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Systematic Review

Digital Simulations in STEM Education: Insights from Recent Empirical Studies, a Systematic Review

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Abstract: This study explores the use of digital simulations in STEM education, addressing the gap in systematic reviews synthesizing recent advancements and their implications for teaching and learning by focusing on their impact on learning outcomes and student engagement across general and special education settings. The review includes 31 peer-reviewed empirical studies published in the last five years, sourced from ERIC, Scopus, and Web of Science, and adheres to the PRISMA methodology to ensure transparency and rigor. The findings reveal that interactive simulations are the most widely used type of digital tool, accounting for 25 of the 31 studies, followed by game-based simulations and virtual labs. Quasi-experimental designs dominate the research landscape, often employing pre- and post-tests to evaluate intervention effectiveness. While inquiry-based learning emerges as the most frequently implemented instructional strategy, hybrid and simulation-based approaches also feature prominently. Despite the evident benefits of digital simulations in enhancing conceptual understanding, engagement, and problem-solving skills, research gaps remain, particularly regarding their application in primary and special education contexts. This review underscores the need for diverse research methodologies and broader population studies to maximize the potential of digital simulations in STEM education.

Keywords: STEM education; digital simulations; inquiry-based learning; learning outcomes; student engagement

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1. Introduction

The integration of digital tools and applications in education has revolutionized learning experiences across general and special education contexts. Research has highlighted the significant role of mobile applications in supporting students with specific needs, such as those on the autism spectrum in secondary education, by enhancing their learning processes and engagement levels [1]. Similarly, mental imagery applications have demonstrated potential for improving learning disabilities and mental health, showcasing the transformative impact of technology on education [2]. Innovations in speech and language therapy through ICTs have also opened up new avenues for intervention, providing tailored solutions for diverse learner populations [3]. Furthermore, STEM education, coupled with metacognitive strategies, has emerged as a critical area for supporting students with specific learning disabilities. Online learning tools for coding and robotics are another example of how digital technologies empower learners by enabling access to practical STEM-related activities, fostering both engagement and skill development [4–6].

In recent years, educational simulations have become increasingly prominent in STEM education, providing dynamic, interactive environments that support experiential learning. Digital simulations, encompassing virtual labs, interactive models, and AR-based applications, are computer-based tools designed to replicate real-world processes or systems. These simulations enable learners to interact with and manipulate variables within a virtual setting, facilitating experiential learning and a deeper understanding of scientific concepts [7,8]. Digital simulations, including virtual labs and interactive models, enable students to explore complex scientific phenomena, practice problem-solving skills, and deepen their understanding of core concepts in ways that traditional methods may not facilitate. The effectiveness of these tools in fostering engagement and enhancing learning outcomes has sparked substantial interest among educators and researchers alike, particularly for both general and special education contexts.

Despite the increasing use of digital simulations in STEM education, there is no systematic review that provides a comprehensive understanding of recent advancements and synthesizes findings across different scientific disciplines. This study fills this gap by offering an integrated perspective on modern approaches and the educational impacts of simulations. Previous reviews on AR in science education [9] have explored specific aspects of digital simulations. However, these studies focused narrowly on AR applications, leaving a broader examination of diverse simulation tools across STEM disciplines unaddressed.

However, despite the growing body of literature, there remains a need for a comprehensive understanding of how digital simulations contribute to measurable educational outcomes across various student populations and educational levels. This systematic review seeks to analyze recent empirical studies that examine the impact of digital simulations on learning outcomes and student engagement in STEM education, thereby offering insights into best practices and highlighting areas for further investigation.

Research Questions

1. What are the predominant research designs employed in studies examining the effectiveness of digital simulations in STEM education?
2. What types of digital simulations are most commonly employed in STEM education?
3. What intervention categories are most commonly implemented in studies utilizing digital simulations in STEM education?

These questions will guide a systematic exploration of recent empirical evidence, focusing on the educational implications and methodological rigor of digital simulations within the STEM domain.

2. Methodology

In order to create a robust foundation for the review, three major academic databases were selected: ERIC, Scopus, and Web of Science. The reason why these three databases were selected was that they were suitable for the focus of the research. The ERIC database mainly focusses on educational research, and provides access to a wide range of studies on educational technology in general and special education. Scopus and Web of Science were used in order to expand our research, since they provide access to high-impact journals in the fields of science, technology, engineering, and mathematics (STEM). By incorporating these three databases, the search approach sought to find a wide range of research that was pertinent to both general and special education, with a focus on using digital simulations to improve engagement and learning outcomes. This review focuses on studies published within the last five years (2019–2024) to ensure the inclusion of recent advancements in digital simulation technologies and their applications in STEM education. This time frame aligns with rapid technological development in educational tools and methodologies.

To ensure a transparent and systematic review process, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was followed. The PRISMA guidelines provided a structured approach for documenting each stage of the study selection, from identification through to screening and final inclusion.

The first step to identify studies best suited to our research questions involved creating a comprehensive set of search terms and filtering criteria tailored to each database. For ERIC, the search string was as follows: ('STEM education' OR 'science education' OR 'technology education' OR 'engineering education' OR 'mathematics education') AND ('simulations' OR 'virtual simulations' OR 'virtual labs' OR 'interactive simulations') AND ('learning outcomes' OR 'student engagement') NOT ('literature review' OR 'systematic review') AND ('experimental study' OR 'case study' OR 'quasi-experimental'). Filters included peer-reviewed journal articles published in the last five years. For Scopus, we used a similar string: ('STEM education' OR 'science education' OR 'technology education' OR 'engineering education' OR 'mathematics education') AND ('simulations' OR 'virtual simulations' OR 'virtual labs' OR 'interactive simulations') AND ('learning outcomes' OR 'student engagement') AND ('experimental study' OR 'case study' OR 'quasi-experimental') AND NOT ('higher education' OR 'adult learners'); in addition, we limited the results to articles published from 2019 to 2024. For Web of Science, the following string was used: ('STEM education' OR 'science education' OR 'technology education' OR 'engineering education' OR 'mathematics education') AND ('simulations' OR 'virtual simulations' OR 'virtual labs' OR 'interactive simulations') AND ('learning outcomes' OR 'student engagement') AND ('experimental study' OR 'case study' OR 'quasi-experimental'). We also excluded reviews and limited the results to the last five years.

2.1. Inclusion Criteria

- Studies focusing on general and special education across various educational levels.
- Studies specifically involving digital simulations (e.g., virtual simulations, virtual labs, interactive simulations).
- Studies reporting measurable outcomes related to learning or student engagement.
- Empirical studies with a clear research design (e.g., experimental, case study, quasi-experimental).
- Peer-reviewed journal articles published within the last five years.

2.2. Exclusion Criteria

- Studies involving digital tools other than simulations (e.g., general digital technology or non-simulation-based tools).
- Studies not focusing on STEM education.
- Studies targeting professional education as the main population.
- Non-empirical studies (e.g., theoretical papers, literature reviews).

Out of the 57 studies in our original records, we retrieved 48, after manually removing 4 duplicate studies and excluding 1 review article. The titles and abstracts of the remaining studies were screened by two independent reviewers (Authors 1 and 2) to ensure accuracy, with disagreements resolved through discussion or a third reviewer (Author 3). Following this process, 5 studies were excluded because they did not use digital simulations, but used other digital tools; 5 were excluded because they did not focus on STEM education; 2 were excluded because their target group was professional education; and 5 were excluded because they were not empirical studies. While a formal risk of bias framework (e.g., ROBIS) was not used, potential biases were minimized through a consistent screening process conducted independently by the two reviewers (Authors 1 and 2). This included evaluating the study design, methodology, and reporting to ensure reliability and relevance to the research questions.

The PRISMA flow diagram [10] shown in Figure 1 illustrates this process, detailing the initial number of articles identified in the database search, the application of exclusion criteria, and the resulting set of 38 studies included in the review.

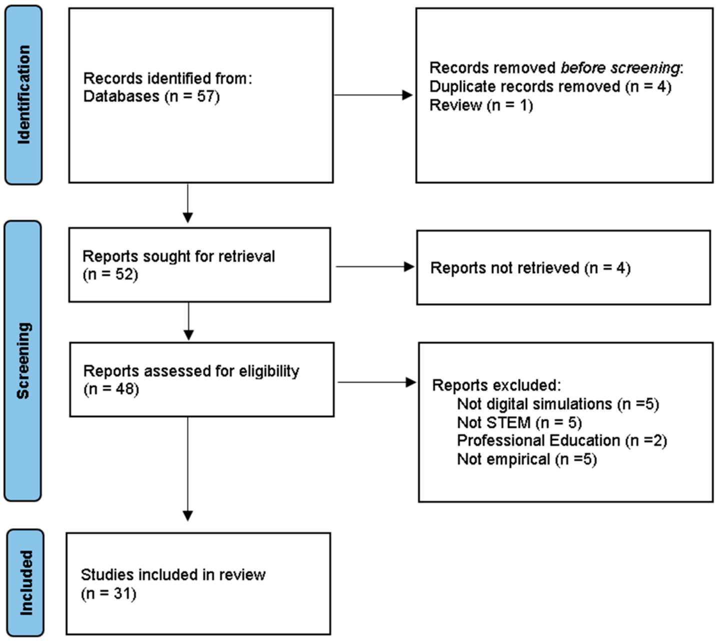

Figure 1. PRISMA flow diagram.

3. Results

This section presents the results of the systematic review, organized around the research questions. Table 1 summarizes the characteristics of the included studies, including their methodologies, target populations, and key findings.

Table 1. Summary of studies included in review.

Author(s)	Year	Study Design	STEM Subject	Intervention Category	Level
AYASRAH, Firas Tayseer Mohammad et al. [11]	2024	Quasi-experimental	Physics	Direct instruction with simulations	Secondary
Hüseyin Ateş, Mustafa Köroğlu [12]	2024	Quasi-experimental	Science	Hybrid/blended learning with simulations	Secondary
Demelash, M., Andargie, D., and Belachew, W. [13]	2024	Quasi-experimental	Chemistry	Project-based learning with simulations	Upper secondary
Yu-Chen Chiang, Shao-Chieh Liu [14]	2023	Quasi-experimental	Engineering	Inquiry-based learning with simulations	Secondary
ALARABI, Khaleel et al. [15]	2022	Quasi-experimental	Physics	Hybrid/blended learning with simulations	Secondary

Table 1. *Cont.*

Author(s)	Year	Study Design	STEM Subject	Intervention Category	Level
Kari Kleine, Elena Pessot [16]	2024	Case study	Engineering	Simulation-based assessment	Upper secondary
Badarudin, R., and Husna, A. F. [17]	2024	Quasi-experimental	Engineering	Simulation-based assessment	Upper secondary
Victoria Olubola Adeyele [18]	2024	Quasi-experimental	Science	Hybrid/blended learning with simulations	Primary
Cottone, Amanda M. et al. [19]	2021	Case study	Science	Inquiry-based learning with simulations	Primary
Turki Alqarni [20]	2021	Quasi-experimental	Science	Hybrid/blended learning with simulations	Secondary
Yang Wang [21]	2022	Quasi-experimental	Physics	Direct instruction with simulations	Secondary
YAN, Shenzhong et al. [22]	2023	Quasi-experimental	Chemistry	Simulation-based assessment	Upper secondary
WENG, Cathy et al. [23]	2023	Quasi-experimental	Engineering	Hybrid/blended learning with simulations	Upper secondary
Zaher, A.A., Hussain, G.A., and Altabbakh [24]	2023	Case study	Engineering	Inquiry-based learning with simulations	Upper secondary
Sui, C.J., Chen, H.C., Cheng, P.H., and Chang, C.Y. [25]	2023	Quasi-experimental	Science	Inquiry-based learning with simulations	Secondary
DAM-O, Punsiri et al. [26]	2024	Quasi-experimental	Physics	Inquiry-based learning with simulations	Secondary
Michal Dvir, Dani Ben-Zvi [27]	2022	Case study	Science	Inquiry-based learning with simulations	Secondary
Li, M., Donnelly-Hermosillo, D.F., and Click, J. [28]	2022	Quasi-experimental	Chemistry	Project-based learning with simulations	Secondary
Yuli Deng, Zhen Zeng, Kritshekhar Jha, Dijiang Huang [29]	2022	Case study	Engineering	Problem-based learning (PBL) with simulations	Upper secondary
Khadija El Kharki, Khalid Berrada, Daniel Burgos [30]	2021	Case study	Physics	Hybrid/blended learning with simulations	Upper secondary
Jaakkola, T., Nurmi, S., and Veermans, K. [31]		Quasi-experimental	Physics	Inquiry-based learning with simulations	Primary
Hua-Huei Chiou [32]	2021	Quasi-experimental	Science	Direct instruction with simulations	Secondary

Table 1. *Cont.*

Author(s)	Year	Study Design	STEM Subject	Intervention Category	Level
Nicholas O. Awuor, Cathy Weng, Isaac M. Matere, Jeng-Hu Chen, Dani Puspitasari, Khanh Nguyen Phuong Tran [33]	2024	Quasi-experimental	Engineering	Direct instruction with simulations	Secondary
Moch Rifai, Siti Masitoh, Bachtiar S. Bachri, Wawan H. Setyawan, Nurdyansyah, Hesty Puspitasari [34]	2020	Quasi-experimental	Engineering	Inquiry-based learning with simulations	Upper secondary
Muhammad Rashid [35]	2020	Case study	Engineering	Problem-based learning (PBL) with simulations	Upper secondary
Cathy Weng, Khanh Nguyen Phuong Tran, Chi-Chuan Yang, Hsuan-I. Huang, Hsuan Chen [36]	2024	Quasi-experimental	Engineering	Hybrid/blended learning with simulations	Secondary
Wang Yang et al. [37]	2023	Quasi-experimental	Science	Hybrid/blended learning with simulations	Secondary
Amélie Chevalier, Kevin Dekemele, Jasper Juchem, Mia Loccufier [38]	2021	Case study	Engineering	Direct instruction with simulations	Upper secondary
Debarati Basu, Vinod K. Lohani [39]	2023	Quasi-experimental	Engineering	Simulation-based assessment	Upper secondary
Paul N. McDaniel [40]	2022	Case study	Science	Inquiry-based learning with Simulations	Upper secondary
Sertaç Arabacıoğlu, Hasan Zühtü Okulu [41]	2021	Case study	Science	Inquiry-based learning with simulations	Upper secondary

3.1. Predominant Research Designs

The studies reviewed in this analysis showcased a range of methodological approaches, primarily split between quasi-experimental and case study designs. Of the 31 studies included, 21 utilized a quasi-experimental design, which allowed for structured comparisons to assess the impact of digital simulations. Among these, nine studies incorporated a control group, enabling direct comparisons between traditional teaching methods and digital simulations. The remaining 12 quasi-experimental studies did not include a control group, and instead relied on alternative methods, such as pre- and post-test assessments, to evaluate learning gains.

In addition to the quasi-experimental studies, 10 studies adopted a case study approach. These case studies provided in-depth qualitative insights, often focusing on specific educational settings or unique student populations, highlighting the practical aspects of implementing digital simulations in STEM education (Figure 2).

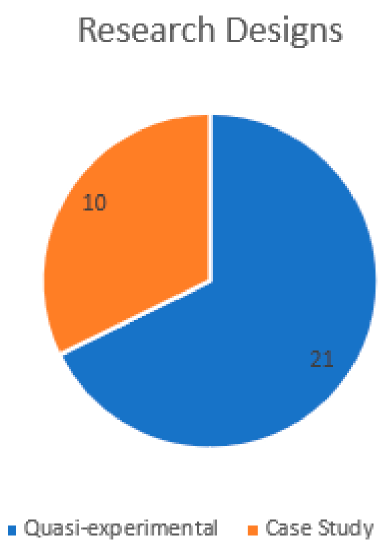

Figure 2. Research designs.

The use of pre- and post-test designs was common across many studies, with 14 studies employing this approach to capture changes in learning outcomes before and after the intervention. In contrast, seven studies opted for alternative assessment methods, such as interviews, observations, or single-time assessments, to gather insights into student learning and engagement with digital simulations (See Table 1 and Figure 3).

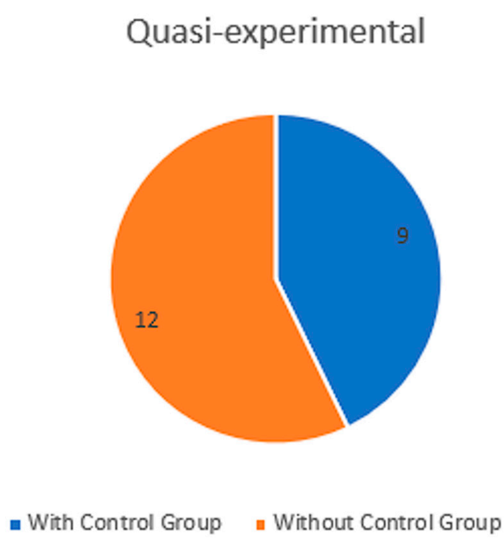

Figure 3. With or without control group.

3.2. Level of Education

The 31 studies included in this review spanned various educational levels, with a focus primarily on secondary and upper secondary education. Specifically, 3 studies were conducted at the primary level, 14 studies at the secondary level, and 14 studies at the upper secondary level. This distribution reflects a stronger research focus on older students, particularly in secondary and upper secondary settings, where digital simulations are often applied to complex STEM subjects (See Table 1).

3.3. STEM Field

The studies reviewed covered a range of STEM subjects, with the majority focused on general science and engineering. Specifically, 3 studies were conducted in chemistry, 12 in engineering, 6 in physics, and 10 in general science. This distribution indicates a particular emphasis on broader science education and engineering applications, in which contexts digital simulations have been frequently explored for enhancing learning outcomes (See Table 1).

3.4. Type of Digital Simulations

The types of digital simulations used in the studies varied.

3.4.1. Game-Based

Game-based simulations incorporate gaming elements to engage students in learning while pursuing educational goals. In STEM education, these simulations often use challenges, rewards, and interactive tasks to make abstract concepts more tangible and enjoyable. This type of simulation can be particularly effective for enhancing student motivation and engagement through immersive, goal-oriented experiences [24].

In a study by Zaher et al. [24], the authors presented a STEAMeD-based active learning approach, aimed at improving learning outcomes and engagement among undergraduate engineering students across various programs at the German International University in Cairo and the American University of Kuwait. Through a case study design, the study incorporated simulations and project-based learning (PBL) activities emphasizing art, entrepreneurship, and design to prepare students for industry demands and the ABET accreditation standards. The findings suggested that STEAMeD components like entrepreneurship and design enhanced students' analytical and business skills. Additionally, integrating arts into engineering curricula fostered creativity and critical thinking, better preparing students for complex, real-world problem-solving.

Another study by Adeyele [18] assessed the effectiveness of simulation games, blended learning, and interactive multimedia for teaching basic science to pupils of varying abilities in south-west Nigeria. Conducted in eight schools (four mainstream and four special education schools), the study utilized a pre-test–post-test quasi-experimental design across six experimental groups (three mainstream and three special education) and two control groups. The experimental groups engaged with interactive simulation-based teaching methods, while the control groups used traditional teaching methods. The results indicated that interactive multimedia were the most effective in mainstream schools, while blended learning proved more beneficial in special schools. Simulation games, though effective, were less impactful than the other methods. The study concluded that integrating technology-enhanced strategies tailored to different abilities significantly improved science learning outcomes.

In another study [21], researchers evaluated the effects of Augmented Reality Game-Based Learning (ARGSL) on engagement, learning performance, and satisfaction in physics among seventh-grade students at a middle school in eastern China. Conducted over three weeks, the quasi-experimental design included two experimental groups (ARGSL and game-based) and a control group (book-based learning), with a total of 155 students. The findings indicated that ARGSL significantly enhanced students' behavioral, cognitive, and emotional engagement compared to other methods. Semi-structured interviews revealed that students found ARGSL engaging and effective for helping them to understand complex concepts like the magnetic field.

3.4.2. Virtual Labs

Virtual labs simulate a laboratory setting where students can perform experiments digitally. They provide a safe and resource-efficient alternative to physical labs, so are especially useful in cases where resources or safety may be a concern. In STEM fields like chemistry and biology, virtual labs allow students to conduct experiments, observe reactions, and analyze results in a controlled, virtual space [14].

A study by Chiang and Liu [14] carried out in a Taiwanese university explored the impact of extended reality (XR) on student engagement and learning performance within a STEM curriculum. Conducted on 102 first-year engineering students at a public university in Taiwan, the study used a quasi-experimental design with control and experimental groups. The experimental group engaged with an extended reality STEM curriculum, while the control group followed conventional computer-based learning materials. Using a learning response questionnaire and a performance assessment, the study measured various response dimensions, including organization, concentration, and teaching aid effectiveness. Analysis revealed that the XR-integrated STEM group demonstrated higher engagement across all response dimensions and significantly outperformed the control group in learning performance. The study suggests that XR's immersive environment supports active engagement and enhances understanding of STEM concepts, making it a valuable tool in promoting students' enthusiasm and performance.

In a study by Alarabi et al. [15], the authors investigated the impact of computer simulations (CSs) on understanding of Newton's Second Law of Motion (NSLOM) among grade 11 students in the UAE. Conducted in two high schools, the research used a quasi-experimental design with pre- and post-tests to compare traditional face-to-face teaching with CS-based instruction. The study included 90 students (45 boys and 45 girls), assigned to either an experimental group using PhET simulations or a control group following conventional methods. The results indicated that students exposed to simulations outperformed those in the control group, with higher post-test scores and improved comprehension of NSLOM. Both male and female students benefited from the intervention, showing that simulations could effectively enhance physics understanding across genders. The findings support the use of CSs to improve engagement and comprehension in physics education, particularly for complex concepts.

3.4.3. Interactive Simulations

Interactive simulations are widely used in STEM education, allowing students to manipulate variables and observe outcomes in real time. These simulations provide an interactive environment where students can experiment with scientific concepts, such as adjusting forces in physics or variables in mathematical models. Interactive simulations are known for supporting conceptual understanding by enabling students to actively explore and test hypotheses [20].

Researchers from Ethiopian universities [13] conducted a study to examine the effectiveness of 7E context-based instructional strategy integrated with simulations in boosting secondary students' engagement in chemistry. Prompted by the low engagement levels often associated with abstract teaching methods that lack real-world application, the study involved 229 grade 10 students from various public schools in Ethiopia's Oromia Region. Using a quasi-experimental pre-/post-test design, the study compared four teaching methods: the 7E model with simulations, the 7E model without simulations, conventional teaching with simulations, and standard teaching. A 15-item chemistry engagement scale (CES) and semi-structured interviews were used to assess engagement across behavioral, cognitive, and emotional dimensions. Quantitative analysis (ANCOVA, MANCOVA, and DFA) demonstrated that the simulation-integrated 7E strategy significantly enhanced over-all engagement and engagement in all three dimensions compared to the other methods. Qualitative student feedback indicated increased understanding, relevance, and interest in chemistry, with academic concepts linked to everyday contexts. These findings suggest that integrating simulations with the 7E framework can substantially improve student engagement in STEM education.

Lastly, a study assessed the impact of theodolite 3D augmented reality (AR) on learning outcomes and satisfaction among vocational high school civil engineering students in Taiwan [23]. Conducted on 197 students from three schools, the study used a quasi-experimental pre-test–post-test design with both control and experimental groups. The experimental group used AR to supplement standard digital teaching materials on measurement error, while the control group used only digital materials. ANCOVA analysis showed that AR-enhanced instruction significantly improved learning outcomes and satisfaction levels. Interviews indicated that students found AR helpful for grasping abstract concepts in angle measurement.

Out of the 31 studies, 25 studies utilized interactive simulations [11–13,16,17,19–23,26–36,38–41], 3 studies employed game-based simulations [18,21,24] and 3 studies used virtual labs [14,15,25]. This distribution highlights the prominence of interactive simulations in enhancing STEM education (Figure 4).

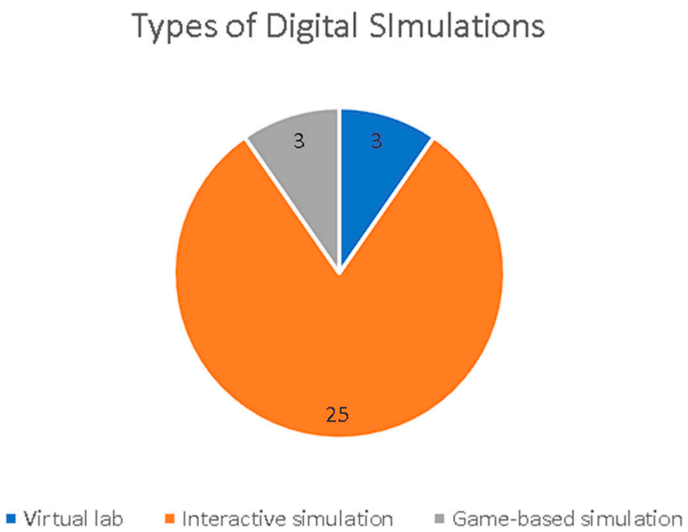

Figure 4. Types of digital simulations.

3.5. Intervention Categories

3.5.1. Direct Instruction with Simulations

Direct instruction with simulations integrates traditional teaching methods with digital simulations, providing structured guidance while allowing students to engage with interactive tools. In this approach, simulations serve as supplementary tools that reinforce lecture-based content, often simplifying complex concepts through visual and interactive elements. Direct instruction offers the advantage of efficiently delivering information and guiding students through new material, while simulations enhance comprehension by enabling students to observe and interact with modeled scenarios in a controlled environment. This method is particularly beneficial when time constraints limit the depth of exploratory learning, allowing students to engage with digital tools while following a teacher-led structure that emphasizes clear, organized content delivery [32].

3.5.2. Hybrid/Blended Learning with Simulations

Hybrid or blended learning with simulations combines face-to-face instruction with online simulation activities, creating a flexible learning environment that enhances students' access to resources. This approach integrates traditional classroom teaching with digital simulations, allowing students to benefit from both direct teacher guidance and self-paced, interactive online experiences. In STEM education, blended learning with simulations supports hands-on learning by enabling students to experiment with virtual models and observe real-time results outside the physical lab. By merging in-person and online elements, this approach aims to foster engagement and improve learning outcomes through dynamic, multimodal experiences that adapt to individual learning paces and needs [30].

3.5.3. Inquiry-Based Learning with Simulations

Inquiry-based learning with simulations is a student-centered approach that encourages learners to explore and experiment within a guided environment. Rather than following step-by-step instructions, students are prompted to investigate scientific or engineering problems through simulations, allowing them to actively construct knowledge and develop critical thinking skills. In this model, simulations serve as virtual environments where students can manipulate variables, test hypotheses, and observe outcomes, fostering deeper engagement and understanding. This approach aligns well with STEM education goals, as it supports hands-on learning and enables students to tackle complex, real-world challenges through inquiry and discovery [24].

3.5.4. Problem-Based Learning (PBL) with Simulations

Problem-based learning (PBL) with simulations is a hands-on, student-centered approach in which learners engage in solving complex, real-world problems using simulated environments. In this model, students are presented with practical challenges rather than traditional lectures, encouraging them to actively apply critical thinking and problem-solving skills. Simulations in PBL settings allow students to experiment and test solutions in a controlled, realistic environment that mimics real-world conditions. The instructor acts as a facilitator, guiding students through problem identification and resolution without directly providing solutions. This approach fosters independent learning, deeper engagement, and the development of skills that are relevant to real-world applications, making it particularly effective in fields requiring technical expertise and practical knowledge [29].

3.5.5. Simulation-Based Assessment

Simulation-based assessment utilizes digital simulations to evaluate students' knowledge, skills, and engagement in a controlled, virtual environment. By replicating real-world scenarios, this approach allows students to demonstrate their understanding and apply concepts practically, which is particularly valuable in STEM fields where hands-on experience is critical. In simulation-based assessments, student interactions are tracked, and metrics such as task completion, engagement, and accuracy provide insights into both learning outcomes and skill proficiency. This form of assessment is especially effective for complex tasks, offering an authentic, data-rich method to measure learning progress and competence without the need for physical resources or direct observation [39].

In total, the studies reviewed included a range of approaches to incorporating simulations in STEM education. Direct instruction with simulations was utilized in five studies, focusing on reinforcing teacher-led instruction with digital tools. Hybrid or blended learning with simulations was present in eight studies, integrating simulations with mixed instructional formats to enhance accessibility and engagement. The most common approach was inquiry-based learning with simulations, used in ten studies, encouraging students to explore and experiment independently. Problem-based learning (PBL) with simulations appeared in four studies, leveraging simulations to support hands-on problem-solving activities. Finally, four studies focused on simulation-based assessment, using simulations to measure students' understanding in realistic scenarios (See Table 1 and Figure 5).

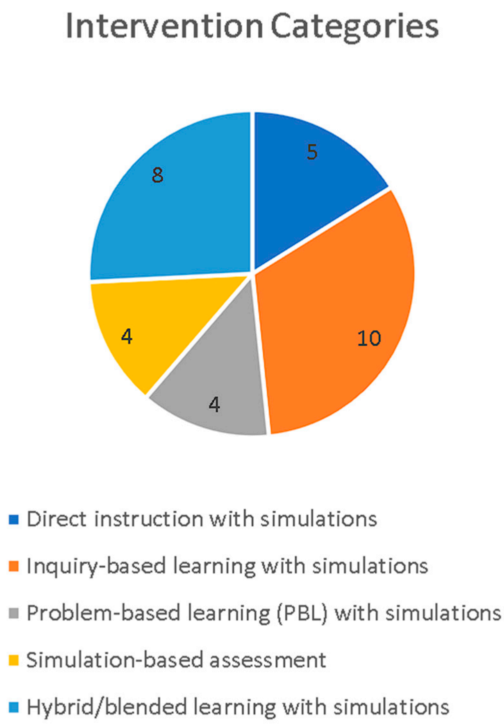

Figure 5. Intervention categories.

3.6. Population

The studies included in this review primarily focused on general education settings, with 31 studies targeting this population. In contrast, one study focused exclusively on special education, while another included both general and special education populations. This distribution highlights the predominant emphasis on general education in research on digital simulations, with limited exploration of its applications in specialized educational contexts (See Table 1).

3.7. Outcome Measures

The studies reviewed explored a wide range of outcome measures, primarily focusing on learning outcomes, student engagement, and practical skill acquisition in STEM education. A significant number of studies assessed learning outcomes in various domains, including conceptual understanding, knowledge retention, and practical application skills. This emphasis reflects a common objective among researchers to gauge the effectiveness of simulations in enhancing both foundational knowledge and applied skills [12,14,23,25,26,28,30–36,38].

Student engagement was another prominent focus, often broken down into behavioral, cognitive, and emotional dimensions. Many studies aimed to understand how simulations impacted students' motivation, interest, and participation in STEM subjects, indicating a strong interest in simulations as a tool for increasing student involvement [13,16,19,21,28,38–40].

Additionally, several studies targeted specific skill sets, such as problem-solving, analytical skills, and reflective thinking. For example, simulations were often used to promote critical thinking and the understanding of complex systems, highlighting the role of digital tools in developing higher-order cognitive skills [22,24,25,29,36].

A few studies focused on attitudinal changes toward science and inquiry, such as students' enjoyment of science lessons, career interest in STEM fields, and general attitudes toward scientific inquiry. This suggests that simulations may also play a role in shaping students' perspectives on STEM disciplines [11,31].

Lastly, some studies extended beyond academic outcomes, measuring competencies related to instructional practices and teacher effectiveness in designing activities involving simulations. This broader scope reflects an awareness of the systemic impact of simulations, not only on students, but also on educators' ability to integrate technology effectively [41].

Table 2 presents a summary of the outcome categories, highlighting the distribution of focus across the reviewed studies.

Table 2. Summary of outcome measures.

Outcome Category	Description	NS	References
Learning outcomes	Conceptual understanding, knowledge retention, and practical application skills	14	[12,14,23,25,26,28,30–36,38]
Student engagement	Behavioral, cognitive, and emotional dimensions, including motivation and interest	8	[13,16,19,21,28,38–40]
Skill development	Problem-solving, analytical skills, and reflective thinking	5	[22,24,25,29,36]
Attitudinal changes	Enjoyment of science lessons, career interest in STEM, and attitudes toward inquiry	2	[11,31]
Teacher competencies	Effectiveness in designing simulation-based activities	1	[41]

3.8. Key Findings

The studies included in this review revealed several significant trends in the effectiveness and impact of simulations across various educational settings. A common finding was the positive influence of simulations on student attitudes and engagement. Simulations consistently enhanced students' interest and motivation in STEM subjects, often making abstract concepts more accessible and engaging, especially in fields like physics and engineering. Several studies noted improved student participation and enthusiasm, with certain methods, like augmented reality and online collaboration tools, leading to high levels of engagement.

In terms of learning outcomes, simulations often led to better comprehension and knowledge retention compared to traditional methods. For example, students using computer-based simulations to study physics concepts, such as Newton's Second Law, showed a deeper understanding of these topics [15]. The integration of simulations with guided inquiry or interactive frameworks, like the KWL approach, further promoted critical thinking, reflective learning, and conceptual understanding [22].

Some studies also highlighted simulations' role in enhancing practical skills and problem-solving abilities, with students benefiting from simulated real-world applications [17,29]. However, their findings suggested that for certain complex skills, such as hands-on lab work, simulations should complement rather than replace physical labs [23]. This was especially evident in studies in which virtual labs were found to be effective substitutes, but faced limitations in replicating hands-on skills in disciplines like engineering and data science [30].

Additionally, several studies focused on skill-based competencies beyond traditional academic outcomes. For instance, simulations supported the development of analytical, entrepreneurial [24], and spatial visualization skills, particularly when tailored to students' unique strengths, such as high spatial ability [32]. The use of simulations in fields like environmental monitoring and geography also helped students to build data literacy [19,39], spatial awareness, and system comprehension [40].

Lastly, a few studies explored the impact of simulations on educator competencies, noting that tools like virtual museums and augmented reality could enhance teachers' ability to design engaging, inquiry-based learning activities [41]. This finding underscores the broader role of simulations, not only in student learning, but also in supporting instructional innovation and teacher development [38].

4. Discussion

This review indicates a strong preference for quasi-experimental designs in the studies analyzed, reflecting the challenges faced in conducting fully randomized experiments in educational settings. Quasi-experimental studies often employ pre- and post-test measures to assess changes in learning outcomes, providing a practical yet rigorous approach to evaluating simulation effectiveness. This design has proven useful for capturing both cognitive gains and shifts in student engagement, especially in settings where control groups are challenging to implement. Other commonly used methodologies include case studies, which offer in-depth insights into specific educational contexts and allow researchers to observe the nuanced effects of simulations on individual or small groups of students. While these studies lack the generalizability of experimental designs, they contribute valuable qualitative data, especially in special education contexts. Some studies also employ hybrid methodologies, combining quantitative and qualitative methods to gain a comprehensive view of how simulations impact learning. However, the review highlights the need for more standardized approaches and a greater diversity in research designs, as current studies often lack the longitudinal perspective needed to understand the lasting effects of simulations on STEM education outcomes.

The overwhelming preference for interactive simulations suggests their effectiveness in catering to a broad range of educational levels and STEM disciplines. However, the limited use of game-based simulations and virtual labs points to potential areas for further exploration. Future research could investigate the comparative effectiveness of these simulation types and explore the barriers to adopting less commonly used formats, such as virtual labs, in diverse educational contexts. This distribution of simulation types highlights the centrality of interactivity in engaging students and supporting STEM education, while also signaling opportunities for broader integration of diverse simulation tools. The preference for interactive simulations aligns with previous findings highlighting their role in fostering student engagement and conceptual understanding [42]. However, the limited use of game-based simulations and virtual labs, as identified in this review, contrasts with studies that suggest a growing interest in augmented reality (AR) applications in science education [9]. Future research could explore barriers to adopting virtual labs and investigate the potential of integrating AR-based simulations in diverse educational contexts.

The analysis reveals a growing preference for inquiry-based learning, aligning with trends in STEM education that prioritize active and student-centered learning. However, the review also highlights the limited exploration of simulations in combination with other innovative approaches, such as flipped classrooms or gamified learning. Additionally, the use of simulations in special education contexts remains underexplored across all intervention categories, indicating a need for further research into their effectiveness in supporting diverse learning needs. These findings underscore the adaptability of digital simulations to various pedagogical approaches, providing educators with tools to enhance STEM education at multiple levels and contexts. The diversity of intervention categories highlights the importance of aligning simulation-based strategies with specific learning objectives and student needs. The emphasis on inquiry-based learning approaches found in this review supports trends in STEM education that prioritize student-centered learning [43]. Nonetheless, the limited exploration of gamification and flipped classroom strategies contrasts with findings from AR-focused studies, which report an increased use of gamified methods to enhance engagement [9]. This highlights the need to further investigate the synergy between digital simulations and innovative teaching strategies.

This review underscores the need for long-term studies to evaluate the lasting impact of simulations on STEM education outcomes, aligning with broader calls for longitudinal research in this area [43]. Additionally, the exploration of combined VR and AR technologies presents a promising avenue for advancing simulation-based learning environments [42].

5. Conclusions

This systematic review aimed to assess the role of simulations in STEM education, focusing on their effectiveness in enhancing learning outcomes and engagement across general and special education settings. Emphasizing empirical research, this review included 31 studies that employed simulation-based interventions across various instructional methods, including direct instruction, hybrid/blended learning, inquiry-based learning, problem-based learning, and simulation-based assessment. These studies covered primary, secondary, and upper secondary education levels, with the majority targeting general education, and only minimal inclusion of special education contexts. Inquiry-based learning was the most frequently used approach, particularly at the secondary and upper secondary levels, while engineering and science were the most represented subjects. The prevalence of quasi-experimental designs, especially those utilizing pre- and post-tests, reflects a methodological focus on assessing the impact of simulations within controlled educational settings.

The findings indicate that simulations are adaptable educational tools, providing benefits across various instructional strategies and educational stages. For instance, the prominence of inquiry-based learning with simulations suggests that hands-on, exploratory approaches may be especially beneficial in engaging students and fostering deeper understanding in subjects like physics and science at the secondary and upper secondary levels. Similarly, the focus on hybrid/blended learning with simulations implies an emerging trend of integrating digital resources within flexible learning environments, especially for STEM education. Despite their versatility, simulations were under-represented in primary education, which might point to a missed opportunity for early engagement in STEM through interactive digital tools. The sparse representation of special education within these studies also highlights a significant gap. Given the potential of simulations to provide customized, adaptive learning experiences, expanding research to include more diverse learner populations, particularly students with special needs, is crucial.

This systematic review highlights the significant role of digital simulations in improving educational outcomes and student engagement in STEM education. Practical implications include guiding educators in selecting and implementing effective digital tools to enhance interactive learning experiences. Theoretically, this study contributes to an understanding of how diverse simulation types support learning objectives across different STEM disciplines. Policy-makers are encouraged to support the development and integration of such tools in education systems, ensuring equitable access for all learners. Finally, future research should examine the intersection of digital simulations with advanced technologies such as AI and VR to explore their untapped potential in transforming STEM education.

While this review provides insights into the application of simulations in STEM education, certain limitations should be acknowledged. The focus on studies published in the last five years and limited to peer-reviewed journals may have excluded relevant research available in other formats, such as technical reports or conference proceedings. Furthermore, while quasi-experimental designs dominated, only a subset of these included control groups or long-term follow-ups, potentially limiting the robustness of causal claims about the efficacy of simulations. Additionally, the studies reviewed primarily addressed secondary and upper secondary education, with fewer studies at the primary level. The focus on general education over special education means that conclusions regarding simulations' utility for students with special needs are tentative. Expanding research to include a broader range of educational levels, more diverse learner populations, and varied instructional designs will improve the generalizability and applicability of these findings.

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