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Dikces and Sengupta (2013) sought to study how students construed key events or elements within a given phenomenon in the beginning, how these interpretations were eventually layered into multi-level explanations, and how engaging different layers of the phenomenon allowed students to see the underlying mechanisms. Their analysis further indicates that while high- and low-achieving students were different in their explanations of population-level behaviors at the beginning, this difference was not evident anymore by the last assessment.

Assessment outcomes indicate that substantial changes in both knowledge structure and content occurred across students between the two years of their investigation. There is some limited evidence that prior knowledge may have affected the extent of conceptual change. The results of Zitek et al. (2013) support the conclusion that DynaLearn is effective in the promotion of a causal and interlinked understanding of environmental systems.

According to Samon and Levy (2017), concepts oppressed by low 'micro-macro compatibility' are best learned with a complexity approach. It helps in differentiating the micro behavioral patterns before macros it under pattern when they do not match directly.

Meanwhile, Louca and Zacharia (2012) reviewed model-based learning (MBL) for contributions to science education. The advantages were cognitive, metacognitive, social, material, and epistemological. They also established that some key information is still missing; problems posed in the effective implementation of MBL in educational venues.

Inquiry-based teaching has been associated with better student achievement. However, Teig et al. (2018) found that more frequent inquiry activities might negatively correlate with performance. It was also found that SES did not moderate the relationship between inquiry-based instruction and student success.

As stated by Saba et al. (2021), engaging students in the construction of models under the Much Matter in Motion (MMM) approach has fostered considerably greater conceptual flow and systems thinking through quantitative questionnaire analysis, compared to their peers undergoing a traditional curriculum. In addition, worksheet responses indicated a symbiotic evolution of modeling practices with the furtherance of conceptual knowledge and systemic thinking skills.

Rates et al. (2016) studied how 32 high-school students conceived aspects of complex systems and whether engagement in an agent-based simulation could improve such an understanding. Changes in the students' reasoning were assessed using pre- and post-test responses coded with respect to six core components, and aimed to gauge whether students had more sophisticated reasoning about the Chesapeake Bay watershed. The findings indicated clear improvement across these dimensions.

The critical review conducted by Clark and Sengupta (2020) comprised a comprehensive examination of the broader research literature with respect to the role of scientific modeling in the making of discipline-integrated games for informational reasoning and practice.

For illustration, Schademan (2015), on his part, posed the question: What do playing cards have in common with science? In A Resource-rich Look at African American Young Men, he associated this question with how hybridization and resources can be used to develop a science education framework that counters deficit narratives often applied to this demographic. Continuing Schademan's thought, Gonsalves et al. (2011) further expanded on definitionraising "hybridism" and its argument for use in science classrooms, drawing attention to the nuances related to how the resources of students are identified and utilized within educational settings.

Lucas and Lewis (2019) studied the effectiveness of problem-solving tasks encouraging the generation of multiple representations as scaffolding in a high school physics modeling course. They conducted cognitive interviews to analyze students' responses to these tasks. Also, they compared the problem-solving performance and use of representations of students who received the full structured scaffolding for the use of representations during the same task with those who had not received specific guidance in the construction of representations during similar activities.

General knowledge in kindergarten turned out to be the most vital predictor of students' general knowledge in first grade, which was the most significant predictor of science achievement from third to eighth grade (Morgan et al., 2016). Assessments of science performance first began in third grade, by which time glaring contrasts in achievement were already being observed and persisted thereat least through eighth grade. Most, if not all, of these differences in science achievement can be explained by the varying predictors included in the study.

According to Hand et al. (2018), it was found that the argumentation-based instruction was not an effective teaching strategy, in that it failed to significantly enhance students' science content knowledge; however, it did significantly increase the students' scores in critical thinking.

Sackes et al. (2013) found that both precursor variables, including gender and socioeconomic status, and trend variables like ability and motivation, predicted children's science achievement. Nevertheless, access to science learning experiences in kindergarten did not have a significant impact on students' growth in science performance between the third and eighth grades.

According to Alt (2018), while using formative assessments less often as summative assessments, students adopted them for their learning processes at various levels. Those educators who had embraced constructivist teaching approaches using collaborative techniques also reported increased use of formative assessment. Unexpectedly, the model of the study did not indicate such a clear and negative effect between teachers' traditional views about teaching and learning and their propensity to embrace constructivist practices in the classroom.

The correlation analysis between scores of model assessment and cognitive achievement showed a variable relationship ranging from small to moderate (Roth et al., 2020). The results suggested that the phases of assessment had a positive effect on students' general cognitive performance as well as their model-specific understanding, thus affirming the effectiveness of the module itself in bringing real practice of science into science education. Although it would involve an increase in workload for the science teachers, scientific modeling deserves the additional effort as an inquiry-based learning strategy.

The research by Or-Bach and Bredeweg (2013) was designed to inform the refinement and advancement of support strategies and provide guidance for effective instruction on the DynaLearn platform. Conversely, the study offered rich insights on how novice modelers engage with modeling tasks, what kind of support they need, how they make use of different forms of support, and what kinds of instructional interventions may further benefit their learning.

According to Demir and Namdar (2021), students did not use emotional reasoning patterns in the post-interview stage. Their informal reasoning remained underdeveloped, and they incorporated references to modeling activities across different components of their reasoning processes.

Lucas (2021) states that the activity requires students that aren't from science streams in a university general education biology class to use Tinkercad website to create and illustrate their constructions about the relationships between the basic dogma of molecular biology with DNA, RNA, and protein and relate it to cellular processes for the whole class.

At the same time, Kamaleeva (2010) argues that modeling can serve as an efficient didactic tool for promoting self-directed learning in science for students from the humanities. Similarly, Ignatova and Ignatov (2017) propose that cognitive models derived from post-non-classical science ought to form the basis for a comprehensive framework of science education.

In a study by Fulmer (2015), it was established that the Force Concept Inventory (FCI) items showed a moderate fit between data and the underlying model, reflecting the anticipated difficulty trend across progressing learning stages. However, the study also threw light upon the limitations in scale reliability and the consistency of thresholds among levels. Curiously, students rated their understanding of Newton's third law higher than their understanding of force and motion, which contradicts the expected correlation between these two fundamental aspects of force.

Jones and Hite (2020) found that although there were no significant differences across schools or between genders in students' perceptions of scientist role models, there was some generalization among the participants regarding scientists in a sense that they saw them as people whose goals were oriented towards intelligence and were viewed as unattainable and not particularly rewarding.

Methodologies

The earlier stages of the study involve a systematic review aimed at investigating the roles and effects of modeling in science education. The literature review was performed through the WoS database, an authority on peer-reviewed, high-impact academic publications in educational and scientific fields. The specified keywords and the above combination are used for the WoS database: ("modeling" or "modelling") and ("science education" or "chemical education" or "biological education" or "physical education").

Following the initial database search, a total of 97 articles were identified. After removing duplicates and irrelevant studies, 67 articles remained for screening. Titles and abstracts were reviewed to assess relevance to the research focus. A further 36 articles were excluded based on full-text evaluation against the inclusion criteria. Ultimately, 31 studies met the eligibility criteria and were included in the systematic review.

The selection process adhered to the PRISMA guidelines. A PRISMA diagram (see Figure 1) illustrates the selection and screening process.

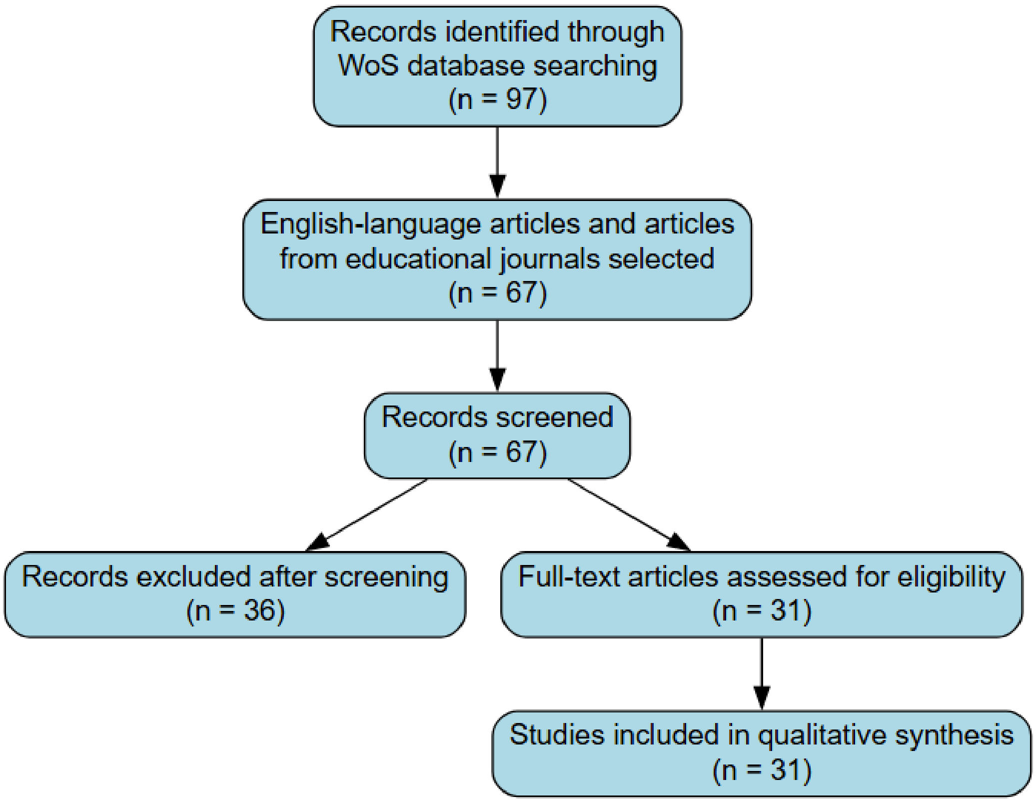

Figure 1. The selection process of articles is depicted using a PRISMA flow diagram.

The articles published between 2010 and 2022 were selected, indexed on the (WoS) and appeared in educational journals reviewed by peers. The inclusion criteria require that articles are written in English, focus specifically on scientific education modeling. The studies were excluded if they were conference summaries, non-empirical reviews, or if they concentrated only on theoretical modeling in professional scientific contexts without addressing educational results. For analysis, a qualitative content analysis approach was used. The selected studies were examined to extract key dimensions, including the type of modeling used (for example, physical models, simulations, mental models, computer-based modeling), the subject's domain (for example, chemistry, physics, biology), the educational levels of primary and secondary education, undergraduate and teacher education, the measured learning outcomes (for example, conceptual understanding, systemic thinking, motivation, and research skills), and the research design (quantitative and qualitative methods). The articles were grouped thematically according to these dimensions to identify common findings, underlying theoretical frameworks, and methodological patterns in the selected literature body.

The selected articles were analyzed using a qualitative thematic analysis, intended to identify recurring patterns, trends, and gaps in the literature. Based on the content and approach of the articles, three main thematic categories were established:

1. Modeling effects on scientific education in specific learning variables (for example, conceptual understanding, systems thinking, research skills, motivation)
2. Cultural and social perspectives on modeling in scientific education (for example, how sociocultural factors influence students' commitment to modeling)
3. Review and theoretical studies on modeling in scientific education (for example, models based on models, epistemological contributions of modeling)

Combinations of words and phrases derived from the set of defined keywords were used to guarantee comprehensive coverage. The distribution of articles published through years showed fluctuation, with a notable increase in the publications observed in 2022, indicating a growing interest in the subject.

MAJOR DISCOVERIES

Modeling effects on scientific education in specific learning variables

Most research has focused on how modeling in scientific education influences cognitive dimensions, including academic performance, conceptual understanding, instructional practices, critical thinking, and problem-solving skills. In addition, some studies have explored the affective aspects of modeling, such as their impact on the perceptions and social interactions of the students. Several studies within the revised literature proposed specific models aimed at improving scientific education and investigated their effectiveness in teaching practices. For example, Lucas (2021) developed a 3D modeling approach for the instruction of molecular biology at the university level and evaluated its impact on the teaching results. Similarly, Or-Bach and Bredweg (2013) introduced the DynaLearn model, which was examined for its role in promoting effective learning environments and supporting instruction strategies. In addition, Fulmer (2015) investigated the influence of modeling on the conceptual understanding of students in scientific education, providing additional evidence of their pedagogical value. Similarly, several studies have provided deeper information about the role of modeling in scientific education in several contexts. Battaglia et al. (2017) explored how the different conceptions of modeling students in physics are related to each other. In another example, Demir and Namdar (2021) examined how modeling activities influenced the informal reasoning of fifth-grade students on real-life scenarios. Similarly, the rates et al. (2016) reported that agent-based simulations improved the understanding of high school students of the complex system components. In addition, Wagh and Wilensky (2018) found that the students involved with the EvoBuild modeling environment demonstrated a stronger understanding of the evolutionary mechanisms. Supporting these findings, Saba et al. (2021) identified a parallel between the development of students' modeling skills and improvements both in conceptual understanding and systems thinking. In addition, the analysis by Samon and Levy (2017) indicated that the concepts with "micro-macro-compatible" are acquired more effectively through the use of complex systems models, which supports the value of approaches based on complexity in the learning of science. In this context, it has been shown that the DynaLearn's interactive environment facilitates learning by involving students in the construction of conceptual models that represent system behaviors. According to Zitek et al. (2013), the results confirm the effectiveness of DynaLearn in the promotion of a causal and integrated understanding of ecological systems. In a related effort, Dickes and Senguta (2013) introduced computational models of multiple agents aimed at helping fourth grade students understand the concept of natural selection. In contrast, Mierdel and Bogner (2019) did not find a clear correlation between the quality of the model and cognitive performance in the evaluation of the creativity of the students, although their results revealed differences based on gender in other learning results. Another group of studies focused on the development and evaluation of alternative learning models in scientific education. For example, Roth et al. (2020) emphasized the potential of scientific modeling as an effective strategy for research-based learning. Similarly, Alt (2018) proposed a model that incorporated training tasks as a component of the learning process. In addition, Hand et al. (2018) examined the influence of an instructional model based on arguments on the scientific learning of primary students and their development of critical thinking skills. In addition, Morgan et al. (2016) stressed that multilevel growth models served as the most reliable predictors of general knowledge both in the first degree scientific achievement and in the long term of grades three to eight.

Furthermore, Lucas and Lewis (2019) highlighted the effectiveness of incorporating problem-solving tasks that promote multiple representations such as a scaffolding technique in a secondary school physics modeling course. In a separate study, Bo et al. (2018) found that the previous experiences of the teachers with simulations revealed a tendency to use them mainly for demonstration purposes within the teacher-centered instruction. In contrast, Teig et al. (2018) reported that although the research-based learning model had a positive correlation with student performance, a greater frequency of exploratory activities was actually linked to lower performance. In addition, the rates et al. (2022) compared ontological and self-control approaches with a participatory simulation based on agents, with the aim of improving the understanding of undergraduate students of complex systems.

Finally, Sackes et al. (2013) developed a model that illustrates the connection between early learning experiences and subsequent academic performance in science, using the opportunity and the propensity framework. This model was evaluated through the modeling of the latent growth curve. The results indicated that both the underlying factors, as the gender and the socioeconomic status (SES), and the predisposition factors, such as the skill and motivation, served as significant predictors of the academic success of the students in science.

Cultural and social perspectives on modeling in scientific education

Some studies in the literature have focused on the social and cultural aspects of modeling within scientific education. For example, Danish and Enyedy (2015) proposed that actor-network theory offers a valuable analytical framework to explore the social interactions of students in science classrooms. Similarly, Pierson et al. (2020) showed that existing social interaction patterns can serve as resources to participate flexibly with computational tools as active participants in the learning process. In another research, Lauca and Zacharia (2012) examined the social and epistemological contributions of models-based learning (MBL) to scientific education. In similar lines, Southerland et al. (2016) found that the participation of teachers in research experiences influenced both their instructional practices and professional beliefs. Schademan (2015) emphasized even more that modeling in scientific education can establish significant connections with the cultural practices of African-American communities. Although Jones and Hite (2020) did not observe statistically significant differences in the perceptions of the students or representations of scientific models to continue based on school or gender, their findings showed that the students generally perceived scientists who were looking for intellectual objectives that seemed difficult to achieve and saw themselves as low desirability. In contrast, Teig et al. (2018) found that the socioeconomic state of students had no impact on the strength of the relationship between research based on academic and performance.

Review and theoretical studies on modeling in scientific education

A review of the literature on the scientific education model reveals that some studies take the form of theoretical or conceptual analysis. For example, Gonsalves et al. (2011) reviewed the work of Schademan (2015) entitled "What do the letters with science have to do? A look rich in resources to young African Americans", in which two central concepts, hybridism and resources are explored. The study proposes an alternative approach to scientific education that defies the prevailing narratives based on the deficit that surrounds this demographic group by analyzing how these concepts are applied in educational contexts. In another research based on the review, Clark and Senguta (2020) conducted a critical analysis of a wide range of research articles to evaluate the potential to integrate modeling in games based on the curriculum, particularly from the perspectives of computational thinking and science as a practice. In addition, Fuchs (2015) established a connection between modeling, particularly through simulation, and story narration, arguing that formal scientific models are closely intertwined with narrative structures that are often found in these worlds of stories.

Discussion, conclusion, and implications

The purpose of this systematic review is to synthesize findings and provide conclusions highlighting the importance and influence of modeling in science education over the journal from 2011 to 2022.

The review reveals that incorporating models into instruction relation to complex and abstract scientific concepts and processes (Battaglia et al., 2017; Dickes and Senguta, 2013; Samon and Levy, 2017; Wagh and Wilensky, 2018). However, in contrast to these positive results, Mierdel and Bogner (2019) reported that modeling did not have a positive or negative impact on cognitive performance, which it suggests that its effectiveness can vary according to the context or other influential factors. The research has specifically highlighted that students tend to understand certain issues more effectively when the concepts are visually presented, as through diagrams or tangible objects such as blocks or balls that symbolize molecules and atoms. In addition, several studies have shown that the use of models during instruction not only supports the acquisition of immediate knowledge but also contributes to better long-term retention compared to traditional teaching methods that depend solely on conferences and reading materials without visual aids (Demir and Namdar, 2021; Fulmer, 2015; Lucas, 2021; Or-Bach and Brewegg, 2013; Rates et al., 2016). Several studies in literature explore how applied learning models in scientific education influence cognitive and affective dimensions. Most of these studies indicate that such models have a positive impact on students' cognitive skills, as well as their emotional and motivational commitment on the learning process (Alt, 2018; Bo et al., 2018; Hand et al., 2018; Lucas and Lewis, 2019; Morgan et al., 2016; Rates et al., 2022; Roth et al., 2020; Sackes et al., 2013; Teig et al., 2018). The majority of literature studies have shown that the integration of models into scientific education has yields positive results for educational stakeholders, particularly in relation to social and cultural dimensions (Danish and Enyedy, 2015; Jones and Hite, 2020; Louca and Zacharia, 2012; Pierson et al., 2020; Schademan, 2015; Southerland et al., 2016; Teig et al., 2018).

A series of review and theoretical studies carried out between 2011 and 2022 on modeling in scientific education have reported findings consisting of those of this review. For example, Clark and Senguta (2020) examined the integration of modeling in curricular games through computational thinking lenses and science frames as a practice. Similarly, Fuchs (2015), in his review study, demonstrated a strong connection between formal scientific models and narrative structures called worlds in history. In addition, Gonsalves et al. (2011) analyzed two fundamental philosophical approaches, hybridism and resource-based learning, to propose an alternative model for scientific education, reviewing literature on the hybridization of educational resources.

Given the findings, educators are strongly recommended to incorporate modeling approaches into the planning of their lessons as long as appropriate opportunities arise, since it has been shown that the modeling improves the understanding of students in a wide range of scientific disciplines. In addition, teachers must take into account that the effectiveness of the different types of representations of models, such as physical models versus visual diagrams, varies according to the nature of the concept taught. Selecting the most appropriate way of representation for each topic can lead to more effective instruction. In conclusion, the implementation of model-based learning strategies (MBL) presents a valuable opportunity to improve educational results in science classrooms. Therefore, its continuous use and additional research are justified, considering the growing body of evidence that supports its positive impact.

Importantly, findings emphasize that modeling is not merely a supplementary instructional tool, but rather an essential component of inquiry-based and constructivist learning approaches. The positive impact of modeling was consistent across diverse geographical regions, suggesting its universal pedagogical value. However, special attention must be given to the socio-cultural context in which modeling practices are implemented, as cultural factors significantly mediate their effectiveness. Considering the broader European educational landscape, where competency-based and active learning approaches are increasingly prioritized, modeling-based learning aligns closely with current educational reforms. Thus, the integration of various types of modeling into science curricula across Europe and beyond holds considerable promise for improving both cognitive and motivational learning outcomes. Future research should continue to explore how different types of modeling (e.g., computational, conceptual, and physical modeling) can be effectively adapted to varied educational contexts and how teacher training programs can be better prepare educators to implement model-based instruction.

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