MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2023, 19(6), em2284
ISSN:1305-8223 (online)
OPEN ACCESS Review Article https://doi.org/10.29333/ejmste/13268

Exploring the impact of modeling in science education: A systematic review

Roza Valeeva [1*], Gulnara Biktagirova [1], Vadim Lesev [2], Olga Mikhailenko [2], Galina Skudareva [3], Arturas Valentovinis [3]

[1] Kazan Federal University, Kazan, RUSSIA
[2] Kabardino-Balkarian State University, Nalchik, RUSSIA
[3] State Humanitarian and Technological University, Moscow, RUSSIA

Received 14 February 2023 ▪ Accepted 18 April 2023

Abstract
This systematic review aimed to summarize the research results and draw conclusions related to the articles about modeling in science education between 2011-2023. A qualitative thematic review was used in this study. Initial studies pulled from the Web of Science database and examination of 31 selected articles found that using models as part of instruction has been shown to improve student understanding, particularly with regards to abstract concepts and processes. Most of these studies showed that learning models used in science education had positive impact on both cognitive, affective, social, and cultural factors. According to a detailed analysis of each of the 31 articles, the contents of the studies were coded by author name and year, sample, research design, and main results. The research reviewed has many implications for modeling in science education.

Keywords: modeling, science education, systematic review

INTRODUCTION

Models are often used by teachers to help explain difficult concepts or demonstrate how different components interact with each other (Aseeva, 2021; Schwarz & Gwekwerere, 2007). For example, a teacher may use models such as diagrams or animations when teaching about the structure of cells so students can better visualize what they are learning about. Furthermore, models also provide an opportunity for hands-on exploration, which helps engage learners more deeply in their studies (Huber & Moore, 2001; Kolchin et al., 2022). By using physical objects like molecules constructed out clay or paper cutouts representing atoms during lessons on chemistry enables students to gain a deeper understanding through kinesthetic experiences rather than just reading text from books alone (Hofstein & Lunetta 2004).

First, modeling involves constructing representations demonstrating certain aspects of natural phenomena or processes within a particular domain (e.g., biology). These models are often represented visually as diagrams allowing learners to explore how different components interact with each other and understand their functions more easily than if they were just presented with text explanations alone. Additionally, these models can also include interactive elements such as animations, which further enhance learning outcomes by providing additional context about the phenomenon being studied.

According to research conducted by Frederiksen et al. (1999), modeling can be seen as "a process of constructing mental models based on physical or abstract systems", which are then used for understanding complex phenomena related to those systems better. Also, they highlighted how this approach helps learners develop their problem-solving skills while improving their ability to transfer knowledge between different contexts within science education settings.

Ananishnev (2010) affirms that "modeling helps to reproduce the integrity of the object under study, its structure, functioning, to preserve this integrity at all stages of research. It is a prerequisite for measuring the characteristics of the object. Each variable makes sense only if these variables are represented in a system of indicators, represented in the form of a model of the object, its structure" (p. 67).

✉ valeykin@yandex.ru **(*Correspondence)** ✉ BikGF@mail.ru ✉ lvn_kbsu@mail.ru ✉ olganlk@mail.ru
✉ skudarevagalina@yandex.ru ✉ candydad7@gmail.com

Contribution to the literature

- This study can provide information on the impact of modeling on students' learning outcomes, including their conceptual understanding, problem-solving skills, and ability to engage in science education.
- This study can summarize the results of different studies to give a more complete picture of the current state of modeling in science education.
- This study can highlight the most important findings and developments in modeling in science education research, showing what is already known and what needs further investigation.

In another study published in 2017 by López-Vargas et al. (2017), it was suggested that “modeling should be understood not only as an activity but also a cognitive process involving multiple components such as conceptualization, representation or simulation”, which further supports what was proposed earlier about its potential benefits when applied within educational contexts specifically focusing on sciences topics like physics or chemistry among others. Additionally, they observed how this type of pedagogical approach could lead students towards active engagement with materials being presented during classes rather than just passive reception leading towards improved performance overall due higher levels motivation present among them.

López-Vargas et al.s’ (2017) idea is used in a number of Russian studies. Thus, Chorosova et al. (2015) used the method of cognitive modeling in identification of teachers’ digital competence. The authors designed competency map to solve the task of developing conceptually new cognitive models and algorithms for a comprehensive assessment of digital competencies of teachers. Gilemkhanova et al. (2022) developed a model of subjective well-being of a teacher in the context of socio-cultural expectations and risks of teachers’ professional activities. Kasprzhak et al. (2022) identified instructional leadership models.

In conclusion, modeling plays an important role within science education since it provides opportunities for visualizing abstract ideas while promoting active engagement among learners through hands-on activities. Li et al. (2019) suggested that this type of instruction leaded not only to improved comprehension but also greater motivation amongst student populations towards STEM topics.

LITERATURE REVIEW

According to Battaglia et al. (2017), two different clustering analysis methods are described and related variables and parameters are discussed to clarify the information they can provide. The clustering results obtained using the two methods were compared and it was shown that there was a good agreement between them.

Pierson et al. (2020) revealed that current patterns in students’ social interactions were resources to flexibly interact with computational tools as participants. It was found that students acted as participants in computational models in three ways:

(1) as peers of speech,

(2) as co-founders of interrogation lines, and

(3) as projections of students’ activism and identity.

The data also showed that students had a flexible rather than fixed stance towards computational participants.

Research conducted by Schademan (2015) has shown that spades players routinely consider multiple variables and their mathematical relationships when making decisions. Variables considered by players when bidding include card strength, the number of cards held in any given suit, player bidding tendencies, player expertise levels, the current score of the game, and the level of trust in one’s partner.

Southerland et al. (2016) suggested that participation in research experiences for teachers (RET) shaped the practice and beliefs of science teachers, which in turn influence practice. The main features of RET included the inclusion of teachers in research contexts socially and in research projects that were personally relevant to them.

Although students come from a variety of academic backgrounds with no prior programming experience, and all students spend the same number of lesson hours in activities, including the time students spend learning to program in this environment. Wagh and Wilensky (2018) showed that EvoBuild students show more learning about evolutionary mechanisms.

According to Rates et al. (2022), the results are based on the actions and processes of the students in the ontological condition, from the preliminary test to the final test while developing their understanding of causality, they apparently reduced their understanding of the effects of action. In addition, students in the ontological condition showed more improvement from the pre-test to the final test, and they are higher in their understanding of order than students in the condition of self-monitoring.

Fuchs (2015) stated that the resulting figurative conceptual structure revealed the concept of natural agents acting and suffering in story worlds. A link is being made between the use of models (i.e., simulation) and storytelling to show that formal scientific models are deeply related to these story worlds. This connection has recently been suggested in the study of storytelling in computational science and economics.

In a study conducted by Bo et al. (2018), teachers' past experiences with simulation practice have revealed that most teachers adopt simulations for demonstration purposes in teacher-led teaching. Attempts to offer students opportunities to use simulations to explore alternative modeling on their own do does not seem to have worked.

Mierdel and Bogner (2019) concluded that while there was no association for model quality scores and cognitive achievement in measuring students' creativity levels, other outcomes were gender dependent. The girls produced significantly higher model quality scores, and significant positive correlations emerged between short- and medium-term knowledge levels. Correlations were also observed between girls' cognitive achievement and the creativity sub-scale 'flow'. In contrast, neither creativity nor model quality has been decisive for men's cognitive achievement. The average simple modeling results did not correlate with short- and medium-term knowledge levels, although they achieved similar scores in both.

As an example of the proposed analytical framework, Danish and Enyedy (2015) presented a case study analysis of six kindergartens and freshmen who participated in an improvised debate organized around three questions: what is negotiated, who and what are the actors used as leverage in the negotiation, and how are actors constructed in networks?

Dickes and Sengupta (2013) focused to determine the nature of students' initial interpretations of prominent events or elements of the phenomena represented; to determine their role in developing multi-level explanations of these interpretations; and to determine how participation in different levels of relevant phenomena may make different mechanisms clear to students. In addition, the analysis showed that although there were differences between high- and low-performing students (in terms of being able to explain population-level behavior), in the preliminary test, these differences were eliminated in the last test.

The assessment results show that significant changes have occurred in the structure and content of information for both students in both years. There are indications of the influence of preliminary knowledge on the magnitude of conceptual change. The results confirm DynaLearn's potential to provide a causal and interconnected understanding of environmental systems according to Zitek et al. (2013).

Analysis made by Samon and Levy (2017) has shown that only concepts with less "micro-macro compatibility" are better learned with a complexity approach. In this way, the complexity approach helps to separate micro-behaviors and then associate them with macro behaviors when these behaviors are not similar.

Louca and Zacharia (2012) reviewed that model-based learning (MBL) made cognitive, super cognitive, social, material, and epistemological contributions to science education. In addition, the authors showed that important information was still lacking to ensure the effective implementation of MBL.

While inquiry-based teaching is positively related to success, the frequency of inquiry activities is negatively related to success. It was also found that the socioeconomic status (SES) of students in the classroom had no effect on the strength of the relationship between inquiry and achievement in a study conducted by Teig et al. (2018).

Saba et al. (2021) showed that incorporating students into model building using much matter in motion (MMM) significantly supported students' conceptual learning and improved system thinking compared to the comparison group following a normative curriculum according to findings from quantitative analysis of questionnaires. Student responses to their worksheets have shown that there are reciprocal effects between the development of modeling practice and promoting conceptual understanding and systemic thinking.

In the study conducted by Rates et al. (2016), 32 high school students' understandings of complex system components and whether an agent-based simulation can develop these understandings were investigated. The pre-test and final test trials were coded for changes in the six components to identify whether students were thinking more expertly about the complex system of the Chesapeake Bay watershed. Results showed significant improvement in components.

Clark and Sengupta (2020) provided a critical review of the work conducting within the wider research literature to analyze the relevance of integrating modeling into discipline-integrated games from science perspectives as informational thinking and practice.

Schademan (2015) asked a question "what do playing cards have to do with science? His work, titled a Resource-rich look at African American young men, examined how he used two key concepts hybridization and resources and suggested a science education approach challenging the notions of permanent deficiency associated with this population. The response given by Gonsalves et al. (2011) to Schademan's (2015) work expanded his definition of hybridism and purpose in science class and highlighted the tensions inherent in allocating student resources in classroom settings.

Lucas and Lewis (2019) explored the use of problem-solving tasks to generate multiple representations as a scaffolding strategy in a high school modeling physics course. Through cognitive problem-solving interviews with students, it was investigated how a group of students responded to tasks and how using such strategies affected their problem-solving performance and use of representation compared to students who did not receive clear, scaffolded guidance to create representations while solving similar problems.

Morgan et al. (2016) stated that kindergarten general knowledge was the most powerful predictor of first-grade general knowledge, and this was the most powerful predictor of children's science success from third through eighth grade. When science success measurements were first used in the third grade, big science success differences emerged. These differences continued until at least the end of the eighth grade. Most or all of the observed science achievement differences were explained by many of the study's predictors.

While there is no statistically significant gain for argumentation-based science content, there is statistically significant evidence that intervention is associated with an improvement in critical thinking scores according to Hand et al. (2018).

Sackes et al. (2013) revealed that precursor (gender and SES) and trend (ability and motivation) variables predicted children's science performance. However, science learning opportunities in kindergarten did not predict the growth in children's science performance from third grade to eighth grade.

Alt (2018) showed that even though they were used less frequently than the final tests, participants used the formative evaluation tasks to some extent in their learning processes. Teachers who also reported using constructivist training activities, more specifically collaborative practices, also reported using formative assessment tasks. Opposite to expectations, this study's model does not point to a meaningful negative link between teachers' traditional understanding of teaching and learning and their tendency to use constructivist activities in their classrooms.

Roth et al. (2020) emphasized that analysis of the correlation between evaluation scores of the models and cognitive achievement revealed small-to-medium correlations. As a result, the assessment stages have affected students' overall and model-related cognitive achievement performance and have proven the value of our module as a means of integrating true scientific practice into science teaching. Although it increases the workload of science teachers, the potential of scientific modeling as an inquiry-based learning strategy is worth the effort.

In the study of Or-Bach and Bredeweg (2013), the results should influence changes and development of support methods, as well as provide guidelines for effective instruction using DynaLearn. Additional contributions to the study are insights into how novice modelers approach a modeling task, what kind of support they seek, how they use each of the different types of support, and what types of teaching interventions might be needed.

Demir and Namdar (2021) showed that students did not use emotional reasoning patterns in the post interview. They were unable to form high-quality informal reasoning and referred to modeling activities in different components of their reasoning.

Lucas (2021) concluded that the activity required non-science students in a university-level general education biology class to use the Tinkercad website to build a model of the relationships between the basic dogma of molecular biology and DNA, RNA, and protein, and explain their models in relation to cellular processes.

Ignatova and Ignatov (2017) propose to use the cognitive models of post-non-classical science as the core of the science teaching complex.

Kamaleeva (2010) argues that modeling can be an effective didactic means of motivating humanities students' self-education in the field of science.

Fulmer (2015) revealed that the force concept inventory (FCI) substances had moderate data-model alignment and showed the expected difficulty pattern between levels of learning stages. However, scale reliability and compliance of thresholds between levels have shown limitations. Students' estimates of ability for Newton's third law are higher than those of force and motion, as opposed to expectations of the relationship between the two aspects of force.

While the results show no significant difference between schools or genders between how scientist role models are perceived or thought, the sampled students saw scientists as embodying intelligence goals with low attainment and desirability in mind according to the study conducted by Jones and Hite (2020).

METHOD

This study is an overview of the literature related to modeling in science education in the Web of Science (WoS) database. Modeling or modeling and science or chemical or biological or physical education were used as keywords in WoS database. 117 publications were found in the first analysis and 80 of them were articles. For the next stage, educational journals were selected. Therefore, this search included a literature review of 31 articles indexed in WoS database.

Figure 1 outlines the process for selecting articles according to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) preferred reporting factors (Moher et al., 2015). A qualitative thematic review was used in this study. The topics chosen were "effects of modeling in science education on some variables", "cultural and social perspectives on modeling in science education", and "review and theoretical studies about modeling in science education". The keywords ("modeling" OR "modelling" AND "science education" OR "chemical education" OR

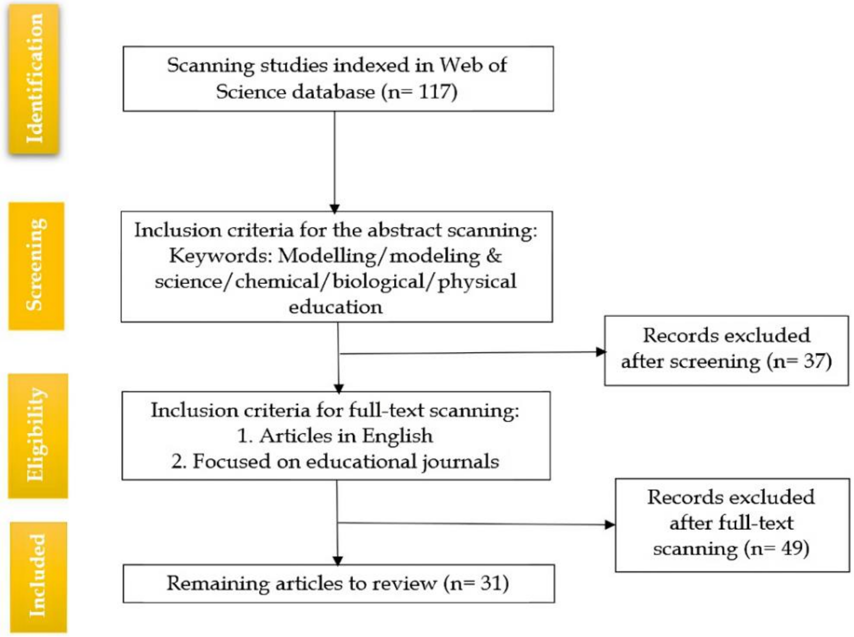

Figure 1. PRISMA flow diagram describing article selection process (Source: Authors' own elaboration)

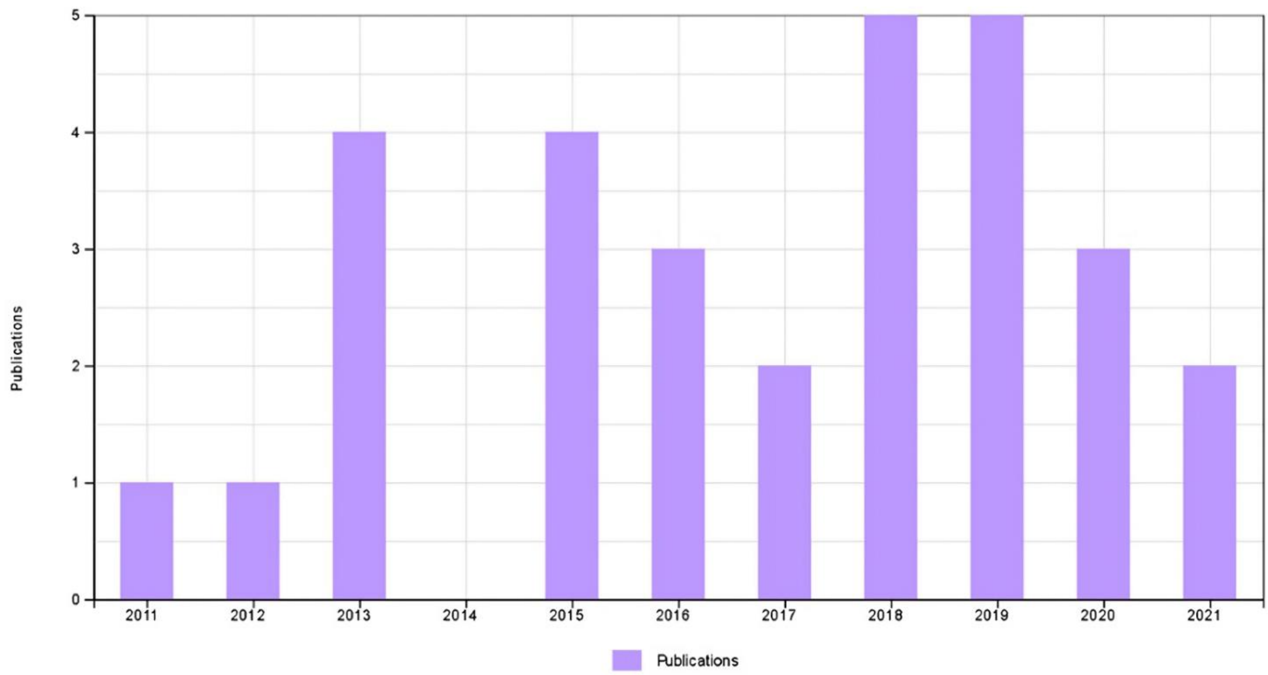

Figure 2. Annual accounts of the articles (Source: Authors' own elaboration)

"biological education" OR "physical education") are included in the groups. Word and phrase combinations were used to search for articles in WoS database.

Inclusion criteria were English-language journal publications focusing on modeling in science education. Other types of documents such as unpublished research, conference abstracts and/or posters, editorials, correspondence, and conceptual papers were eliminated.

Distribution of the Articles by Years

The distribution of articles on modeling in science education by year is shown in **Figure 2**. The first article was published in 2011, and articles on the topic of modeling in science education showed a fluctuating distribution up to 2013, with 2021 being the year that articles on this topic were published.

Coding and Analysis

Based on the results of a detailed analysis of 31 articles each, the content of the studies was coded by author's name and year, sample, research design and main results (**Appendix A**). The main purpose of this review was to analyze articles indexed in WoS database related to modeling in science education.

FINDINGS

Effects of Modeling in Science Education on Some Variables

Most studies have examined the impact of modeling in science education on cognitive factors such as academic achievement, conceptual learning, teaching, critical thinking, and problem solving. In part of the studies, the effect of modeling in science education on sensory factors such as perception and social interaction was examined. First, when studies on the effect of modeling on cognitive factors in science education are examined, it is seen that many of them are in the context of cognitive factors and their impact on science teaching (Alt, 2018; Battaglia et al., 2017; Bo et al., 2018; Demir & Namdar, 2021; Dickes & Sengupta, 2013; Fulmer, 2015; Hand et al., 2018; Louca & Zacharia, 2012; Lucas, 2021; Lucas & Lewis, 2019; Mierdel & Bogner, 2019; Morgan et al., 2016; Or-Bach & Bredeweg, 2013; Rates et al., 2016, 2022; Roth et al., 2020; Saba et al., 2021; Sackes et al., 2013; Samon & Levy, 2017; Teig et al., 2018; Wagh & Wilensky, 2018; Zitek et al., 2013).

In some of the studies, a model proposal related to science education was made and the effects of this developed model on science teaching were investigated. For example, Lucas (2021) developed 3D modeling for molecular biology teaching at the university level and examined its impact on biology teaching. Similarly, Or-Bach and Bredeweg (2013) proposed a model called DynaLearn, and its effects on creating a learning environment and effective teaching were researched. Furthermore, Fulmer (20215) examined the effect of modeling on learning science concepts in science education. In the same way, more detailed information was obtained on the relationship between different student ideas about modeling in physics by a study conducted by Battaglia et al. (2017). In another study, Demir and Namdar (2021) investigated the effects of modeling in science education on 5th grade students' informal reasoning about real-life experiences. Likewise, Rates et al. (2016) stated that an agent-based simulation could improve high school students' understanding of complex system components. Besides, Wagh and Wilensky (2018) showed that EvoBuild modeling students learned more about evolutionary mechanisms. In addition, Saba et al. (2021) showed a parallel effect between the development of model systems and the promotion of conceptual understanding and systems thinking. Moreover, analysis performed by Samon and Levy (2017) has shown that only concepts that are less "micro-macro-compatible" are better learned with a complex approach model and complex approach exploration uphold science learning. In line with this, DynaLearn's interactive learning environment enables learning by challenging students to create conceptual models of system behavior and the results confirm DynaLearn's potential to generate a causal and coherent understanding of ecological systems with respect to the study conducted by Zitek et al. (2013). Besides, Dickes and Sengupta (2013) developed multi-agent-based computational models for learning natural selection in 4th grade. On the other hand, Mierdel and Bogner (2019) found no association between model quality scores and cognitive performance when measuring student creativity levels but concluded that other outcomes were gender dependent.

In another type of study, different learning models were proposed, and their effectiveness was investigated. For example, Roth et al. (2020) concluded the potential of scientific modeling as an inquiry-based learning strategy. Likewise, Alt (2018) suggested a learning model of formative assessment tasks to some extent in their learning processes. Moreover, Hand et al. (2018) investigated the impact of an argument-based approach model to teaching science in elementary school on science learning and critical thinking skills. Besides, Morgan et al. (2026) stated that multilevel growth models were the strongest predictors of first grade general knowledge and the strongest predictors of children's science performance in grades 3 through 8. Furthermore, Lucas and Lewis (2019) emphasized the use of problem-solving tasks generating multiple representations as scaffolding strategies in a high school modeling physics course. In another study conducted by Bo et al. (2018), teachers' past experiences with simulation practice have revealed that most teachers adopt simulations for demonstration purposes in teacher-led teaching. On the other hand, Teig et al. (2018) concluded that while inquiry-based learning model is positively associated with success, the frequency of exploratory activity is negatively associated with success. In another study, Rates et al. (2022) compared an ontological and self-monitoring framework with an agent-based participatory simulation, primarily for undergraduates to understand complex systems. Finally, A model reflecting the relationship between early learning experience and later academic achievement in science was developed by Sackes et al. (2013) using the opportunity and propensity framework, and the model was tested using the latent growth curve modeling method. Results showed that history (gender and SES) and predisposition (ability and motivation) predicted children's academic achievement.

Cultural and Social Perspectives on Modeling in Science Education

Some of the studies in literature examined the social and cultural dimensions of modeling in science education. For example, Danish and Enyedy (2015) suggested that actor-network theory model provided a useful analytic frame for examining students' social interaction in science class. Likewise, Pierson et al. (2020) showed that existing student social interaction models are resources for flexible interaction with computer tools as participants. In another study, Louca and Zacharia (2012) reviewed the social, and epistemological contributions of MBL to science education. Similarly, Southerland et al. (2016) reported that participation in research for teachers shaped the performance and beliefs of science teachers. Furthermore, Schademan (2015) stated that modeling in science education build connections of the cultural practices in African American communities. Although the results show no significant difference between perceptions or presentation of science role models by school or gender, the students included in the sample considered scientists to embody intelligence goals with low perceptions of attainability and desirability in the study conducted by Jones and Hite (2020). On the other hand, a study by Teig et al. (2018) found that the socio-economic status of students in the classroom does not affect the strength of the association between inquiry and academic achievement.

Review and Theoretical Studies About Modeling in Science Education

When the literature on modeling in science education is examined, some studies consist of review or theoretical studies. For instance, Gonsalves et al. (2011) examined Schademan's (2015) "what do playing cards have to do to do with science?" A witty look at African American young men" explores two key philosophies–hybrid and resource–to propose an approach to science education countering the persistent notion of deficits associated with this demographic by considering how the concepts are used in the review study. In another review study, Clark and Sengupta (2020) provided a critical review of the research being done in a wide range of research articles to assess the potential of incorporating models into curricular games from computational thinking and science as practice perspectives. Finally, a link is being made between the use of models (i.e., simulation) and storytelling to show that formal science models are deeply related to these story worlds according to Fuchs (2015).

DISCUSSION, CONCLUSIONS, AND IMPLICATIONS

The aim of this systematic review is to summarize the results and draw conclusions on the significance and impact of modeling in science education from 2011 to 2023.

This systematic review found that using models as part of instruction has been shown to improve student understanding, particularly with regards to abstract concepts and processes (Battaglia et al., 2017; Dickes & Sengupta, 2013; Samon & Levy, 2017; Wagh & Wilensky, 2018; Zitek et al., 2013). In contrast to this situation, one of the studies that modeling in science education does not have a positive or negative effect on cognitive factors is the study conducted by Mierdel and Bogner (2019).

Specifically, it was noted that students were able to better understand certain topics when they could see them represented visually through diagrams or physical objects like blocks or balls representing molecules or atoms respectively. Additionally, research showed positive effects on both short-term knowledge acquisition as well as long-term retention rates compared with traditional methods alone such as lectures and readings without any visual support material provided by models used during instruction time periods (Demir & Namdar, 2021; Fulmer, 2015; Lucas, 2021; Or-Bach & Bredeweg, 2013; Rates et al., 2016; Saba et al., 2021).

Some of the studies in the literature are related to the effects of learning models used in science education on cognitive and affective factors. Most of these studies show that learning models used in science education have positive effects on both cognitive and affective factors (Alt, 2018; Bo et al., 2018; Hand et al., 2018; Lucas & Lewis, 2019; Morgan et al., 2016; Rates et al., 2022; Roth et al., 2020; Sackes et al., 2013; Teig et al., 2018).

Studies in the literature mostly showed that the use of models in science education had positive impacts on the stakeholders of education in terms of social and cultural aspects (Danish & Enyedy, 2015; Jones & Hite, 2020; Louca & Zacharia, 2012; Pierson et al., 2020; Schademan, 2015; Southerland et al., 2016; Teig et al., 2018).

In the review and theoretical studies on modeling in science education between 2011-2023 years in the literature, similar results to this review study were obtained. Clark and Sengupta (2020) reviewed computational thinking and science as practice perspectives to assess the potential of incorporating models into curricular games. Moreover, formal science models are deeply related to these story worlds by a review study conducted by Fuchs (2015). In addition, Gonsalves et al. (2011) explored two key philosophies–hybrid and resource–to propose a model to science education and reviewed the studies about hybridization of resources.

Based on these results, educators should strongly consider implementing modeling into their lesson plans whenever appropriate opportunities arise due its proven effectiveness at improving student comprehension levels across multiple disciplines within the sciences field . Furthermore, teachers should also note how different types of model representations (e.g., physical objects versus diagrams) may have varying degrees success depending upon what type of concept needs be taught so they can best choose which one would work most effectively for each particular situation accordingly. In conclusion, utilizing MBL strategies appears promising for enhancing educational outcomes among learners studying science topics within classrooms settings today hence why its merits are worth considering further exploration moving forward given all available data collected thus far about its potential benefits overall.

One implication from this systematic review is the need for teachers to be aware of different types of models available when designing instruction or activities related to science education topics. Different types may include physical objects such as diagrams or graphs; mathematical equations; computer simulations; analogies; metaphors/stories, etc., each with its own advantages depending on the context being taught within a given curriculum unit or lesson plan design activity (e.g., which model best conveys what needs explaining). By being mindful when selecting appropriate models for teaching purposes, instructors can better facilitate learning by making sure students are exposed not only to content but also how it relates back into real world contexts through modelling activities during class time.

Author contributions: All authors have sufficiently contributed to the study and agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: Authors stated that the study did not require ethics committee approval since it is a review of existing literature.

Declaration of interest: No conflict of interest is declared by authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

Alt, D. (2018). Science teachers' conceptions of teaching, attitudes toward testing, and use of contemporary educational activities and assessment tasks. *Journal of Science Teacher Education, 29*(7), 600-619. https://doi.org/10.1080/1046560X.2018.1485398

Ananishnev, V. M. (2010). Modeling in the field of education. *Sistemnaya Psikhologiya i Sotsiologiya* [*System Psychology and Sociology*], *1*(2), 67-84.

Aseeva, O. M. (2021). Modeling as a method of cognition of the surrounding reality. *Molodoy Uchenyy* [*Young Researcher*], *6*(348), 403-404.

Battaglia, O. R., Di Paola, B., & Fazio, C. (2017). A quantitative analysis of educational data through the comparison between hierarchical and not-hierarchical clustering. *EURASIA Journal of Mathematics, Science and Technology Education, 13*(8), 4491-4512. https://doi.org/10.12973/eurasia.2017.00943a

Bo, W. V., Fulmer, G. W., Lee, C. K. E., & Chen, V. D. T. (2018). How do secondary science teachers perceive the use of interactive simulations? The affordance in Singapore context. *Journal of Science Education and Technology, 27*, 550-565. https://doi.org/10.1007/s10956-018-9744-2

Chorosova, O. M., Aetdinova, R. R., Solomonova, G. S., & Protodyakonova, G. Y. (2020). Conceptual approaches to the identification of teachers' digital competence: Cognitive modeling. *Education and Self Development, 15*(3), 189-202. https://doi.org/10.26907/esd15.3.16

Clark, D. B., & Sengupta, P. (2020). Reconceptualizing games for integrating computational thinking and science as practice: Collaborative agent-based disciplinarily-integrated games. *Interactive Learning Environments, 28*(3), 328-346. https://doi.org/10.1080/10494820.2019.1636071

Danish, J. A., & Enyedy, N. (2015). Latour goes to kindergarten: Children marshaling allies in a spontaneous argument about what counts as science. *Learning, Culture and Social Interaction, 5*, 5-19. https://doi.org/10.1016/j.lcsi.2014.08.002

Demir, A., & Namdar, B. (2021). The effect of modeling activities on grade 5 students' informal reasoning about a real-life issue. *Research in Science Education, 51*(Suppl 1), 429-442. https://doi.org/10.1007/s11165-019-09896-8

Dickes, A. C., & Sengupta, P. (2013). Learning natural selection in 4th grade with multi-agent-based computational models. *Research in Science Education, 43*, 921-953. https://doi.org/10.1007/s11165-012-9293-2

Frederiksen, J. R., White, B. Y., & Gutwill, J. (1999). Dynamic mental models in learning science: The importance of constructing derivational linkages among models. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching, 36*(7), 806-836. https://doi.org/10.1002/(SICI)1098-2736(199909)36:7<806::AID-TEA5>3.0.CO;2-2

Fuchs, H. U. (2015). From stories to scientific models and back: Narrative framing in modern macroscopic physics. *International Journal of Science Education, 37*(5-6), 934-957. https://doi.org/10.1080/09500693.2015.1025311

Fulmer, G. W. (2015). Validating proposed learning progressions on force and motion using the force concept inventory: Findings from Singapore secondary schools. *International Journal of Science and Mathematics Education, 13*, 1235-1254. https://doi.org/10.1007/s10763-014-9553-x

Gilemkhanova, E. N., Khusainova, R. M., Lushpaeva, I. I., & Khairutdinova, M. R. (2022). A model of subjective well-being of a teacher in the context of the safety of educational environment. *Education and Self Development, 17*(4), 288-303. https://doi.org/10.26907/esd.17.4.20

Gonsalves, A. J., Seiler, G., & Salter, D. E. (2011). Rethinking resources and hybridity. *Cultural*

Studies of Science Education, 6, 389-399. https://doi.org/10.1007/s11422-010-9295-1

Hand, B., Shelley, M. C., Laugerman, M., Fostvedt, L., & Therrien, W. (2018). Improving critical thinking growth for disadvantaged groups within elementary school science: A randomized controlled trial using the science writing heuristic approach. *Science Education, 102*(4), 693-710. https://doi.org/10.1002/sce.21341

Hofstein, A., & Lunetta, V. N. (2004). The laboratory in science education: Foundations for the twenty first century. *Science Education, 88*(1), 28-54. https://doi.org/10.1002/sce.10106

Huber, R. A., & Moore, C. J. (2001). A model for extending hands on science to be inquiry based. *School Science and Mathematics, 101*(1), 32-42. https://doi.org/10.1111/j.1949-8594.2001.tb18187.x

Ignatova, V. A., & Ignatov, S. B. (2017). Conceptual approaches to modeling the content of science education for students of social and humanitarian areas of training at the university. *Vestnik Tyumenskogo Gosudarstvennogo Universiteta. Gumanitarnyye issledovaniya* [*Bulletin of the Tyumen State University. Humanitarian research*], *3*(3), 222-232. https://doi.org/10.21684/2411-197X-2017-3-3-222-232

Jones, L. K., & Hite, R. L. (2020). Who wants to be a scientist in South Korea: Assessing role model influences on Korean students' perceptions of science and scientists. *International Journal of Science Education, 42*(16), 2674-2695. https://doi.org/10.1080/09500693.2020.1829158

Kamaleeva, A. R. (2010). Modeling of the system of work on the formation of science competencies of students in the humanities. *Alma Mater, 4*, 36-42.

Kasprzhak, A., Kobtseva, A., & Tsatrian, M. (2022). Instructional leadership models in modern schools. *Education and Self Development, 17*(2), 172-187. https://doi.org/10.26907/esd.17.2.02

Kolchin, I. S., Miroshnichenko, A. S., Kadeeva, O. E., & Syritsyna, V. N. (2022). 3D modeling as a tool for gamification of the process of studying science disciplines. *Sovremennyye Problemy Nauki i Obrazovaniya* [*Modern Problems of Science and Education*], *6*(1), 45. https://doi.org/10.17513/spno.32256

Li, Y., Schoenfeld, A. H., diSessa, A. A., Graesser, A. C., Benson, L. C., English, L. D., & Duschl, R. A. (2019). Design and design thinking in STEM education. *Journal for STEM Education Research, 2*, 93-104. https://doi.org/10.1007/s41979-019-00020-z

López-Vargas, O., Ibáñez-Ibáñez, J., & Racines-Prada, O. (2017). Students' metacognition and cognitive style and their effect on cognitive load and learning achievement. *Journal of Educational Technology & Society, 20*(3), 145-157. https://doi.org/10.1177/1365480217704263

Louca, L. T., & Zacharia, Z. C. (2012). Modeling-based learning in science education: Cognitive, metacognitive, social, material and epistemological contributions. *Educational Review, 64*(4), 471-492. https://doi.org/10.1080/00131911.2011.628748

Lucas, K. L. (2021). The use of 3-D modeling and printing to teach the central dogma of molecular biology. *Science Activities, 58*(2), 70-76. https://doi.org/10.1080/00368121.2021.1918048

Lucas, L. L., & Lewis, E. B. (2019). High school students' use of representations in physics problem solving. *School Science and Mathematics, 119*(6), 327-339. https://doi.org/10.1111/ssm.12357

Mierdel, J., & Bogner, F. X. (2019). Is creativity, hands-on modeling and cognitive learning gender-dependent? *Thinking Skills and Creativity, 31*, 91-102. https://doi.org/10.1016/j.tsc.2018.11.001

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L. A., & PRISMA-P Group. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews, 4*, 1. https://doi.org/10.1186/2046-4053-4-1

Morgan, P. L., Farkas, G., Hillemeier, M. M., & Maczuga, S. (2016). Science achievement gaps begin very early, persist, and are largely explained by modifiable factors. *Educational Researcher, 45*(1), 18-35. https://doi.org/10.3102/0013189X16633182

Or-Bach, R., & Bredeweg, B. (2013). Support options provided and required for modeling with DynaLearn. A case study. *Education and Information Technologies, 18*, 621-639. https://doi.org/10.1007/s10639-012-9194-z

Pierson, A. E., Brady, C. E., & Clark, D. B. (2020). Balancing the environment: Computational models as interactive participants in a STEM classroom. *Journal of Science Education and Technology, 29*, 101-119. https://doi.org/10.1007/s10956-019-09797-5

Rates, C. A., Mulvey, B. K., & Feldon, D. F. (2016). Promoting conceptual change for complex systems understanding: Outcomes of an agent-based participatory simulation. *Journal of Science Education and Technology, 25*, 610-627. https://doi.org/10.1007/s10956-016-9616-6

Rates, C. A., Mulvey, B. K., Chiu, J. L., & Stenger, K. (2022). Examining ontological and self-monitoring scaffolding to improve complex systems thinking with a participatory simulation. *Instructional Science, 50*, 199-211. https://doi.org/10.1007/s11251-021-09573-2

Roth, T., Scharfenberg, F. J., Mierdel, J., & Bogner, F. X. (2020). Self-evaluative scientific modeling in an outreach gene technology laboratory. *Journal of Science Education and Technology, 29*(6), 725-739. https://doi.org/10.1007/s10956-020-09848-2

Saba, J., Hel-Or, H., & Levy, S. T. (2021). Much.Matter.in.Motion: Learning by modeling systems in chemistry and physics with a universal programing platform. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2021.1919905

Sackes, M., Trudle, K. C., & Bell, R. L. (2013). Science learning experiences in kindergarten and children's growth in science performance in elementary grades. *Eğitim ve Bilim* [*Education and Science*], *38*(167), 114-127.

Samon, S., & Levy, S. T. (2017). Micro-macro compatibility: When does a complex systems approach strongly benefit science learning? *Science Education, 101*(6), 985-1014. https://doi.org/10.1002/sce.21301

Schademan, A. R. (2015). Building connections between a cultural practice and modeling in science education. *International Journal of Science and Mathematics Education, 13*, 1425-1448. https://doi.org/10.1007/s10763-014-9554-9

Schwarz, C. V., & Gwekwerere, Y. N. (2007). Using a guided inquiry and modeling instructional framework (EIMA) to support preservice K-8 science teaching. *Science Education, 91*(1), 158-186. https://doi.org/10.1002/sce.20177

Shwartz, Y., Weizman, A., Fortus, D., Krajcik, J., & Reiser, B. (2008). The IQWST experience: Using coherence as a design principle for a middle school science curriculum. *The Elementary School Journal, 109*(2), 199-219. https://doi.org/10.1086/590526

Southerland, S. A., Granger, E. M., Hughes, R., Enderle, P., Ke, F., Roseler, K., Saka, Y., & Tekkumru-Kisa, M. (2016). Essential aspects of science teacher professional development: Making research participation instructionally effective. *AERA Open, 2*(4), 2332858416674200. https://doi.org/10.1177/2332858416674200

Teig, N., Scherer, R., & Nilsen, T. (2018). More isn't always better: The curvilinear relationship between inquiry-based teaching and student achievement in science. *Learning and Instruction, 56*, 20-29. https://doi.org/10.1016/j.learninstruc.2018.02.006

Wagh, A., & Wilensky, U. (2018). EvoBuild: A quickstart toolkit for programming agent-based models of evolutionary processes. *Journal of Science Education and Technology, 27*(2), 131-146. https://doi.org/10.1007/s10956-017-9713-1

Zitek, A., Poppe, M., Stelzhammer, M., Muhar, S., & Bredeweg, B. (2013). Learning by conceptual modeling--Changes in knowledge structure and content. *IEEE Transactions on Learning Technologies, 6*(3), 217-227. https://doi.org/10.1109/TLT.2013.7

APPENDIX A

Table A1. Variables of the selected papers

No	Article	Sample	Research design	Main results
1	Alt (2018)	127 primary school science teachers	Quantitative	Although used less frequently than final tests, participants used formative assessment tasks to some extent in learning processes.
2	Battaglia et al. (2017)	124 freshmen students	Quantitative	Clustering outcomes received use of 2 techniques had been as compared & it became proven that there has been a very good settlement among them.
3	Bo et al. (2018)	12 teachers	Qualitative	Most teachers use simulations for demonstration purposes in teacher-led lessons.
4	Clark and Sengupta (2020)	No participants	Systematic review	Providing a critical review of work being done in broader research literature to analyze relevance of integrating simulation into discipline-integrated games from perspective of science as informational thinking & acting.
5	Danish and Enyedy (2015)	21 students	Quantitative	A case study was presented of 6 kindergarten & first graders participating in an impromptu debate framed by 3 questions: What is being discussed, who & what character traits are used as strengths in conversation, & how character is built on the Internet?
6	Demir and Namdar (2021)	17 students	Quantitative	Students did not use emotional thought patterns in post-interviews. They failed to develop high-quality informal thinking & referred to modeling activities in various components of their reasoning.
7	Dickes and Sengupta (2013)	4th grade students	Quantitative & qualitative	Although there were differences between high- & low-scoring students on first test, these differences were eliminated on final test.
8	Fuchs (2015)	No participant	Theoretical study	Resulting paradigmatic conceptualization proposes notions of role & suffering of natural phenomena in historical world.
9	Fulmer (2015)	174 Singaporean secondary students	Quantitative	FCI substances fit medium data model & showed expected pattern of difficulty across levels.
10	Gonsalves et al. (2011)	No participants	Systematic review	Definition of hybridism & goals in science education & highlighted tensions associated with allocation of student resources in classroom.
11	Hand et al. (2018)	9,963 students	Quantitative	Although there was no statistically significant increase in argument-based science content, there was statistically significant evidence that intervention was associated with improved critical thinking scores.
12	Jones and Hite (2020)	159 South Korean students’	Quantitative	Students in sample believed that scientists embodied intelligence goals with low achievement & desirability in mind.
13	Louca and Zacharia (2012)	No participants	Systematic review study	MBL provides informed, qualitative, social, economic, & epistemological approaches to science education.
14	Lucas (2021)	30 students	Quantitative	Activity asked non-science majors in a college-level general education biology course to use Tinkercad website to build a model of relationship between fundamental dogma of molecular biology & DNA, RNA & proteins, & explain their patterns in relation to cellular processes.
15	Lucas and Lewis (2019)	High school with a population of 1,785	Mixed	Learning how to use problem-solving problems to create multiple views as a scaffolding strategy in a high school simulation physics course.
16	Mierdel and Bogner (2019)	114 9th graders at highest stratification secondary school level	Quantitative	Results of simple model were not related to short & medium knowledge levels, although they had an equal benefit in both.
17	Morgan et al. (2016)	7,757 children	Quantitative	General knowledge in kindergarten was strongest predictor of general knowledge in 1st grade, & it was strongest predictor of children’s science achievement from 3rd through 8th grades.
18	Or-Bach and Bredeweg (2013)	2 students	Qualitative	Results should influence changes & development of support methods & give recommendations for effective learning with DynaLearn.
19	Pierson et al. (2020)	25 6th grade students	Qualitative	Current models of student social interactions have been resources for flexible interaction using computer tools as participants.
20	Rates et al. (2016)	32 high school students	Quantitative	Students are becoming more interested in complex systems of Chesapeake Bay watershed. Results showed a significant improvement in product.
21	Rates et al. (2022)	96 undergraduate & graduate students	Quantitative	Students in ontological state improved more from pre-test to final test, & their sequence comprehension was higher than those in self-control state.

Table A1 (Continued). Variables of the selected papers

No	Article	Sample	Research design	Main results
22	Roth et al. (2020)	296 9th graders (higher secondary school)	Quantitative	Assessment level reflects student's overall & academic performance standards & demonstrates value of our model to truly teaching skills as an integrated model of actual practice.
23	Saba et al. (2021)	50 7th grade students	Mixed	Modeling supported students' conceptual learning & improved system thinking.
24	Sackes et al. (2013)	3,501 children	Quantitative	Different factors (ability & motivation) predict children's science performance.
25	Samon and Levy (2017)	104 7th grade students	Mixed	Only concepts with low "micro-macro compatibility" are better learned with complex approaches.
26	Schademan (2015)	20 African American young men, & 1 self-described Mexican-Italian young man	Qualitative	Spade players typically consider many variables & their mathematical relationships when making decisions.
27	Southerland et al. (2016)	106 teachers from urban, suburban, & rural schools	Quantitative	One of main features of RET was involvement of teachers in societal research contexts & in research projects that were personally important to them.
28	Teig et al. (2018)	4,382 students & 211 science teachers	Quantitative	SES of students in class did not affect strength of association between inquiry & achievement.
29	Wagh and Wilensky (2018)	149 students	Quantitative	EvoBuild students learn more about evolution mechanisms.
30	Zitek et al. (2013)	2 students	Mixed	Results support DynaLearn's ability to provide cause-effect & interrelated understanding of ecological systems.
31				