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Computer-based Modelling for Science Teaching and Learning: A Literature Review

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ABSTRACT

Purpose – Recently, science education has shifted its focus toward computer-based modelling. While there is a considerable body of research on tools and practical applications, a significant gap exists in systematic reviews of these studies. This study aims to address the lack of comprehensive, systematic reviews in the field of computer-based modelling in science education. While numerous studies explore tools and applications, many existing reviews fail to adhere to standardised definitions and to include key literature. The goal is to synthesise current research trends and identify gaps to inform future investigations.

Method – A systematic literature review was conducted using databases such as Web of Science (WOS) and Scopus, as well as selected peer-reviewed journals. The process involved defining precise search keywords and inclusion/exclusion criteria. Multiple screening rounds were conducted to refine the selection, ultimately identifying 11 relevant studies focused on computer-based modelling tools in science education.

Results – The selected studies reveal evolving interest in computer-based modelling, with notable shifts in research focus over time. Discrepancies were found in how modelling tools are defined and applied, highlighting inconsistencies across studies. After multiple screening rounds, the study ultimately identified eleven works related to computer-based modelling tools. The results begin with an analysis of publication distribution, research trends, and the types and methodologies used. Next, it examines participant profiles, including their geographical distribution, educational levels, and sample sizes.

Practical Implications – Educators and curriculum designers can use these insights to integrate computer-based modelling into science instruction better. The review also helps researchers refine their methodologies and align their work with standardised definitions, improving the coherence and impact of future studies. The findings provide valuable insights to guide future research directions.

Originality/Novelty – This review stands out for rigorously applying a systematic methodology to evaluate the literature on computer-based modelling in science education. It fills a critical gap by offering a structured synthesis of existing research, clarifying definitions, and spotlighting overlooked studies that are essential for advancing the field.

Keywords – *computer-based model, interaction, science teaching, assessment, challenges*

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1. INTRODUCTION

A model can be understood as something that stands for something else but provides an affordance that goes beyond simple representation, thus allowing it to serve as a tool for some action (Gilbert, 1998; Guo et al., 2024). Sometimes a model may be a physical action, but often models used in science are primarily thinking tools (Cisterna et al., 2019). In particular, models are used to develop and test scientific explanations. Modelling is one of seven Science and Engineering Practices in the Next Generation Science Standards and a core priority of international science education reform (Cisterna et al., 2019). Although models and the modelling process are crucial to science, their function in science is typically overlooked, even though models and modelling are fundamental to science (Taber, 2017). Models are essential to scientific thinking and practice, and they form the foundation of scientific procedures, products, and key teaching and learning resources (Cisterna et al., 2019). Considering this, a model of an object or a phenomenon is a simplified imitation that, hopefully, helps our understanding.

Despite the educational benefits of computer-based modelling tools in science education, many science teachers have a limited understanding of how to adopt these tools and practices to support students' sensemaking discussions and active engagement in scientific practices (Louca & Zacharia, 2008; Louca & Zacharia, 2015). In fact, a recent literature review (Nguyen & Santagata, 2021) found very few studies on computer-based tools for primary school students, and none on computer-based teaching, learning, classroom interaction, or pedagogical strategies. Such insights are crucial for understanding which computer-based modelling tools could be incorporated into educational practice and which pedagogical strategies are effective for integrating them (Windschitl et al., 2018). Despite the increasing use of computer-based modelling as an instructional strategy in science education, there remains limited clarity on how to assess students' learning outcomes in such environments effectively (Lin et al., 2022). Studies also reveal common challenges educators face when integrating technology into the classroom (Johnson et al., 2016). Both researchers and educators need to understand which modelling enactments are used in science education. The decision to focus on school science, from elementary to secondary school, was motivated by the idea that interest in science education is often assumed to be sparked and sustained at an early age (Sanford & Sokol, 2017). Therefore, the following research questions are addressed in this study:

1. What tools have been used in teaching and learning science education?
2. How do computer-based modelling tools integrate classroom interactions?
3. What are the pedagogical approaches used in teaching and learning in science education?
4. How is computer-based modelling learning assessed in science education?
5. What challenges do teachers face when using computer-based modelling tools?

2. METHODOLOGY

To conduct a thorough review of the research, two approaches were used to identify pertinent studies published through June 2025. The process for locating these sources is explained as follows. First, the relevant literature was reviewed using academic search engines such as Education Resources Information Centre (ERIC), Google Scholar, ScienceDirect, SAGE Journals, MDPI Education Journal, Taylor & Francis, Emerald, and Web of Science. The information drawn from these journal articles in the construction of the literature review was empirical resources. The academic search engines' findings indicated that these studies were based on systematic experimentation or experience. Additionally, these journal articles used predictable structures in which the authors identified the research questions, reviewed the relevant literature, and presented the findings and conclusions. The researcher used keywords when conducting the literature review. For example, "computer-based modelling tools", "science learning", and "review". Studies published between 1992 and 2024 were considered to reflect the most recent research trends. Second, the search references included articles about models used in science education (Taber, 2017; Windschitl et al., 2018; Cisterna et al., 2019;

Guo et al., 2024). Using the quotation mark (“”) helps the researchers find the specific phrases in the literature. In addition, the following exclusion criteria were established: First, a computer-based model was not stated as the study's purpose or at least as one of its purposes. Second, studies that focused on just models. Third, studies that are not based on empirical research and are not in English.

3. RESULTS

After applying the inclusion criterion, the final 27 studies were selected for review. Among these studies, 11 were quantitative, 10 were qualitative, and 6 used mixed methods. Most study cohorts consisted of school teachers. The foci of the studies’ disciplines were diverse. See Table 1.

Table 1. Selected Reviewed Studies

Authors	Title	Context	Subject learning area
Louca and Zacharia (2008)	The Use of Computer-based Programming Environments as Computer Modelling Tools in Early Science Education: The cases of textual and graphical program languages	elementary school in Maryland, USA	Computer
Nguyen and Santagata (2021)	Impact of computer modelling on learning and teaching systems thinking	Middle school in the Southwestern U.S.	Biology
Mercer (2007)	Sociocultural discourse analysis: Analysing classroom talk as a social mode of thinking	Language school in the UK.	Language
D'Angelo et al. (2017)	Modelling the Internet of Things: a simulation perspective	University of Bologna	Computer science and engineering
Alonzo & Gotwals (2012)	Learning progressions in science: Current challenges and future directions	Teacher education in the U.S.	Environmental Literacy Project
Windschitl et al. (2018)	Ambitious science teaching	K-12 classrooms in the U.S.	Science subjects
Srisawasdi (2011)	Design of an interactive computer-based laboratory tool for an inquiry-based learning environment	Khon Kaen University, Thailand	Biology
Pellegrino (2005)	The challenge of knowing what students know	University of Illinois at Chicago, USA	Psychology
Zhang et al. (2006)	Using Computer-based Modelling for Primary Science Learning and Assessment	Nanyang Technological University, Singapore	Science Learning and Assessment
Johnson et al. (2016)	Challenges and solutions when using technologies in the classroom	Arizona State University	Technology
Guo et al. (2024)	Design and application of computational modelling in science education research: a systematic review	China	Computational Modeling
Ogegbo and Ramnarain (2022)	A systematic review of computational thinking in science classrooms	University of Johannesburg, South Africa	Computational Thinking
Lin et al. (2022)	Interactive computer assessment and analysis of students’ ability in scientific modelling	Beijing Normal University, China	Science Education

Palrecha et al. (2025)	NetLogo Models for Pattern Recognition in Problem-Based Learning	KLE Technological University, Hubli, India.	Computer Science
Banda & Nzabahimana (2023).	The Impact of Physics Education Technology (PhET) Interactive Simulation-Based Learning on Motivation and Academic Achievement Among Malawian Physics Students	University of Rwanda-College of Education, Rwanda	Mathematics
Diab et al. (2024)	Transforming Science Education in Elementary Schools: The Power of PhET Simulations in Enhancing Student Learning	Al-Qasemi Academic College, Baka, Israel	Chemistry
Cantero et al. (2015)	STELLA 3D: Introducing Art and Creativity in Engineering Graphics Education	University of Valencia, Spain	Engineering
Flanagan (2012).	Key challenges to model-based design: distinguishing model confidence from model validation	Purdue University	Medical engineering
Barjis et al. (2012)	Innovative teaching using simulation and virtual environments.	Delft University of Technology, Netherlands	Computer Science
Alenezi (2017)	Obstacles for teachers to integrate technology with instruction	Northern Borders University	Technology
Peng et al. (2022)	Computer-based scaffolding for sustainable project-based learning: Impact on high-and low-achieving students	City University of Macau	STEM

3.1. Computer-Based Modelling Tools

A computer-based modelling tool consists of an open-ended, dynamic, and exploratory learning environment (Sins et al., 2005; Guo et al., 2024). This, among others, supports the construction of representations of complex phenomena or natural systems by simultaneously applying or executing multiple processes to go beyond static representations or static structural depictions toward dynamic representations of cause-and-effect relationships among variables. Currently, a large number of computer-based modelling tools are available and suitable for educational purposes in science education. For example, NetLogo is an excellent tool for introducing the concepts and lets students open simulations and "play" with them, exploring their behaviour under various conditions. As a free, publicly available tool, NetLogo allows teachers to select models based on specific learning requirements. They can then design assessments aligned with those intended outcomes (Palrecha et al., 2025). According to the authors, this computer-based modelling tool simplifies facilitation by providing an interactive platform for exploration, a key component of problem-based learning.

PhET is another modelling tool that provides fun, free, interactive, research-based simulations in science and mathematics (Banda & Nzabahimana, 2023). The authors further noted that, through the use of visualisations and teaching aids, PhET simulation-based learning enhances content comprehension, thereby improving students' academic achievement and motivation. Tools like PhET simulations are potent drivers of student engagement and comprehension (Diab et al., 2024). The results of Diab et al.'s (2024) study revealed that students using PhET simulations not only achieved significantly higher scores but also demonstrated their ability to explain their reasoning during problem-solving tasks. Also, Stella is a computer program that contains numbers, equations, and rules that, together, form a description of how we think a system works (Louca & Zacharia, 2008). It is a simplified mathematical representation of a part of the real world that helps students deepen their understanding. Stella is a computer-based creative tool that not only helps improve knowledge but also develops competencies such as spatial skills and creativity (Cantero et al., 2015). The real value of the Stella modelling package lies in the cognitive processing that goes into creating and developing its model. Despite their similarities, most of these tools have unique characteristics that set them apart—such as Tinkercad, Simul8, Modelling Toolkits, ChemCollective, Labster, and BioDigital Human.

3.2. Computer-Based Modelling Tool Use and Classroom Interactions

Prior work on classroom interactions between teachers and students using computer tools suggests two propositions (Nguyen & Santagata, 2021). First, teachers' initial enactment of educational technology relates to their existing pedagogical beliefs about structuring classroom participation as more procedural or more inquiry-driven. Second, engagement with computer tools may deepen teachers' understanding of the subject matter and the ways they notice, reason about, and support students' ideas. Evolving engagement with tool use in turn motivates teachers to modify classroom interactions, moving from direct instruction to student-driven exploration of concepts. When utilising computer-based modelling tools in the classroom, we think of interaction as discourse between teachers and students. Mercer (2007) emphasised expanding on the Vygotskian conception that discourse is a tool for creating knowledge. This is because teacher discourse that creates opportunity for student elaboration has been associated with productive student engagement in modelling practices. “How” and “why” questions create opportunities for students to reason about evidence and causal links and develop a deeper understanding of scientific phenomena.

Furthermore, more complicated student interaction patterns in scientific sense-making result from teacher discourse that is conversational rather than limited to fact-oriented questions (Klein & Bell, 2023). When students see the modelling activity as a sense-making process, they are more likely to engage in scientific practices, including iteratively formulating questions, gathering data, and refining their explanations (Alonzo & Gotwals, 2012). In a technology-mediated environment, the importance of classroom interaction in science education remains valid (Nguyen & Santagata, 2021). For example, when the researchers observed classrooms using the same scientific concept-mapping tool, they discovered that students whose teachers spent more time asking them to elaborate on how the tools related to the scientific principles learned much more effectively than those whose teachers mainly focused on procedural matters. Therefore, teachers can guide classroom interaction toward the elaboration of scientific phenomena by using computer-based models.

3.3. Pedagogical Approaches to Teaching with Computer-Based Modelling Tools

One practical teaching strategy for integrating computer-modelling tools into the science curriculum is inquiry-based learning (Ogegbo & Ramnarain, 2022). With this in mind, Windschitl et al. (2018) propose four stages to follow. The first stage is planning for engagement with important science ideas. Small groups of students collaborate to plan and conduct experiments to answer or clarify the question. The second stage is eliciting students’ ideas. Teachers introduce the anchoring phenomenon and driving question to the students at the beginning of this stage. Students develop initial hypotheses and initial models based on observation and shared ideas. The third stage is supporting ongoing changes in thinking. Students in this stage will have opportunities to reconstruct, test, evaluate, and revise their initial models based on the results of scientific inquiry (e.g., observations, experiments, or discussions) and on their engagement with many other science practices. Finally, the fourth stage is pressing for evidence-based explanations. In this last stage, students finalise their models by considering all they have learned across the unit through investigations, activities, opportunities to read relevant texts, and working collectively as a class to reach a general agreement on their models. According to Srisawasdi (2011), this approach can help students improve their thinking and learning about scientific concepts and procedures.

Project-based learning as a pedagogical approach. Students participated in a project-based learning course delivered through an online learning system (Peng et al., 2022). The system incorporated computer-based cognitive scaffolding to make the complex process involved in project-based learning visible to students. The computer-based cognitive scaffolding was designed based on the four-component instructional design model, a conceptual model for systematic learning with complex tasks. Based on this model, the system specifies the key phases a learner must go through to complete a programming project, along with rules of thumb or heuristics that might help the learner complete each phase. Problem understanding. In Phase 1, students are guided to formulate a problem statement for a clear understanding of the problem. Relevant heuristics are also presented in the system. For example, a structured form is provided for students to formulate the problem statement by specifying the project requirements and project goals. Solution planning. In Phase 2, students are requested to generate a solution plan based on their understanding of the project requirements and goals. They are guided to develop a solution plan by proposing a set of functional modules and specifying their relationships. Solution design. In Phase 3, students are guided to develop a detailed solution design based on the modular design. They are given relevant guidance and a diagramming tool to design the solution by building a program flowchart demonstrating the solution process within and across the functional modules. Solution implementation. In Phase 4, students are requested to translate the modular design and process design into an executable program by writing source code in ASP.NET, a programming language. Students can submit their programs via an online coding tool in the system and modify them throughout the project.

Immersive learning is another pedagogical approach in computer-based teaching. Immersion is a fundamental state of human consciousness that arises from the willingness to engage with a stimulus that captures attention and induces interest (Mystakidis & Lympouridis, 2023). Immersive learning, according to the authors, can be implemented using both physical and digital means, methods and technologies. Immersive learning methods include simulations, role plays and games (Barjis et al., 2012). Although these three methods share similarities and differences, they all belong to a continuum where overlaps are possible. They all share the tacit notion that the aim of education should not be content delivery but behavioural change towards a desirable end goal through learners' self-regulated activation. Simulations provide a structured, hands-on, realistic representation of a real-world situation or event with the intention of familiarising students with the procedures of professional practice (Mystakidis & Lympouridis, 2023). Simulations are valuable for education and training because they activate cognitive, affective, and psychomotor learning processes, making them more effective than other passive instructional techniques.

One form of organised role play is live-action role-playing. Role-playing constitutes a complex social experience that involves free-form roleplay (Mystakidis & Lympouridis, 2023). Educational role-playing can be organised to support experiential learning in improvisation, imagination and experimentation. Players assume a specific role in a fictional world with objectives that are within a set of agreed-upon rules. Games such as serious, epistemic escape rooms can be used to create immersive experiences with a pedagogical objective (Grande-de-Prado et al., 2020). These breakout games are organised around individual or team missions, usually aimed at finding a way out of a confined space or solving a mystery within a limited time.

3.4. Assessment Procedure in Computer-Based Modelling Tools

Many teachers say that the most challenging part of teaching with models is assessment. Assessing student knowledge and educational outcomes is far more complex than measuring physical traits such as height or weight (Zhang et al., 2006). This is because the attributes being assessed involve internal mental representations and cognitive processes that are not directly observable. Examples of unobservable cognitive processes and mental representations include memory, attention, decision-making, language, and perception, which are all studied through observable behaviours and are the focus of cognitive psychology (Smith & Queller; S., 2001). For instance, a person's "memory" is not directly seen, but it is assessed by their ability to recall a list of words. Similarly, "decision-making" is not directly observed, but it is inferred from choices made in a controlled setting. Computer-based systems often feature tools designed to monitor learning progress and provide immediate feedback (Lin et al., 2022). This may involve features such as auto-graded quizzes, real-time scoring, and in-depth performance reports. According to Pellegrino (2005), reasoning about students’ knowledge from evidence obtained in an educational assessment is portrayed as a triad of three interconnected elements – the assessment triangle. The vertices of this triangle represent the three key elements underlying any educational assessment: a model of student cognition and learning in an academic domain; a set of beliefs about the kinds of observations that will provide evidence of students' competencies; and an interpretation process for making sense of the evidence. These three elements may be explicit or implicit, but an assessment cannot be designed and implemented without consideration of each (Guo et al., 2024).

3.5. Challenges Faced by Teachers with Computer-based Tools

There are several challenges when integrating technological tools for assessment, including the following:

- **Lack of training**: Teachers may not have the skills to set up and use the tools, or they may not understand how to use their features (Johnson et al., 2016). Lack of training poses a major challenge for practical computer-based model assessment, as users may lack the specialised knowledge to interpret complex outputs correctly.

- **Lack of confidence**: Teachers who do not feel confident in their technological skills may use less technology, or they may stick to traditional teaching methods (Flanagan, 2012). Lack of confidence can severely hinder the adoption of computer-based model assessments, as decision-makers may be reluctant to trust results they do not fully understand.

- **Equipment maintenance**: Equipment may break down, which can be a chronic problem (Alenezi, 2017). Inadequate equipment maintenance can directly compromise the integrity of computer-based model assessment by causing unexpected hardware failures or performance degradation during critical computational tasks. These interruptions not only risk corrupting data and losing progress but also cast doubt on the reliability of any results produced by an unstable system.

- **Lack of software**: Teachers may not have access to the software they need (Alenezi, 2017). A significant digital divide persists due to limited access to essential software, which hinders productivity and academic learning. This barrier is often financial, as the high cost of proprietary programs places them out of reach for teachers and institutions with limited budgets. Consequently, teachers may lack the practical skills needed to compete effectively in a technology-driven economy.

- **Slow internet**: Slow internet speeds can make it challenging to use computer-modelling tools. Slow internet speeds can make it difficult to use computer-based modelling tools, causing significant lag and latency during data transfer. This often results in delayed visual rendering and interrupted collaboration, severely hampering productivity (D'Angelo et al., 2017).

- **Lack of motivation**: Teachers and students may not be motivated to use the tools (Johnson et al., 2016). Without proper training and clear curricular connections, teachers and students may not be motivated to use computer-based modelling tools. The perceived complexity and lack of immediate, tangible benefits can make these tools feel like unnecessary obstacles rather than valuable resources.

- **Lack of administrative support**: Teachers may not have the administrative support they need to use the tools (Flanagan, 2012). A lack of administrative support can cripple the use of computer-based modelling tools by failing to provide the necessary funding for software licenses or up-to-date hardware. Without this crucial backing, teachers are often left without the training or technical support needed to integrate these tools into their curriculum confidently.

- **Distracting students**: Technology can be distracting for students. Computer-based modelling tools can sometimes distract students from core learning objectives if the interface is overly complex or game-like (Mystakidis & Lympouridis, 2023). This distraction can shift their focus from understanding the scientific model to simply manipulating the digital environment.

- **Less face time**: Technology can lead to less face time with students (Lin et al., 2022). An over-reliance on computer-based modelling tools can result in less face-to-face time for students, limiting valuable opportunities for direct mentorship and immediate instructor feedback. This reduced personal interaction can hinder the development of crucial collaborative and communication skills that are often fostered in a traditional lab or classroom setting.

- **Cost**: Technology can be expensive. The high cost of software licenses for advanced computer-based modelling tools can be prohibitive for many schools and individuals (Flanagan, 2012). Furthermore, these expenses are often compounded by the need for powerful computer hardware to run the software effectively.

4. CONCLUSION

Research interest in computer-based modelling tools has increased significantly in recent years, as indicated by the systematic review in this study. In recent years, the impact of computer-based modelling tools in science education has led to a global increase in publications. There are many computer-based modelling tools used in science education, with both similarities and unique characteristics. Using computer-based modelling tools to enhance student engagement, in turn, motivates teachers to modify classroom interactions, moving from direct instruction to student-driven exploration of concepts. Teachers can guide classroom interaction toward the elaboration of scientific phenomena by using computer-based models. Students can improve their thinking and learning about scientific procedures when teachers integrate inquiry-based instruction while using computer-based modelling tools. Several challenges in integrating computer-based modelling tools were identified in this study.

4.1. Future Directions for Research

First, future studies should focus on the comparative effectiveness of various computer-based modelling tools across different subjects and educational levels to determine which tools are most effective for specific learning outcomes. Second, future studies should focus on how well different computer-based modelling tools support diverse learners, including those with disabilities, English language learners, and students from various cultural backgrounds. This also includes differentiated instructions on tailoring modelling tools to meet the needs of students with varying abilities and learning styles. Third, future studies should focus on how effectively computer-based modelling tools can be integrated into existing curricula and the barriers teachers face in doing so. Also, explore the use of modelling tools across different subjects and how this interdisciplinary approach affects learning.

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