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A systematic review of serious games as tools for STEM education

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Objective: Serious games are increasingly recognized as innovative tools in STEM (Science, Technology, Engineering, and Mathematics) education, providing engaging and interactive learning environments that can enhance student performance, engagement, and learning outcomes. This systematic review aims to synthesize current research on serious games in STEM education, evaluating their impact and identifying implications for educators, policymakers, and future research.

Methods: A comprehensive literature search was conducted across Scopus, Web of Science, PubMed, and IEEE Xplore databases, yielding 584 articles. A total of 37 peer-reviewed journal articles met the inclusion criteria, guided by the PICOS framework, which focused on studies reporting the use of serious games in STEM education contexts. Data extraction included study characteristics, game types, participant demographics, educational contexts, and reported outcomes.

Analysis: The selected studies were analyzed to assess the effectiveness of serious games in enhancing learning outcomes, engagement, and performance in STEM education. The analysis also explored challenges related to the implementation of serious games, including technological limitations, the need for comprehensive educator training, and ethical considerations around data privacy, all of which may impact adoption in educational settings.

Results: Serious games demonstrated a positive impact on learning outcomes, such as knowledge acquisition, skill retention, and the application of STEM concepts, along with increased student engagement and motivation. These findings suggest that serious games can serve as valuable tools for educators seeking to foster active learning environments. For policymakers, the results indicate a need for strategic investments in technology infrastructure, teacher training, and curriculum integration to maximize the benefits of serious games in STEM education. However, significant limitations were identified, including technological barriers, variability in study quality, and the need for sustained educator support, which may impact generalizability and implementation.

Conclusion: This review highlights the transformative potential of serious games as tools for STEM education but emphasizes the importance of addressing key challenges to realize their full benefits. For educators, implementing serious games requires alignment with curriculum goals and access to adequate training and resources. Policymakers are encouraged to support these efforts by providing financial resources and promoting frameworks for ethical, datasecure use of serious games in education. Future research should focus on establishing a globally recognized framework for serious games in STEM, conducting longitudinal studies to evaluate long-term impacts, and exploring diverse educational contexts to ensure inclusive and effective integration.

KEYWORDS

serious game, STEM education, PICOS, PRISMA guidelines, teaching and learning

1 Introduction

In recent years, the integration of digital technology in education has garnered significant attention, leading to innovative teaching methods that enhance student engagement and learning outcomes (Oglu and Babazade, 2024). One such innovation is the use of serious games, which are designed with specific educational purposes beyond mere entertainment (Stamatakis et al., 2024). Serious games leverage the engaging nature of gameplay to impart knowledge, develop skills, and promote problem-solving abilities, making them a promising tool for educational contexts (Steinkuehler and Squire, 2024), particularly in STEM education. STEM stands for Science, Technology, Engineering, and Mathematics, including fields that drive innovation and problem-solving. Science focuses on understanding the natural world, while Mathematics provides the analytical tools needed for this understanding. Technology involves creating tools and systems using scientific knowledge, such as software and electronic devices. Engineering, distinct from technology, applies scientific and mathematical principles to design and build structures, machines, and processes, such as bridges or energy systems, emphasizing practical solutions and physical applications (Al Hamad et al., 2024; Hwang et al., 2024; Felder and Brent, 2024).

STEM education is critical in preparing students for a world increasingly driven by technology and scientific advancements. It encompasses an interdisciplinary approach that integrates science, technology, engineering, and mathematics into a cohesive learning experience (Hwang et al., 2024). The key aspects of STEM education include critical thinking and problem-solving, which encourage students to analyze complex issues and develop solutions using scientific and mathematical principles (Felder and Brent, 2024). Additionally, STEM education fosters innovation and creativity, providing an environment where students can think creatively and develop new technologies and solutions (Ammar et al., 2024). To remark, this interdisciplinary learning integrates multiple disciplines to provide a comprehensive understanding of how scientific and technical concepts are interconnected and applied in practical situations (Rizki and Suprapto, 2024).

On the other hand, serious games are particularly effective in STEM education due to their key didactic characteristics. These games are created with specific educational or training objectives, such as teaching academic content (Almeida and Simoes, 2019), enhancing professional skills (Buzady et al., 2024), raising awareness about social issues (Dallaqua et al., 2024), or promoting health and well-being (Cavioni et al., 2024). By incorporating game mechanics like challenges, rewards, feedback, and narratives, serious games keep users engaged and motivated (Naul and Liu, 2020). Their interactive nature makes learning more enjoyable and immersive compared to traditional methods. Additionally, serious games often provide immediate feedback, allowing players to understand their mistakes and learn from them in real time (Susi et al., 2007). Many serious games use simulations to recreate practical environments or scenarios, allowing players to practice skills and make decisions in a safe and controlled setting (Williams-Bell et al., 2015).

With these ideas in mind, there are various types of serious games, each tailored to different educational needs and contexts.

- Educational games are designed to teach specific subjects such as mathematics, science, history, or languages. For example, “Math Blaster” helps students practice mathematical skills through engaging challenges (Play Math Blaster Plus Online, n.d.), while “ChemCaper” introduces players to fundamental concepts in chemistry through an adventure-based game (ChemCaper, n.d.).
- Training simulations are used in professional and vocational training, simulating real-world tasks and environments. For instance, “Flight Simulator” is widely used for pilot training, providing a realistic and risk-free environment to practice flying skills (Microsoft Flight Simulator, n.d.), and “Pulse!!” is a medical simulation game used to train healthcare professionals in clinical decision-making and patient care (Pulse: The Virtual Clinical Learning Lab, n.d.).
- Health and fitness games promote physical activity, mental health, or rehabilitation. Examples include “Wii Fit,” which encourages physical exercise through interactive games and activities (Archived Nintendo Game Title Information, n.d.), and “Re-Mission,” a game designed to help young cancer patients understand and manage their treatment (History of Hopelab, n.d.).
- Social impact games aim to raise awareness about social issues or promote social change. “PeaceMaker,” for example, simulates the Israeli-Palestinian conflict and encourages players to seek peaceful solutions (PeaceMaker Game, n.d.). At the same time “Half the Sky Movement: The Game” focuses on women’s rights and empowerment, highlighting global gender issues and promoting social change (Half the Sky Movement: The Game, n.d.).

The concept of serious games is particularly relevant in the context of Higher Education’s transformation toward Education 4.0 (Brandl and Schrader, 2024). Education 4.0 aligns with the fourth industrial revolution, emphasizing the integration of digital technologies, personalized learning experiences, and the development of skills needed for the future workforce. Serious games can contribute to this transformation by providing interactive, engaging, and personalized learning experiences. Moreover, mobile game-based learning is a significant trend within STEM education (Gao et al., 2020). The widespread availability of mobile devices offers new opportunities for learning anywhere and anytime. Mobile games can make STEM subjects more accessible and engaging, particularly for younger students who are digital natives. For example, mobile apps like "DragonBox Algebra" (DragonBox Algebra 12+, n.d.) and "Khan Academy Kids" (Khan Academy Kids, n.d.) use game-based approaches to teach complex mathematical concepts and foundational STEM skills. These mobile learning platforms provide flexibility and convenience, allowing students to learn at their own pace and in diverse environments, thus enhancing their overall engagement and learning outcomes.

Despite the extensive body of research on the effectiveness of serious games across various educational domains, there remains a significant gap in understanding their specific impact on STEM education. While general findings on serious games can provide useful insights, STEM education poses unique challenges and opportunities due to its interdisciplinary nature, the complexity of concepts, and the need for hands-on and experiential learning approaches (Ullah et al., 2022; Sharifzadeh et al., 2020; Ghoman et al., 2020). Consequently, a systematic review focused explicitly on the use of serious games in STEM education is essential to identify tailored strategies and best practices that are effective in this particular context. This targeted review aims to build on existing literature and provide a nuanced understanding that can better inform the design and implementation of serious games for STEM learning.

Hence, our systematic review aims to investigate how serious games impact performance, engagement, and learning outcomes in STEM education for both students and professionals. Additionally, this review seeks to identify effective practices for integrating serious games into STEM curricula and educational settings. For this purpose, the research question is defined as:

- *"How do serious games enhance performance, engagement, and learning outcomes in STEM education for students and professionals?"*

By systematically analyzing the existing literature, this review pretends to contribute to the body of knowledge on serious games in education, highlighting their potential to transform STEM learning and providing a foundation for future research and practice in this field.

2 Methodology

In this section, we detail the methodology used to conduct this systematic review, focusing on the PICOS framework for defining the inclusion and exclusion criteria and the PRISMA guidelines for ensuring a transparent and replicable study selection process.

2.1 Review goal

The goal of this systematic review is to analyze and synthesize the current state of research on the role of serious games in enhancing performance, engagement, and learning outcomes in STEM education for students and professionals. While numerous reviews are available on related topics (discussed in Section 5), a systematic review is urgently needed to provide a more structured, transparent, and replicable assessment of the existing literature. The PICOS framework (Population, Intervention, Comparison, Outcomes, and Study Design) is essential for structuring the research question to guide the systematic review process (Amir-Behghadami and Janati, 2020). As stated, the research question is: "*How do serious games enhance performance, engagement, and learning outcomes in STEM education for students and professionals?*." Understanding the key aspects formulated by the research question is crucial for educators, policymakers, and developers to effectively integrate serious games into educational practices, thereby enhancing the quality and impact of STEM education for both students and professionals. Keeping this in mind, we can distinguish students and professionals as follows:

- Students are individuals engaged in formal STEM education at various levels, including tertiary education (undergraduate and postgraduate).
- Professionals are individuals working in STEM fields, such as engineers, scientists, IT (information technology) specialists, and healthcare professionals, who seek to further their knowledge and skills through professional development and continuing education.

By clearly defining these components, the PICOS approach ensures that the review addresses specific and relevant aspects of the research topic, thereby enhancing the focus and relevance of the findings. The components of the research question for this systematic review are outlined in Table 1.

To emphasize, the PICOS framework defines the scope of this systematic review, highlighting key components such as students, professionals, learning outcomes, performance, and engagement. These components are contextualized as follows:

- P: The review focuses on both students and professionals in the STEM fields. This includes undergraduate and graduate students, as well as practicing professionals engaged in continuous education and training. Understanding how serious games impact different levels of learners and practitioners is crucial for evaluating their effectiveness and applicability in these fields.
- I: The interventions of interest are the use of serious games in education and training. These games are implemented to create interactive and immersive learning experiences that can enhance understanding and skills acquisition. The review aims to capture various applications of serious games, such as simulations of scientific experiments, engineering challenges, and interactive mathematical problem-solving.
- C: Traditional educational methods or other forms of training serve as comparison tools. These traditional methods typically

TABLE 1 Components of the research question using the PICOS Framework.

P	Population	Students and professionals in STEM education
I	Intervention	Use of serious games in education and training
C	Comparison	Traditional educational methods or other forms of training
O	Outcomes	Learning outcomes, performance, and engagement
S	Study Design	All study designs, including full articles, review articles, and conference papers

involve theoretical instruction through lectures and textbooks, hands-on laboratory exercises, and practical problem-solving sessions. Comparing serious games to these established methods provides insights into their relative advantages and potential areas for improvement.

- O: The primary outcomes of interest are learning outcomes, performance, and engagement.
  - Learning outcomes refer to the knowledge and skills acquired through training.
  - Performance encompasses the ability to apply this knowledge and skills in practical settings.
  - Engagement involves the level of interest, motivation, and participation of learners during the training process. Assessing these outcomes helps determine the effectiveness of serious games in enhancing educational experiences.
- S: The review includes all study designs, such as full articles and conference papers. This inclusive approach allows for a comprehensive understanding of the current state of research and the diverse methodologies employed to study the impact of serious games.

Moreover, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2020) offer a standardized methodology for reporting systematic reviews and meta-analyses. These guidelines enhance the transparency and completeness of the review process by ensuring that all relevant aspects are thoroughly documented and reported. Key elements of the PRISMA guidelines include the detailed documentation of the search strategy, clear articulation of selection criteria, systematic data extraction, rigorous assessment of the risk of bias, and the synthesis of results. Blending the PRISMA guidelines with the PICOS framework ensures a robust and structured approach to our systematic review. Figure 1 illustrates the systematic review process guided by these frameworks.

2.2 Identification stage

The chosen timeframe of 2010 to 2023 for this systematic review is crucial for several reasons:

- The field of serious games has seen significant advancements and a surge in scientific publications over the past decade. The application of serious games in educational contexts, particularly in STEM education, has evolved substantially during this period. The increasing sophistication and accessibility of these games have led to numerous innovative applications in training and education. The data, illustrated in Figure 1, shows a substantial rise in the number of publications on serious games since 2010, highlighting the growing interest and research in this field.
- Similarly, the integration of STEM education has seen a marked increase in scholarly attention. Starting in 2010, there has been a noticeable growth in studies focusing on STEM education, capturing the maturation of educational strategies and technologies from basic research to more applied studies. This period includes comparative studies that assess the performance improvements brought by innovative educational tools, including serious games. As shown in Figure 1, the number of documents

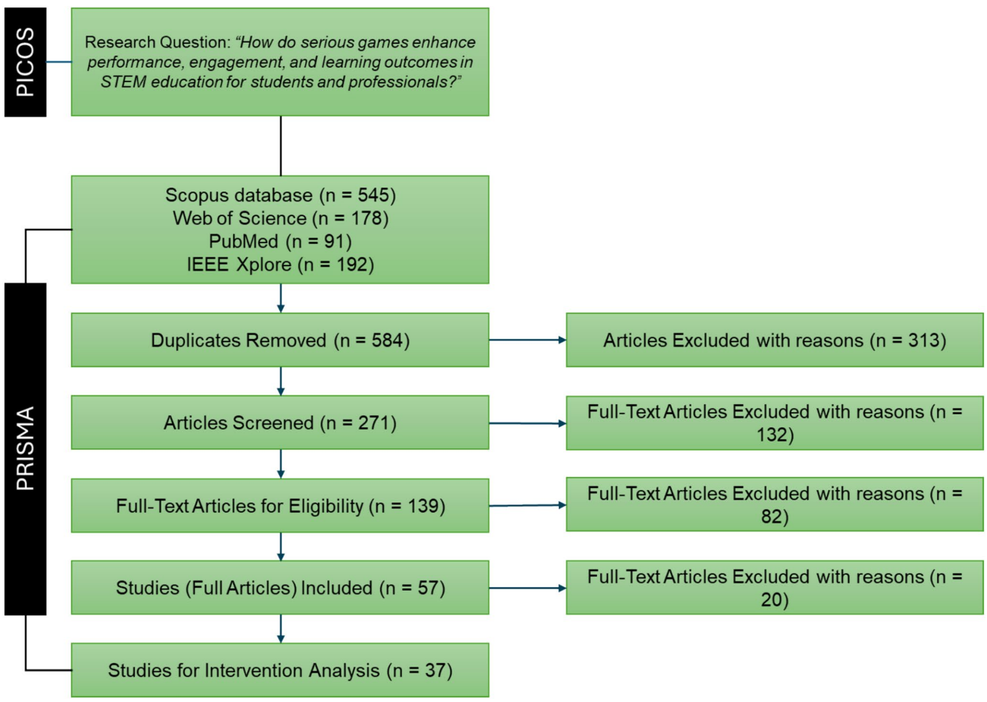

FIGURE 1
Flowchart representation of systematic review.

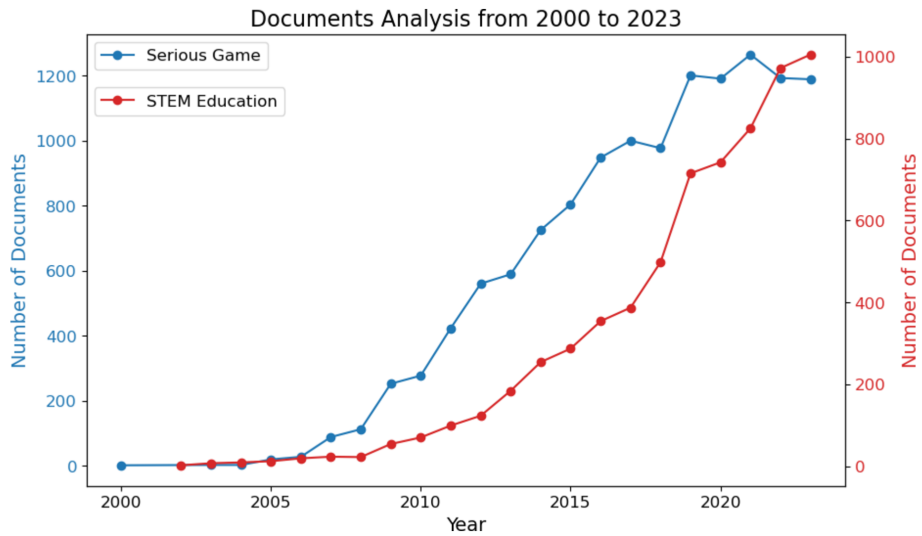

FIGURE 2
The number of documents identified by searching: "Serious Game" (blue) and "STEM Education" (red). Data was obtained from the Scopus database.

TABLE 2 Query type and the corresponding results.

Database	Query	Results
Scopus Web of Sciences PubMed IEEE Xplore	("Serious Games" OR "game-based learning" OR "game" OR "algorithms" OR "programming" OR "data bases" OR "software") AND ("STEM" OR "STEM Education" OR "Sciences" OR "Physics" OR "Chemistry" OR "Biology" OR "Mathematics" OR "Technology" OR "Engineering") AND ("Teaching" AND "Learning ")	545 178 91 192

Year restriction applied from 2010 to 2023.

related to STEM education has steadily increased, underscoring its significance in contemporary educational research (Figure 2).

On the other hand, the selection of Scopus, Web of Science, PubMed, and IEEE Xplore as the primary databases for this systematic review is strategic and justified by their comprehensive coverage, relevance, and reputation in the scientific community. These databases encompass a wide range of scientific disciplines and provide extensive coverage of journals and conference proceedings, making them essential resources for a systematic review (Falagas et al., 2008; Mongeon and Paul-Hus, 2016; Lefebvre et al., n.d.; AlRyalat et al., 2019). This strategic choice enhances the thoroughness and reliability of the review by capturing diverse perspectives and research findings related to the use of serious games in STEM education. In the identification stage of this systematic review, a precise and comprehensive query strategy was employed to retrieve relevant studies from the selected databases. The query terms were carefully chosen to capture a wide range of studies while maintaining specificity to the topic. This approach depicted in Table 2, ensures that the review includes a broad spectrum of research, contributing to a more comprehensive understanding of the use of serious games in enhancing STEM education.

2.3 Screening stage

We conducted a comprehensive literature search to identify relevant studies using four major academic databases: Scopus, Web of Science, PubMed, and IEEE Xplore. The initial search yielded a total of 1,006 articles, distributed as follows: 545 from Scopus, 178 from Web of Science, 91 from PubMed, and 192 from IEEE Xplore. After removing duplicates, 584 unique articles remained for further screening based on their titles and abstracts.

2.3.1 Inclusion criteria

- Type of Publication: We included review articles, full research articles, and proceedings papers to ensure a comprehensive overview of both theoretical frameworks and empirical research findings related to serious games.
- Focus on Serious Games: Articles were included if they explicitly focused on the development, implementation, or evaluation of serious games. Studies that used gamification without a structured game-based approach were excluded.
- Relevance to STEM Education: The study had to specifically address the application of serious games within STEM education. Studies focusing on non-STEM fields were excluded.
- Language Inclusivity: Articles were included regardless of the language in which they were published to avoid language bias and to capture a global perspective on the use of serious games in STEM education.

2.3.2 Exclusion criteria

- Irrelevant Focus: A total of 157 articles were excluded because they did not focus on serious games. These articles either discussed general educational technology or unrelated gaming concepts such as entertainment or commercial video games.
- Non-STEM Context: 143 articles were excluded because they did not pertain to education or training in STEM fields. These studies

focused on areas such as social sciences, humanities, or medical education outside of STEM disciplines.
- Unavailable Full Text: 13 articles were excluded as their full texts were not accessible, preventing a thorough review of their content.

After applying these criteria, 271 articles were deemed eligible for full-text review. This rigorous screening process ensured that only studies directly relevant to the research question were included, providing a focused and meaningful analysis of the role of serious games in STEM education.

2.4 Eligibility stage

During the eligibility phase, a systematic approach was taken to ensure that only the most relevant studies were included in the final review. The remaining 271 articles from the screening phase were randomly assigned to the authors for in-depth full-text analysis. This distribution ensured unbiased evaluation and efficient processing of the large number of articles. Each article was assessed based on the following eligibility criteria:

2.4.1 Eligibility criteria

- Full-Text Availability: The article must be available in full text, regardless of the language, to allow for a comprehensive analysis. This criterion ensured inclusivity and minimized language bias, enabling the inclusion of diverse perspectives from different educational and cultural contexts.
- Focus on Serious Games: The article must explicitly address the use of serious games in educational or training settings. This criterion excluded studies that only touched on serious games superficially or focused on gamification techniques without integrating structured game-based learning elements.
- STEM Education Relevance: The study must specifically relate to STEM education. This focus was crucial to maintaining the relevance of the review and ensuring that the findings directly contribute to the understanding of serious games in STEM contexts.
- Educational Context: The article must discuss the application of serious games in educational or training settings, either formal (schools, universities) or informal (workshops, community education). This criterion excluded studies that explored serious games in purely theoretical, developmental, or entertainment contexts without an educational component.

After applying these criteria, 139 articles were deemed eligible for inclusion and data extraction, while 132 articles were excluded for the following reasons:

2.4.2 Reasons for exclusion

- Lack of Educational Focus: A total of 107 articles were excluded because they did not focus on the educational applications of serious games. These studies either explored serious games in non-educational settings (e.g., health interventions, commercial use) or discussed gaming technologies without an educational framework.
- General Discussions on Serious Games: 25 articles were excluded because they were narrative reviews that discussed the broad topic of serious games without a specific focus on their application in STEM education. These papers often provided overviews of serious game design and usage but lacked direct relevance to STEM education or detailed analysis of educational outcomes.

2.5 Included stage

To conclude the selection process, the eligible articles were thoroughly analyzed to extract relevant interventions that impact educational outcomes in STEM education using serious games. A total of 139 articles undertook a comprehensive evaluation, focusing on three key metrics:

- Learning Outcomes: The extent to which the serious game interventions improved knowledge, skills, and understanding in STEM disciplines.
- Performance: The measurable impact of serious games on students' ability to apply learned concepts and problem-solving skills in practical or assessment settings.
- Engagement: The effectiveness of serious games in maintaining students' interest, motivation, and active participation in the learning process.

At this stage, 82 articles were deemed ineligible, leaving 57 articles suitable for further data extraction and analysis. The reasons for exclusion were as follows:

- 47 articles did not report conclusive metrics. For example, these articles lacked rigorous methodologies or did not provide sufficient data on educational outcomes. Some studies presented anecdotal evidence or descriptive observations without robust quantitative or qualitative measures to support their findings.
- 35 articles presented a limited focus on STEM education. These studies, while addressing serious games, did not specifically evaluate their impact on STEM subjects. For instance, some articles concentrated on broader educational themes such as general literacy, social skills, or arts education, which were not aligned with the STEM focus of this review.

Additionally, out of the 57 remaining articles, 20 were further excluded because they were review papers. Although these reviews provided valuable overviews of serious games in education, they did not contribute original data or empirical findings required for this analysis. Consequently, 37 articles were selected for an in-depth study to contextualize and analyze the role of serious games in enhancing education and training in STEM fields.

2.6 Bias mitigation

We recognize that publication bias can influence systematic reviews, as studies with positive findings are often more likely to be published than studies with neutral or negative results. To mitigate this:

- We included a range of sources from both journal articles and conference papers, recognizing that conference papers may sometimes present preliminary or neutral findings not yet expanded in full journal publications.
- Searches were conducted across multiple databases (Scopus, Web of Science, PubMed, and IEEE Xplore) to capture a broad set of studies, which helps to counterbalance any bias toward positive results that might exist within individual databases.
- Different databases may prioritize certain types of studies. By using four major databases, we aimed to reduce the likelihood of overlooking relevant studies that might only appear in specific publication venues.
- During our screening process, studies were evaluated based on clearly defined PICOS criteria which helped minimize subjective selection and ensured that studies were included based on their relevance and methodological quality, not solely on their findings.
- We openly admit the potential for bias in our review due to the focus on English-language studies and the databases selected, which may limit inclusivity. Future research could benefit from expanding the language scope and exploring additional databases to further address this bias (see subsection 4.4).

3 Results and discussions

3.1 Summary of search results

Initially, a total of 347 articles were identified across the selected databases. After removing duplicates, 173 articles remained for further screening. Following the screening process, 76 articles were selected, and after the eligibility stage, 41 articles were deemed suitable. Ultimately, 31 articles were included in the final data extraction. These articles were analyzed to extract parameters and interventions to contextualize the role of serious games in STEM education and their impact on various performance metrics. The interventions identified in the selected articles were categorized into several key aspects:

- Type of Intervention includes the specific serious game used and its application in educational contexts.
- Type of Variable focuses on performance and engagement metrics, evaluating how these games impact learning consequences.
- Type of Effect evidence the results as positive, negative, increased, decreased, or neutral, based on the observed impact on educational outcomes.
- Type of Serious Game specify types of serious games used in the studies.
- Stage of the Serious Game whether the game was fully implemented, in a pilot stage, or a prototype.
- Number of Participants refers to the sample size of each study, providing context for the robustness of the findings.
- Study Design represents the methodological design of each study, including randomized controlled trials, experimental studies, case studies, and qualitative research.
- Participants' Demographics give information about the participants, such as their educational level, professional status, or other relevant demographics.
- Limitations and Challenges identify key aspects in the implementation and evaluation of serious games in educational settings.

This detailed extraction and categorization offers a comprehensive insight into the influence of serious games on STEM education. It highlights the most effective methods and pinpoints areas needing further research, ensuring that educational practices are based on the best available evidence.

3.2 Summary of interventions

The interventions in the reviewed studies (Câmara Olim et al., 2024; Zhao et al., 2022; Klein et al., 2020; Ferro et al., 2022; Falah et al., 2021; Mystakidis et al., 2021; Hodges et al., 2020; Gocheva et al., 2020; Ameerbakhsh et al., 2019; Bul et al., 2018; Mostafa and Faragallah, 2019; Di Fuccio et al., 2019; Playfoot et al., 2020; Playfoot et al., 2019; Riera and Vigário, 2016; Bouzid et al., 2017; Rozhkova et al., 2016; Nunes et al., 2016; Prihatin et al., 2015; Iqbal et al., 2015; Iturrate et al., 2013; Rajan et al., 2010; Chacón-Castro et al., 2022; Chee, 2010; Rajan et al., 2014; González-Tablas et al., 1993; Troiano et al., 2019; Christopoulos et al., 2023; Chan et al., 2023; Clark et al., 2022; Koupritzioti and Xinogalos, 2020) span a broad range of serious games and immersive technologies applied to various educational contexts (see Table 3 and Supplementary Tables S1–S3). These interventions demonstrate innovative approaches to integrating technology with education, aiming to enhance the learning experience and engagement of students. A significant focus is placed on the application of augmented reality (AR) and virtual reality (VR) technologies. Câmara Olim et al. (2024) explored AR game-based learning for teaching basic chemistry concepts, illustrating AR's ability to make abstract concepts more tangible. Similarly, Falah et al. (2021) utilized a VR application for medicinal chemistry education, and Chan et al. (2023) developed a VR serious game named VR LaboSafe Game for chemical laboratory safety training. These studies showcase how AR and VR can create immersive and interactive learning environments, making complex scientific concepts more accessible and engaging for students.

Game-based learning for programming and computer science also features prominently. Zhao et al. (2022) investigated game-based learning focused on variables and loops using interactive video games in programming courses. Additionally, Iturrate et al. (2013) developed a remote laboratory-based serious game using a mobile robot in a maze, integrating Google Blockly for programming learning. Koupritzioti and Xinogalos (2020) introduced the PyDiophantus maze game to teach arithmetic expressions and game programming in Python. These interventions highlight the efficacy of game-based learning in enhancing computational thinking and programming skills.

Furthermore, game-based learning proves effective in improving fundamental skills in mathematics and science. Klein et al. (2020) created a serious game to improve the representational fluency of vector fields in introductory physics, while Chee (2010) focused on game-based learning for chemistry. Bouzid et al. (2017) developed a digital game to support elementary mathematics learning by promoting the understanding and application of basic arithmetic operations. Similarly, Rajan et al. (2014) and González-Tablas et al.

TABLE 3 Summary of interventions considering variable, effect, and limitations of the work.

Reference	Intervention	Variable	Effect	Area	Limitations
Câmara Olim et al. (2024)	AR game-based learning for basic chemistry concepts	Engagement, performance	Positive	Chemistry	Small sample size, short duration, technology reliability issues
Zhao et al. (2022)	Game-based learning for programming courses, focusing on variables and loops using interactive video games	Learning outcomes, engagement	Positive	Computer science	Differences in student backgrounds and prior knowledge
Klein et al. (2020)	Serious game for improving representational fluency of vector fields in introductory physics	Learning outcomes, performance	Positive	Physics	Small sample size, informal initial distribution
Ferro et al. (2022)	Game-based learning for STEM topics and 21st-century skills	Learning outcomes, engagement, performance	Positive	STEM	Need for further empirical studies to identify effective designs
Falah et al. (2021)	VR application for medicinal chemistry education	Engagement, performance	Positive	Medicinal chemistry	Single university cohort, pre-pandemic data, small sample size for prototype evaluation
Mystakidis et al. (2021)	Digital educational escape room focusing on the role of enzymes in biology	Engagement, learning outcomes	Positive	Biology	Small sample size, convenience sampling, no external support
Hodges et al. (2020)	Virtual Vet, a narrative-centered educational game focused on human body systems	Learning outcomes, performance	Positive	Anatomy	Small sample size, particularly for mindset transition analysis, difficulty for younger students
Gocheva et al. (2020)	Development of a suite of mobile mathematics educational games for 3rd grade students	Learning outcomes, engagement, performance	Positive	Mathematics	Small number of existing educational games in Bulgarian, language barriers, and a lack of specific participant numbers and intervention duration details.
Ameerbakhsh et al. (2019)	Digital game-based simulation for teaching marine ecology, comparing student-led exploration versus expert demonstration methods	Learning outcomes, performance	Positive	Marine ecology and aquaculture	Small sample size, single case study context, limited generalizability.
Bul et al. (2018)	The digital game 'Plan-It Commander designed to improve functional outcomes in children with ADHD	Engagement, performance	Positive	STEM	Small sample size for subgroup analysis, limited generalizability, and potential unmeasured moderator variables.
Mostafa and Faragallah (2019)	Educational games for information security, comparing different game genres to traditional teaching methods	Learning outcomes, engagement, performance	Positive	Information security	Not considered
Di Fuccio et al. (2019)	Role-playing game designed for teachers to train and apply digital creativity in classrooms, including scenarios for coding activities	Engagement, learning outcomes	Positive	STEM	Specific sample size and detailed participant demographics not provided
Playfoot et al. (2020)	Integration of various novel technologies (AR/VR, Fab-Lab, Virtual Labs, gamification) for teaching STEM subjects	Learning outcomes, engagement	Positive	STEM	Specific sample size and detailed participant demographics not provided
Playfoot et al. (2019)	Integration of gamification and game-based learning within STEM education, utilizing AR/VR, Fab-Lab, Virtual Labs, user profiling, self-directed learning	Learning outcomes, engagement, performance	Positive	STEM	Potential issues with the efficacy of game-based learning if not correctly designed, resistance from educators, variability in student engagement with games

(Continued)

TABLE 3 (Continued)

Reference	Intervention	Variable	Effect	Area	Limitations
Riera and Vigário (2016)	Use of two dynamic 3D simulators, HOME I/O and FACTORY I/O, for control education	Engagement, learning outcomes	Positive	STEM	Potential issues with the efficacy of game-based learning if not correctly designed, resistance from educators, variability in student engagement with games
Bouzid et al. (2017)	Digital game-based learning to support elementary mathematics learning by creating a game that promotes the understanding and application of basic arithmetic operations	Learning outcomes, engagement	Positive	Mathematics	The study was conducted on a small sample size and in a controlled environment
Rozhkova et al. (2016)	Integrating gaming technologies with smart technologies in education, focusing on the gamification of fundamental disciplines like Mathematics, Physics, Economics, and Foreign Languages	Engagement, learning outcomes	Positive	Mathematics	Variability in student engagement and challenges in game design and implementation
Nunes et al. (2016)	Game-based learning focusing on environmental awareness through three stages: recycling, reusing garbage, and practicing waste reduction	Engagement, learning outcomes	Positive	Environmental education	Small sample size, initial technical difficulties, future studies needed for broader validation
Prihatin et al. (2015)	Digital game-based learning for mathematics and biology, specifically focusing on exponential numbers and living things interaction patterns using the 5/10 method	Learning outcomes, engagement	Positive	Mathematics and Biology	Small sample size; specific to one educational setting
Iqbal et al. (2015)	Digital game-based learning for mathematics	Learning outcomes, performance	Positive	Mathematics	Small sample size
Iturrate et al. (2013)	Remote laboratory-based serious game using a mobile robot in a maze, integrating Google Blockly for programming learning	Learning outcomes, engagement, performance	Positive	Engineering and Programming	Initial implementation, not tested with a large sample size
Rajan et al. (2010)	Game teaching the engineering design process, with 'Engineering Heights' simulation and pasta tower activity	Learning outcomes, engagement, performance	Positive	Engineering	Initial implementation, small sample size
Chacón-Castro et al. (2022)	Educational practice laboratory where high school students created video games for teaching recycling using the Scratch application	Learning outcomes, engagement	Positive	Environmental education	No considered
Chee (2010)	Game-based learning for chemistry	Learning outcomes, engagement	Positive	Chemistry	Not considered
Rajan et al. (2014)	Game-based learning for engineering design	Learning outcomes, engagement	Positive	Engineering	Lack of control group, reliance on self-reported data, short duration
González-Tablas et al. (1993)	Card game-based learning for cryptography	Engagement, learning outcomes	Positive	Cryptography	Preliminary study, need for longitudinal evaluation
Troiano et al. (2019)	Uses Dr. Scratch to evaluate computational thinking in 8th graders' Scratch games for a climate change STEM curriculum	Learning outcomes	Positive, Increased	Computational science	Include the focus on a single geographic area and a specific age group
Christopoulos et al. (2023)	Virtual reality escape room (VRER) designed for biology education focusing on biochemistry, specifically the operation of enzymes	Learning outcomes, engagement	Positive	Biology	Small sample size, limited generalizability, short duration of the intervention, potential novelty effect

(Continued)

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TABLE 3 (Continued)

Reference	Intervention	Variable	Effect	Area	Limitations
Chan et al. (2023)	VR serious game, named VR LaboSafe Game, used for chemical laboratory safety training	Engagement	Positive	Chemistry	Small sample size, potential volunteer bias, and initial novelty effect of VR technology may diminish over time
Clark et al. (2022)	Designing digital games for the classroom to support meaningful gameplay, meaningful learning, and meaningful access	Engagement, learning outcomes	Positive	Mathematics	Importance of balancing gameplay and academic learning, and the challenges of integrating precise academic concepts within engaging game mechanics
Koupritzioti and Xinogalos (2020)	Use the PyDiophantus maze game to teach and learn mathematics, specifically arithmetic expressions and the priority of operators, and to teach game programming in Python	Learning outcomes, engagement	Positive	Mathematics and Programming	Small sample size, potential variability in prior programming experience among participants
García et al. (2020)	3D simulation game, "Requengin," designed to teach undergraduate students the fundamentals of requirements engineering based on the ISO/IEC/IEEE 29148:2011 standard	Performance	Positive	Engineer	The study acknowledges the necessity of conducting further evaluations with different student groups and institutions to enhance the reliability and validity of the game as an educational resource.
Romanov and Holler (2021)	The game allows players (government, producers, consumers) to explore the interdependencies between technical, economic, ecological, and sociopolitical aspects, and develop strategies for a successful transition to sustainable, low-temperature district heating.	Engagement	Positive	Engineer	The study mentions that further evaluations are needed with different groups and settings to assess the game's educational impact comprehensively
Georgieva-Tsaneva (2019)	Using serious games to enhance medical students' training in cardiology.	Engagement	increased	Medical training	Was conducted on a small scale and may not fully represent the broader student population. More extensive evaluations are needed to establish the generalizability of the results.
Schwarz et al. (2013)	Use of interactive algorithms designed as simulation-based learning objects	Engagement	Positive	Medicine	Not observe direct effects on real clinical performance; feedback was based on self-reported perceptions of learning impact
Fonseca et al. (2021)	using a VR-based serious game developed with Unreal Engine 4 and HTC Vive sensors. The game aims to improve spatial comprehension and decision-making in architectural and urban design	Engagement	Increased	Architecture	The need for broader implementation and further assessments to address different user profiles and educational contexts
Ammouriova et al. (2022)	Simulation-based serious game designed as a virtual teaching lab to educate students on optimization problems in logistics and transportation, such as vehicle routing, arc routing, and team orienteering.	Performance	Increased	Logistics	Need for broader testing across different educational contexts and more diverse student populations.

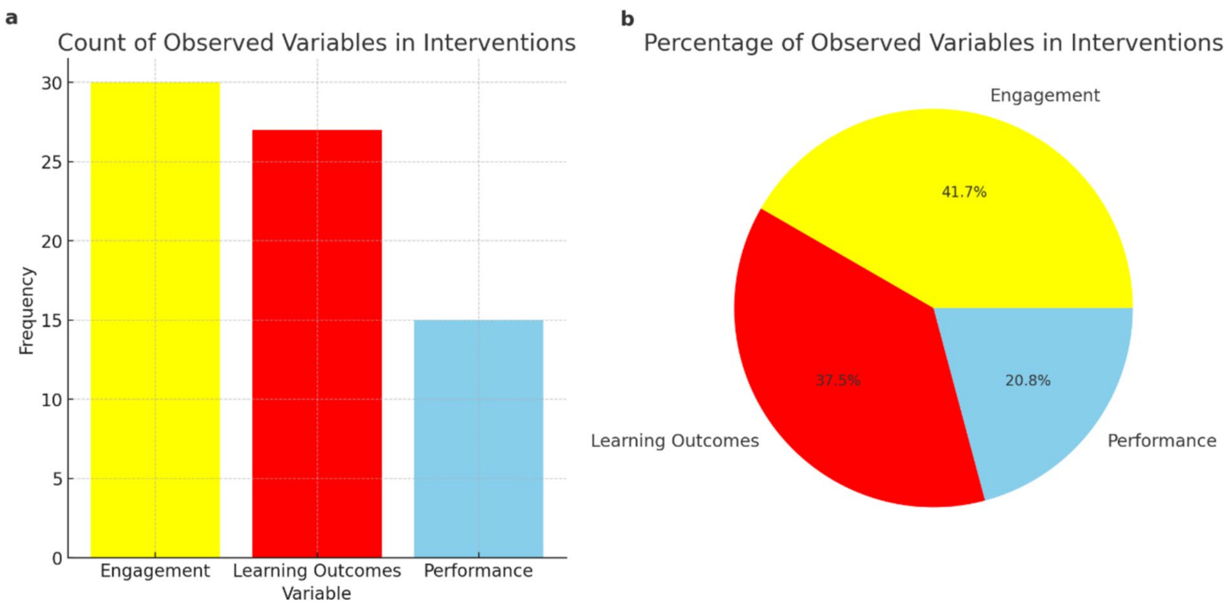

FIGURE 3
(A) Bar chart showing the count of observed variables (Learning Outcomes, Engagement, and Performance) in the evaluated interventions. **(B)** Pie chart displaying the percentage distribution of the observed variables.

(1993) employed game-based learning to teach engineering design and cryptography, respectively. These studies underline the potential of serious games to facilitate a more engaging and effective learning process across various STEM subjects.

Integrating multiple technologies into educational frameworks has also been explored. Playfoot et al. (2020) described the integration of various novel technologies, including AR/VR, Fab-Lab, Virtual Labs, and gamification, for teaching STEM subjects. In a related study, Playfoot et al. (2019) focused on integrating gamification and game-based learning within STEM education, utilizing AR/VR, Fab-Lab, Virtual Labs, user profiling, and self-directed learning. These comprehensive approaches demonstrate the potential of combining different technologies to create rich, interactive learning environments that cater to diverse educational needs.

Addressing environmental and biological education through serious games has been another key focus. Mystakidis et al. (2021) developed a digital educational escape room focusing on the role of enzymes in biology, while Christopoulos et al. (2023) designed a VR escape room for biology education, specifically on the operation of enzymes. Nunes et al. (2016) implemented game-based learning to raise environmental awareness through activities focused on recycling, reusing garbage, and practicing waste reduction. These interventions highlight the applicability of serious games in teaching complex biological processes and environmental sustainability concepts.

Narrative-centered educational games and role-playing games also feature prominently in the evaluated studies. Hodges et al. (2020) introduced Virtual Vet, a game focused on human body systems, while Di Fuccio et al. (2019) designed a role-playing game for teachers to train and apply digital creativity in classrooms, including coding activities. Riera and Vigário (2016) utilized dynamic 3D simulators, HOME I/O and FACTORY I/O, for control education. These studies reflect the diverse applications of serious games in different educational contexts, emphasizing the role of narrative and simulation in enhancing learning experiences.

3.3 Analysis of observed variables

The analysis of interventions highlights the predominant focus on three key variables: Learning Outcomes, Engagement, and Performance (Figure 3, Tables 1, and Supplementary Table S1). Engagement was the most frequently observed variable (Figure 3A), appearing in 41.7% of the interventions (Figure 3B). This suggests that maintaining student interest and motivation is a primary goal of educational interventions using serious games. Studies like Mystakidis et al. (2021) and Playfoot et al. (2020) emphasize the importance of engagement as it directly impacts the willingness of students to participate and immerse themselves in the learning process. The use of narrative-centered games, as noted in Hodges et al. (2020), and the integration of AR and VR technologies, such as in Câmara Olim et al. (2024), are effective strategies to captivate students' attention and encourage active learning.

Learning Outcomes were the second most frequently observed variable, accounting for 37.5% of the interventions. This emphasizes the role of serious games in enhancing the knowledge and skills of students. Studies such as Klein et al. (2020) and Chee (2010) demonstrate the effectiveness of serious games in improving representational fluency in physics and understanding of chemistry concepts, respectively. These findings suggest that serious games are particularly effective in conveying complex scientific ideas, making them more understandable and retainable for students. This focus aligns well with the overarching aim of STEM education, which is to cultivate a deep understanding of scientific and mathematical principles.

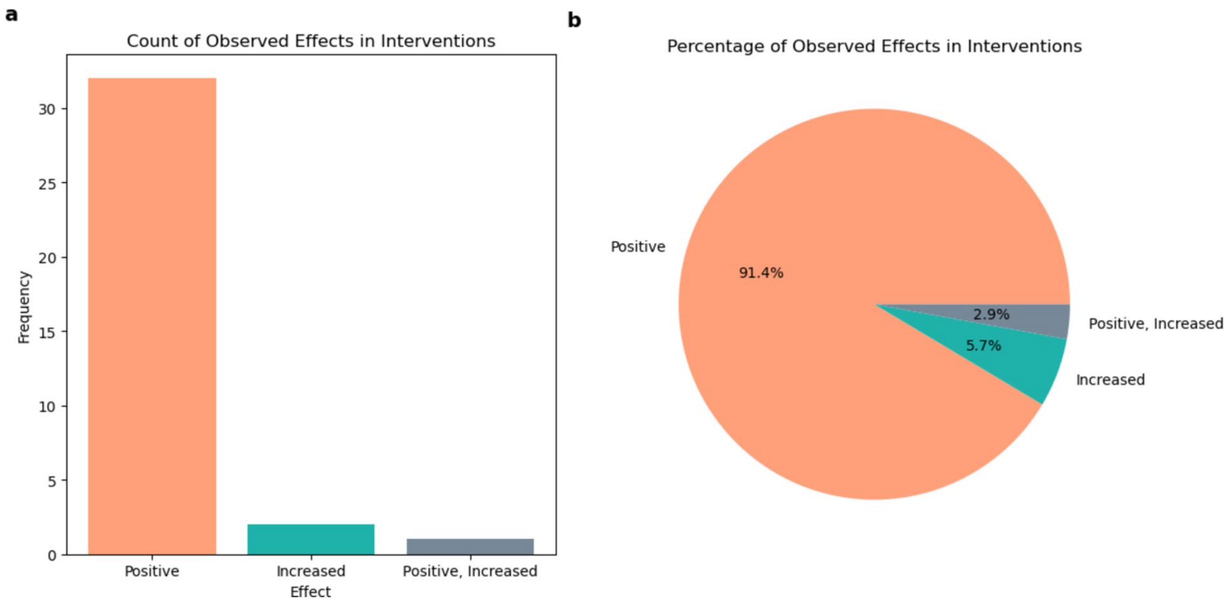

FIGURE 4
(A) Bar chart showing the count of observed effects (Positive and Increased) in the evaluated interventions. **(B)** Pie chart displaying the percentage distribution of the observed effects.

Performance, although observed less frequently (20.8%), remains a significant variable in assessing the effectiveness of serious games. Performance outcomes measure the practical application of learned knowledge and skills. Studies like Gocheva et al. (2020) and Iturrate et al. (2013) demonstrate how serious games can improve students' performance in specific tasks, such as solving mathematical problems and programming. These findings suggest that serious games not only enhance theoretical understanding but also improve practical competencies, which are crucial in STEM fields.

The observed results from interventions provide compelling evidence for the effectiveness of serious games in enhancing STEM education. The balanced focus on engagement, learning outcomes, and performance ensures that these interventions are not only educational but also engaging and practically relevant. Additionally, the integration of interactive elements such as VR, AR, and game-based learning appears to be a successful strategy for achieving these educational goals.

3.4 Analysis of observed effects

The data presented in Figure 4 illustrates the predominantly positive impact of these interventions, with a noteworthy absence of negative or neutral effects (see Table 1 and Supplementary Table S1). In particular, Figure 4A shows the count of observed effects in the evaluated interventions. Out of 37 studies, 34 reported a positive effect, while 2 studies reported an increased effect and 1 study reported both a positive and increased effect. This strong prevalence of positive outcomes, representing 91.4% of the interventions, highlights the efficacy of serious games in enhancing educational experiences in STEM fields. Interventions such as those by Di Fuccio et al. (2019) and Gocheva et al. (2020), which focus on improving digital creativity in classrooms and developing mobile mathematics educational games, respectively, exemplify how serious games can positively influence learning outcomes and performance.

Figure 4B presents the percentage distribution of observed effects. The data shows that 91.4% of the studies reported a positive effect, 5.7% reported an increased effect, and 2.9% reported both a positive and increased effect. This distribution reflects the successful integration of serious games into educational contexts. Studies such as Chan et al. (2023) and Nunes et al. (2016) demonstrated positive effects on learning outcomes and engagement, further supporting the widespread applicability of serious games in diverse STEM disciplines. Interestingly, no interventions reported negative, decreased, or neutral effects. Several factors could contribute to this observation:

- Publication Bias, there may be a publication bias where studies with positive outcomes are more likely to be published than those with negative or neutral results. Researchers and journals might favor reporting successful interventions, thus skewing the available data toward positive effects.
- Design Efficacy, serious games are inherently designed to engage and educate, utilizing interactive and immersive methods that are typically more effective than traditional teaching techniques. This design efficacy likely contributes to the predominance of positive outcomes.
- Continuous Improvement, the field of educational technology and serious games is rapidly evolving, with continuous improvements in design, implementation, and evaluation. The iterative development processes ensure that only the most effective strategies are deployed, leading to predominantly positive outcomes.
- Gamification Elements, serious games often incorporate elements of gamification that enhance motivation and engagement, which

are critical factors for effective learning. A strong emphasis on these aspects can naturally lead to more positive educational experiences and outcomes.

To emphasize, most of the interventions analyzed in this study demonstrate a positive effect. This consistent trend can be attributed to several key factors, which align with contemporary educational theories emphasizing active and experiential learning.

- Firstly, the use of interactive and immersive technologies, such as serious games and VR, facilitates deeper cognitive engagement by making abstract and complex concepts tangible and accessible. For example, Câmara Olim et al. (2024) reported that a tangible interface using physical cubes representing chemical elements significantly enhanced students' understanding and retention of abstract chemistry concepts. Similarly, Falah et al. (2021) demonstrated that a VR-based game allowed students to visualize 3D molecular structures, resulting in improved performance and student perceptions.
- Secondly, the incorporation of adaptive advice mechanisms and gamification elements, such as points, badges, and leaderboards, effectively boosts motivation and engagement. These elements provide immediate feedback and recognition, which align well with intrinsic motivation theories. Zhao et al. (2022) showed that interactive animations in programming games provided adaptive feedback that made complex concepts easier to grasp. Klein et al. (2020) also found that interactive puzzles designed to teach vector fields encouraged thoughtful engagement by providing immediate feedback and discouraging trial-and-error approaches.
- Moreover, the integration of educational content with game mechanics and storytelling appears to create a compelling and motivating learning environment, which enhances the educational experience. Ferro et al. (2022) noted that a 3D game set in a virtual environment, where students played as characters such as physicists and chemists, fostered engagement and acquisition of 21st-century skills despite some language barriers. This supports the notion that aligning game design with educational objectives, as discussed by Mostafa and Faragallah (2019), enhances knowledge retention and learning outcomes through immersive, context-rich scenarios.
- Finally, the alignment of these interventions with constructivist learning theories, which advocate for active learning through exploration and hands-on experiences, further highlights their positive impact. For instance, Hodges et al. (2020) reported that a veterinary office simulation game significantly improved students' understanding of body systems through role-playing and interactive feedback. This practical application of theoretical knowledge in a simulated environment allows learners to actively engage with the content, which is critical for retention and deeper understanding.

3.5 Areas of serious game interest

The analysis of the distribution of studies by STEM categories, as presented in Figure 5, provides a comprehensive overview of how serious games have been applied across different educational components (Table 3). The categorization into Sciences, Technology, Engineering, and Mathematics (i.e., STEM) helps to elucidate the focus areas and potential gaps in the research panorama. To categorize the studies, each field of application was assigned to one of the four STEM categories based on the primary subject matter of the intervention:

- Sciences. This category includes studies related to disciplines such as Chemistry, Medicinal Chemistry, Biology, Anatomy, Marine Ecology and Aquaculture, Environmental Education, and Computational Science. For instance, the study by Falah et al. (2021) focused on the use of VR for medicinal chemistry education, and Nunes et al. (2016) implemented game-based learning for environmental awareness.
- Technology. This category covers studies related to Computer Science and Information Security. For example, Zhao et al. (2022) explored game-based learning for programming courses, and Mostafa and Faragallah (2019) examined educational games for information security.
- Engineering. This category includes studies related to Engineering and Programming. An example is Rajan et al. (2010), which developed a game teaching the engineering design process, and Iturrate et al. (2013), which used a remote laboratory-based serious game for programming learning.
- This category includes studies focused on Mathematics, Mathematics and Biology, and Cryptography. Bouzid et al. (2017) developed a digital game to support elementary mathematics learning, and González-Tablas et al. (1993) utilized a card game for learning cryptography.

Then, Figure 5A shows the count of studies by STEM categories. The highest number of studies is in the Sciences category, with 25 studies, followed by Mathematics with 5 studies, Engineering with 4 studies, and Technology with 1 study. This distribution suggests a strong emphasis on applying serious games in scientific education. The high number of studies in sciences might be due to the wide range of disciplines it encompasses, including both physical and life sciences.

Figure 5B presents the percentage distribution of studies by STEM categories. The Sciences category accounts for 71.4% of the studies, indicating a significant portion of the interventions focus on scientific subjects. Mathematics represents 14.3%, Engineering accounts for 11.4%, and Technology makes up 2.9%. The substantial proportion of studies in Sciences and Mathematics demonstrates the potential of serious games to enhance understanding and skills in these areas. For instance, Gocheva et al. (2020) developed mobile mathematics educational games for 3rd-grade students, highlighting the use of serious games to make mathematics more engaging and accessible.

The predominant focus on Sciences indicates that this area is currently leading in the application of serious games for educational purposes. The relatively lower representation of Technology and Engineering suggests potential areas for further research and development. Given the rapid advancements in technology and the increasing importance of engineering skills in the modern workforce, there is a significant opportunity to expand the use of serious games in these fields. Future studies should aim to balance the distribution across all STEM categories, ensuring that innovative educational tools like serious games are utilized to their full potential in every discipline. Additionally, interdisciplinary approaches that integrate elements

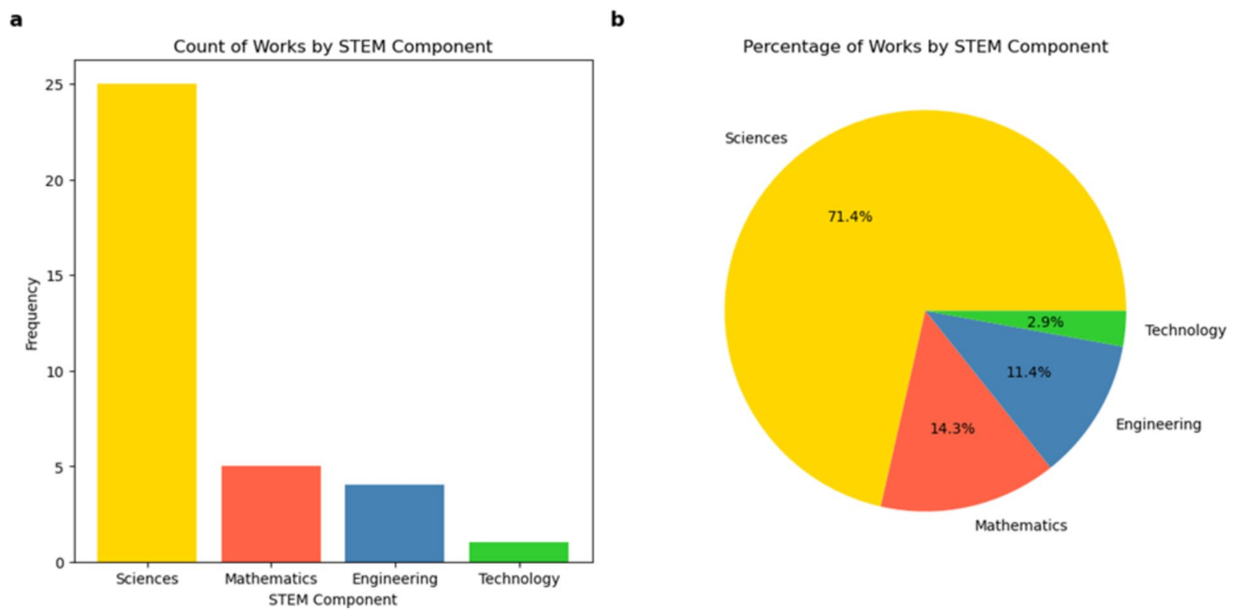

FIGURE 5
(A) Bar chart showing the count of studies by STEM categories. The categories include Science, Technology, Engineering, and Mathematics. **(B)** Pie chart displaying the percentage distribution of studies by STEM categories.

from multiple STEM categories could provide holistic educational experiences and foster a more comprehensive skill set among learners.

3.6 Stage of employed serious game

The analysis of the stages of serious game tools, as illustrated in Figure 6 and Supplementary Table S2, provides valuable insights into the development and implementation of these educational interventions across STEM education. Figure 6A shows the count of studies at various stages of implementation. Most studies (ChemCaper, n.d.) are categorized as Prototypes, indicating that many tools are still in the developmental and testing phases. This stage allows for iterative improvements and adjustments based on initial feedback and testing outcomes. Fully implemented tools, representing 15 studies, have been developed and applied in real educational settings, suggesting strong confidence in the efficacy of serious games for educational purposes and reflecting the extensive testing and validation these tools have undergone. Furthermore, Figure 6B presents the percentage distribution of studies by stage. Prototypes account for 48.6% of the studies, demonstrating significant ongoing development and experimentation. Fully implemented tools represent 42.9%, indicating a substantial portion of research has focused on tools ready for practical application. Pilot studies constitute 8.6%, reflecting early-stage testing and initial feasibility assessments.

The high proportion of prototype and fully implemented serious game tools suggests that these interventions are increasingly being recognized for their practical utility in enhancing STEM education. Studies such as Nunes et al. (2016) and Riera and Vigário (2016) have shown positive outcomes in terms of engagement and learning effectiveness, supporting the viability of these tools in educational settings. The presence of a significant number of prototypes indicates ongoing innovation and refinement in the field of serious games. For instance, Ferro et al. (2022) and Falah et al. (2021) highlight the experimental nature of these tools, where developers continuously seek to optimize and tailor gaming experiences to meet educational needs better. The relatively smaller proportion of pilot studies suggests that while many tools have progressed beyond the initial testing phase, there is still a need for more preliminary research to explore novel approaches and innovative game designs. Pilot studies, such as those conducted by Câmara Olim et al. (2024) and Rajan et al. (2010), play a critical role in identifying potential challenges and gathering initial feedback that can inform subsequent stages of development.

While the high rate of fully implemented tools is promising, it is essential to address the challenges associated with the integration of serious games into educational curricula. Issues such as technology reliability, educator resistance, and variability in student engagement, as noted in studies like Gocheva et al. (2020), must be carefully managed to ensure successful implementation. Moreover, the transition from prototype to fully implemented tools requires rigorous testing and validation. Researchers and developers should focus on longitudinal studies to assess the long-term impact of serious games on student learning outcomes and engagement. Additionally, incorporating feedback from educators and students during the development phase can help create more user-centered designs that are both effective and engaging.

3.7 Type of serious game used

The analysis of the types of serious games used in STEM education, as illustrated in Figure 7 and Supplementary Table S3, provides insights into the current landscape and diversity of these educational tools. Figure 7A shows that the most prominent type of serious game identified in the review is the Digital Game category, which constitutes 60.0% of the studies (as also depicted in Figure 7B).

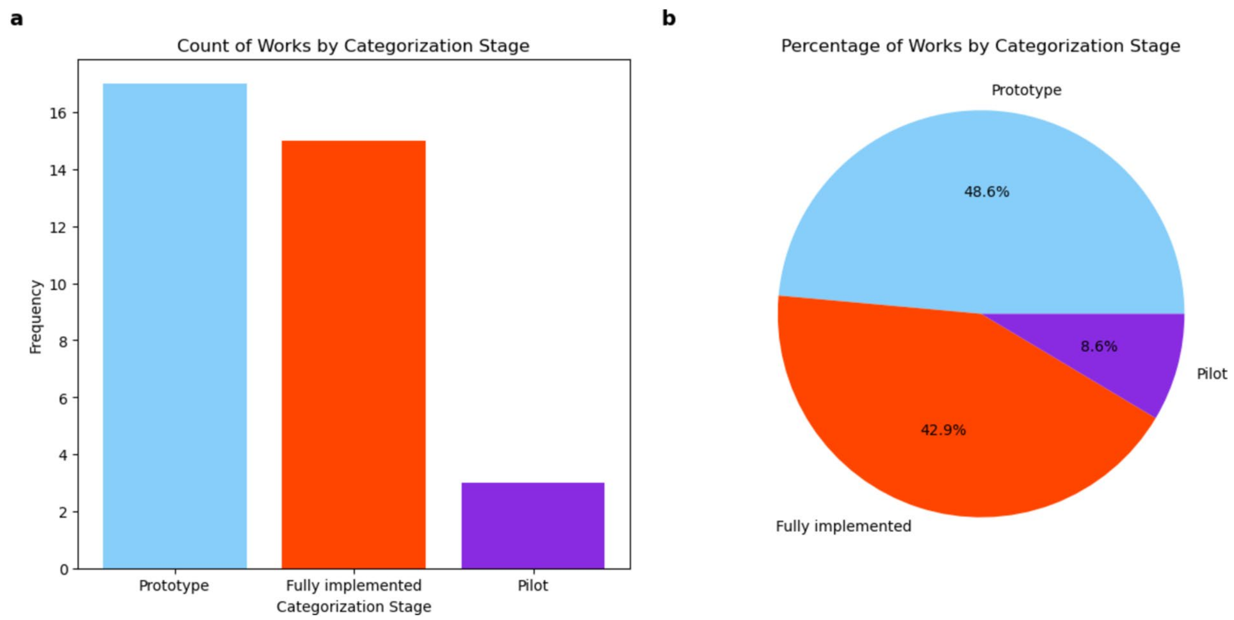

FIGURE 6
(A) Bar chart showing the count of studies by the stage of serious game tool. The stages include Fully implemented, Prototype, and Pilot. **(B)** Pie chart displaying the percentage distribution of studies by the stage of serious game tool.

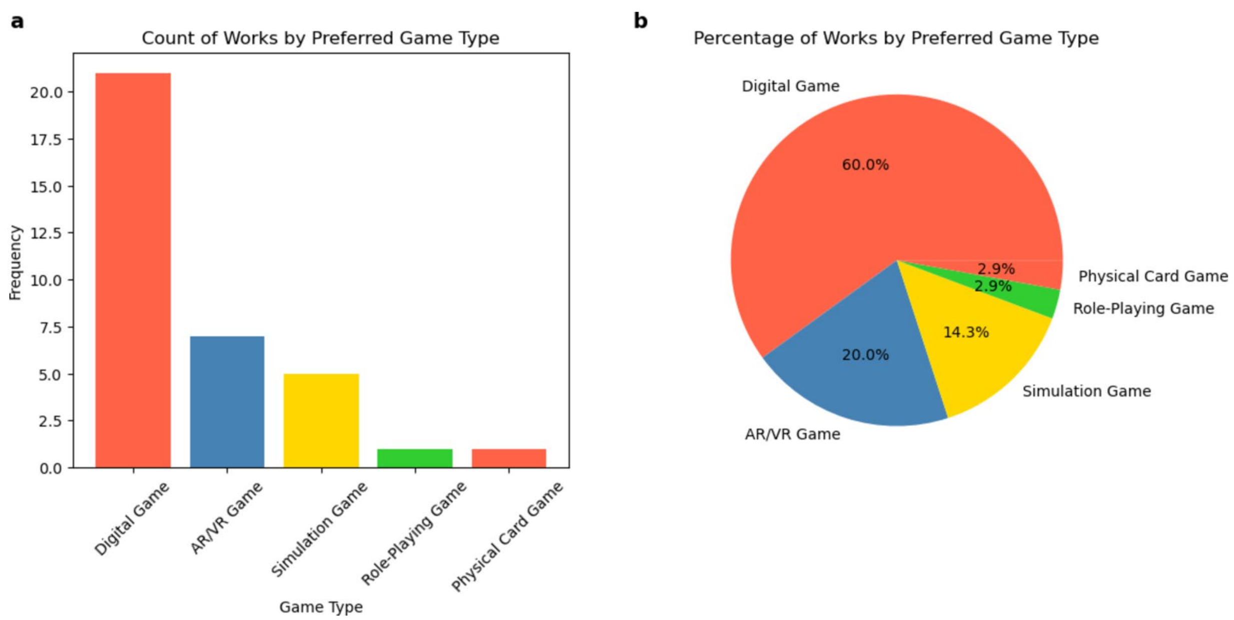

FIGURE 7
(A) Bar chart showing the count of studies by type of serious game. **(B)** Pie chart displaying the percentage distribution of studies by type of serious game.

This prevalence indicates a strong preference for digital platforms to deliver interactive and engaging educational content. Digital games are versatile and can be easily distributed across various devices, making them accessible to a wide range of learners. Studies such as Zhao et al. (2022) and Hodges et al. (2020) have demonstrated the effectiveness of digital games in enhancing engagement and learning outcomes in STEM education. Their widespread adoption is likely due to the ease of integration with existing digital infrastructure in educational institutions.

The second most common category is AR/VR Games, accounting for 20.0% of the studies. These games utilize VR and AR technologies to create immersive and interactive learning experiences. Studies like Falah et al. (2021) and Mystakidis et al. (2021) have shown that VR-based games can significantly increase engagement and motivation among students by offering unique advantages in presenting complex scientific concepts in an accessible and engaging manner.

Simulation Games, representing 14.3% of the studies, offer another valuable approach to STEM education. These games are designed to replicate real-world processes or systems, allowing students to experiment and explore within a controlled virtual environment. Simulation games are particularly beneficial for subjects that involve complex systems or phenomena, such as engineering, physics, and environmental science. For instance, studies like Rajan et al. (2010) used simulation games to teach engineering design processes, highlighting their potential to enhance practical understanding and problem-solving skills.

Role-Playing Games and Physical Card Games, each constituting 2.9% of the studies, are less prevalent but still valuable. Role-playing games allow students to take on different characters or roles, fostering collaboration, communication, and social interaction. Physical card games, while more traditional, can be used effectively to teach concepts such as cryptography and information security, as demonstrated by González-Tablas et al. (1993).

The diversity of serious game types in STEM education underscores the multifaceted approach educators are taking to enhance learning outcomes. Moving forward, it is essential to continue exploring and validating the effectiveness of these different types of serious games in diverse educational contexts. This comprehensive approach will ensure that educational practices are not only engaging but also effective in achieving desired learning outcomes. Additionally, further research is needed to address the challenges associated with integrating these technologies into the curriculum, such as technical issues, educator training, and student accessibility.

To point out, Figure 7A highlights five distinct types of serious games used in STEM education studies: Digital Games, AR/VR Games, Simulation Games, Role-Playing Games, and Physical Card Games. The frequency data provides insights into the popularity and perhaps the accessibility of these game types within educational research.

- Digital Games
  - Popularity and Accessibility: Digital games are the most frequently studied type, likely due to their accessibility and ease of use across various devices. This high frequency suggests that digital games are a preferred choice for educators looking to incorporate game-based learning in STEM due to lower technological and cost barriers compared to VR or simulation-based games.
  - Effectiveness: The studies on digital games often report positive outcomes in student engagement and knowledge retention, particularly in general STEM topics like mathematics and introductory programming. However, digital games may not provide the immersive depth found in simulation or AR/VR games, which could limit their effectiveness in complex subjects requiring hands-on experience.
- AR/VR Games
  - Immersive Learning: AR/VR games are popular for their immersive qualities, allowing students to interact with 3D environments. These games are particularly valuable in subjects requiring spatial understanding, such as chemistry and biology, where abstract concepts can be visualized in a more concrete form.
  - Challenges: Despite their benefits, AR/VR games have significant technological requirements, making them less accessible to under-resourced institutions. They also require more robust hardware, which may not be available in all educational settings. The moderate frequency of these games in the studies may reflect these logistical and financial challenges.
- Simulation Games
  - Real-World Application: Simulation games allow students to practice skills in a virtual yet realistic environment, which is particularly valuable for engineering and environmental science. This type of game helps students develop problem-solving skills and apply theoretical knowledge in practical scenarios.
  - Implementation Barriers: Simulation games, however, often require specialized software and significant computational power, which may limit their use in typical classroom settings. Their relatively lower frequency suggests that while effective, simulations are less commonly used due to these additional requirements.
- Role-Playing Games
  - Engagement through Storytelling: Role-playing games, though less common, are known for increasing engagement by allowing students to assume specific roles or characters within a storyline. In STEM education, these games can encourage ethical thinking and decision-making, which may be particularly useful in fields like environmental science.
  - Alignment with STEM Goals: However, role-playing games may not always align well with rigorous STEM curricula, as they often prioritize narrative and engagement over content depth. Their lower frequency likely reflects these alignment challenges, as well as the additional time and planning required for educators to integrate role-playing effectively.
- Physical Card Games
  - Limited Applicability: Physical card games were the least represented type. While they may be useful for specific concepts, like cryptography or basic math, their scope and interactivity are limited compared to digital and VR games. Physical card games may be constrained to simpler educational tasks, which may explain their infrequent use in the studies reviewed.

3.8 Analysis of the number of participants or sample size

The analysis of the sample sizes across various studies on serious games for STEM education, as depicted in Figure 8, reveals several critical insights into the design and execution of these studies. Figure 8A illustrates the number of participants in each study, showcasing a significant range from as few as 10 participants to over 500. The largest sample size was observed in the study by Troiano et al. (2019), which included 317 participants for proficiency

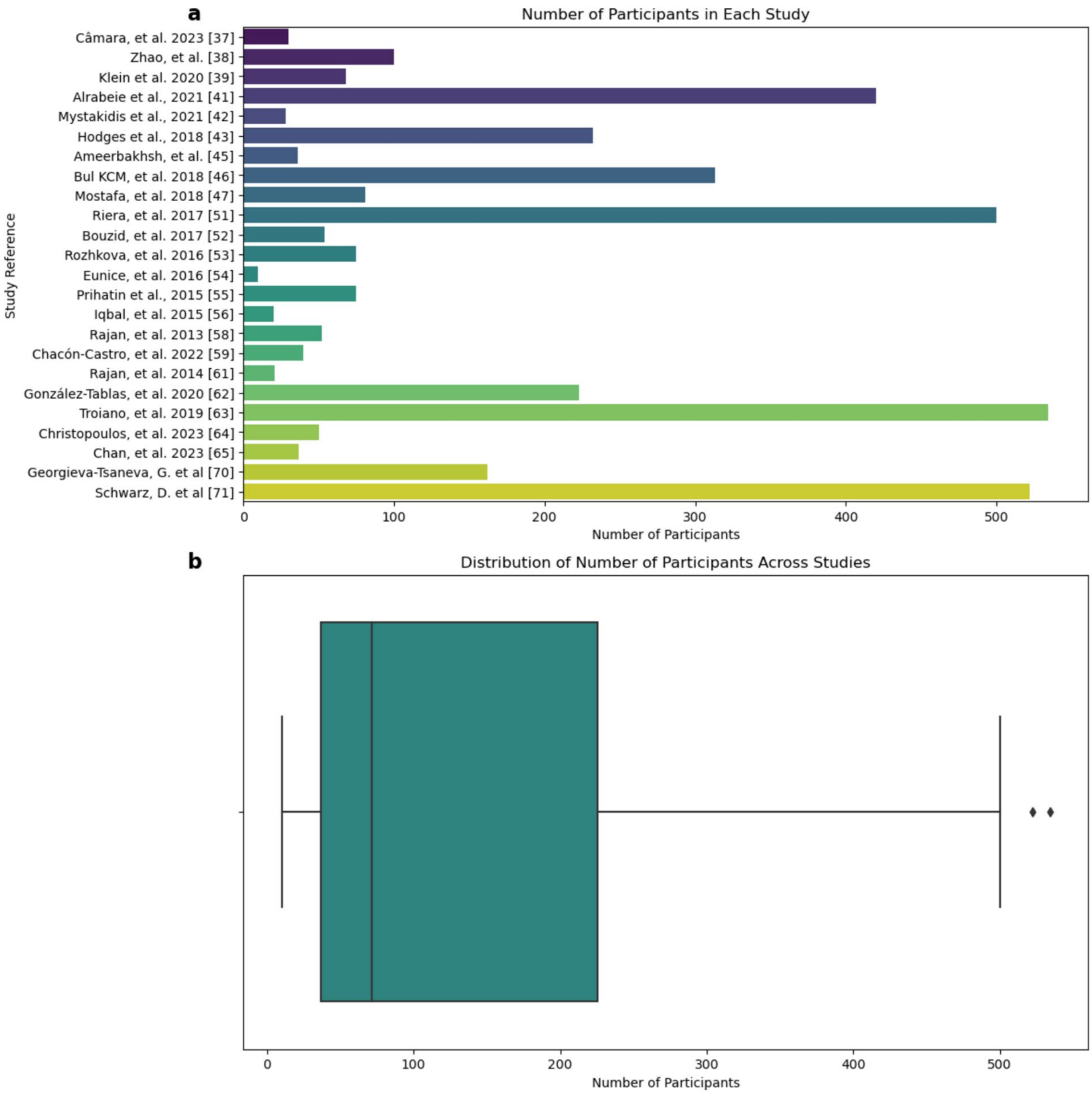

FIGURE 8
(A) Bar chart showing the number of participants in each study. **(B)** Box plot displaying the distribution of the number of participants across all studies. The box plot indicates the median, interquartile range, and potential outliers in the sample sizes, providing insights into the central tendency and variability of the participant numbers.

assessment and 217 for development assessment. On the other hand, studies such as those by Nunes et al. (2016) and Prihatin et al. (2015) had relatively small sample sizes of 10 and 75 participants, respectively. This variability in sample sizes highlights the diverse approaches and resources available to researchers in this field. Larger sample sizes, as seen in studies by Troiano et al. (2019) and González-Tablas et al. (1993), are generally indicative of more robust and generalizable findings. However, smaller studies can provide detailed insights and are often more feasible for initial exploratory research or pilot studies.

Figure 8B provides a summary of the distribution of the number of participants across all studies. The median sample size is relatively modest, and the interquartile range suggests that many studies have fewer than 150 participants. This concentration of smaller sample sizes may impact the statistical power of the studies and their ability to detect significant effects. Additionally, Figure 8B identifies outliers, such as the studies by Troiano et al. (2019) and Schwarz et al. (2013), which had significantly larger sample sizes compared to the median. These outliers highlight the disparity in study designs and resource availability among different research teams. While large sample sizes can enhance the validity of conclusions drawn, they also require more substantial logistical and financial support.

To improve the reliability and validity of research on serious games for STEM education, future studies could consider the following recommendations:

- Increase Sample Sizes: Researchers should aim to increase their sample sizes to enhance the generalizability of their findings. Collaborative studies across multiple institutions can help achieve this.
- Provide Detailed Demographics: Studies should provide detailed demographic information about participants to better understand the context and potential biases. This includes age, gender, educational background, and prior experience with serious games.
- Standardized Methodologies: Developing standardized methodologies for measuring the impact of serious games can help reduce variability and allow for more direct comparisons across studies.
- Pilot Studies: For new or exploratory interventions, conducting pilot studies with smaller sample sizes can help refine methodologies before scaling up.
- Combining Quantitative and Qualitative Data: Combining quantitative and qualitative data can provide a more comprehensive understanding of the impact of serious games. This approach allows for capturing detailed participant experiences alongside measurable outcomes.

In terms of sample size to further emphasize, Figure 8 highlights a significant variation across studies, with many studies involving relatively small numbers of participants, while only a few have large sample sizes. This variation in participant numbers introduces several limitations that impact the reliability, generalizability, and interpretability of findings in serious games research within STEM education.

- Limited Generalizability Due to Small Sample Sizes:
  - The majority of studies in the review have sample sizes below 100 participants, as shown in the distribution boxplot (Panel b). Small sample sizes can restrict the generalizability of results, as findings from these studies may not accurately represent broader populations. For instance, educational outcomes observed in a small group might vary significantly when applied to a larger or more diverse population.
  - Small sample sizes also increase the risk of statistical anomalies, making it challenging to differentiate between genuine effects of serious games on STEM learning and random variations. This limitation is particularly critical for educators and policymakers who rely on such research to inform large-scale decisions.
- Reduced Statistical Power and Increased Error Margins:
  - Studies with small participant numbers often suffer from reduced statistical power, meaning they may not detect meaningful differences or effects of serious game interventions in STEM education. Consequently, some studies may report inconclusive or non-significant findings not because the intervention lacks impact, but due to insufficient sample sizes to reveal subtle effects.
  - This limitation affects the ability of researchers to draw definitive conclusions, which may contribute to inconsistent findings across studies in the field of serious games. Moreover, studies with limited statistical power can yield larger error margins, further complicating efforts to interpret and synthesize results across different studies.
- Potential Overreliance on Short Intervention Durations:
  - While not explicitly shown in the figure, many studies in serious games research, especially those with small samples, tend to use shorter intervention durations. Short interventions can provide a limited view of the long-term effects of serious games on student engagement and learning outcomes in STEM. Short-term studies may show initial improvements in motivation or knowledge acquisition, but these effects may diminish over time or fail to translate into sustained educational gains.
  - Future research with larger samples and longer study durations could provide a more comprehensive understanding of how serious games impact STEM education over time, addressing both immediate and sustained effects on learning.
- Skewed Representation of Larger Studies:
  - While there are a few studies with sample sizes exceeding 300 participants, these outliers (visible in Panel b) may exert a disproportionate influence on the overall conclusions of meta-analyses or reviews. Studies with unusually large samples can create an imbalance, as they may dominate pooled analyses despite the broader trend of smaller sample sizes. This imbalance can lead to overgeneralized interpretations, assuming the results from a few large studies represent typical outcomes in serious games research.
- Implications for Future Research:
  - To overcome these limitations, future studies should aim to include larger, more diverse samples that better reflect the varied educational settings in which serious games might be applied. Increasing the sample size across studies would enhance the reliability and generalizability of findings, offering more robust evidence for the effectiveness of serious games in STEM.
  - Researchers should also consider extending intervention durations to capture the long-term impacts of serious games. Longer-term studies can provide valuable insights into whether the initial benefits observed in short-term studies persist and translate into lasting improvements in STEM skills and knowledge.

3.9 Study design used

The analysis of the study designs provides important insights into the methodologies employed and their prevalence. Figure 9 and Supplementary Table S3 illustrates the distribution of study designs, grouped into broader categories to facilitate understanding and comparison. To systematically analyze the study designs, we categorized them into three broader groups:

- Observational Studies: This category includes studies such as large-scale observational studies, those with practical applications, and studies with feedback from participants. These studies focus on understanding the effects of serious games in natural educational settings without manipulating variables.
- Experimental and Quasi-Experimental Designs: This group encompasses randomized controlled trials (RCTs), quasi-experimental designs, and experimental research. These studies

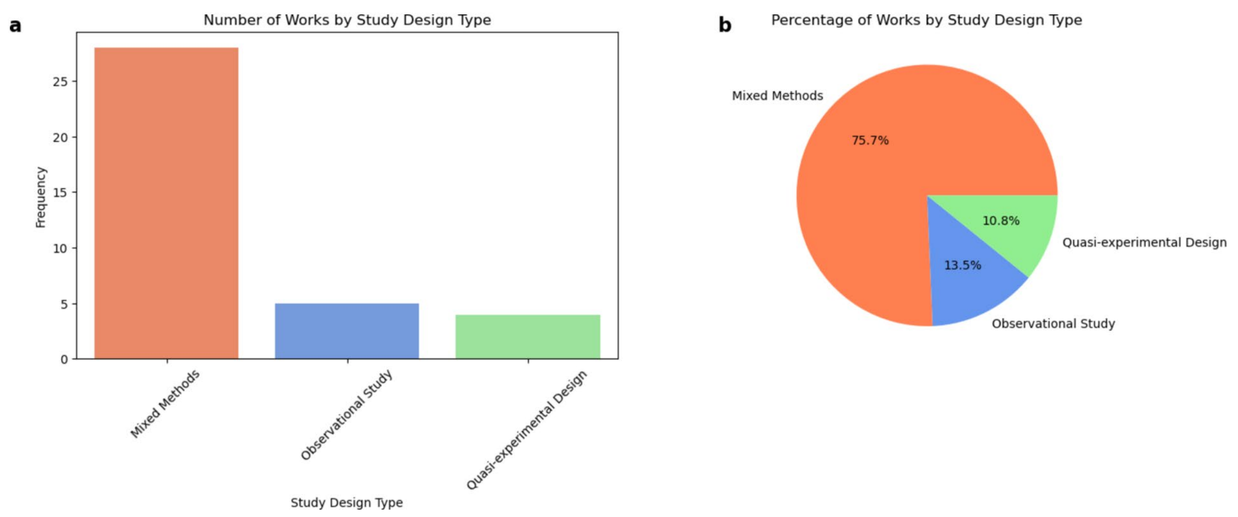

FIGURE 9
(A) Number of Works by Study Design Type: Mixed Methods, Observational Studies, and Quasi-experimental Designs. **(B)** Percentage of Works by Study Design Typ.

aim to establish causality and test the effectiveness of serious games under controlled conditions.

- Mixed-Methods and Design-Based Research: This category includes studies utilizing both qualitative and quantitative methods, as well as those based on design-based research (DBR). These approaches offer a holistic view of the impact of serious games, integrating multiple data sources and perspectives to understand the educational outcomes comprehensively.

Now, Figure 9A shows the count of studies by study design type, indicating the prevalence of each type of research design among the reviewed studies. The most common study design is Mixed Methods, with 28 studies (75.7%), followed by Observational Studies with 5 studies (13.5%), and Quasi-experimental Designs with 4 studies (10.8%). This prevalence suggests that a significant portion of the research relies on mixed-methods approaches to capture the complex and multifaceted impacts of serious games on STEM education.

In this context, the prominence of mixed-methods approaches in the reviewed studies highlights a focus on capturing both qualitative and quantitative aspects of serious games' impact. Mixed-methods and design-based research provide a comprehensive understanding by integrating different types of data, such as test scores, engagement metrics, and participant feedback. This approach allows researchers to capture a more nuanced view of how serious games influence learning outcomes, engagement, and motivation in STEM education.

Observational Studies provide valuable insights into how serious games are used in real-world educational settings, capturing diverse contexts and participant experiences. These studies are crucial for understanding how serious games function in practice and the various factors that influence their effectiveness.

Experimental and Quasi-Experimental Designs allow for controlled comparisons and causal inferences, establishing the efficacy of serious games in enhancing learning outcomes. The inclusion of randomized controlled trials (RCTs) in this category underscores the rigorous efforts to validate the educational benefits of serious games through well-structured and scientifically robust methodologies.

Hence, the distribution of study designs in research on serious games for STEM education reflects a balanced emphasis on empirical validation, practical implementation, and comprehensive analysis. By leveraging these diverse methodologies, future research can continue to advance the field and contribute to the effective integration of serious games in educational practice.

3.10 Participants demographics

Based on Supplementary Table S3 and Figure 10 presents a pie chart categorizing the participant demographics of studies into five broad groups:

- Primary School Students includes studies focused on children in primary school, ranging from young children to pre-adolescents.
- Secondary School Students encompasses junior high and high school students.
- University Students consist of undergraduate and postgraduate students, as well as specific groups of university-level students such as first-term physics students and pharmacy students.
- Teachers and Educational Professionals includes studies involving primary and secondary school teachers and educational professionals.
- Mixed Demographic and Special Categories covers studies involving participants from multiple demographic backgrounds or those with special characteristics, such as vocational school students and children with attention deficit hyperactivity disorder (ADHD).

In Figure 10, the largest portions of the studies focus on Secondary School Students (26.9%), University Students (26.9%), and Mixed Demographic and Special Categories (26.9%). This balanced distribution indicates a comprehensive research approach, addressing various educational levels and special needs. Representing 15.4% of the studies, primary school students are a significant focus group, highlighting the interest in early STEM education and the potential of

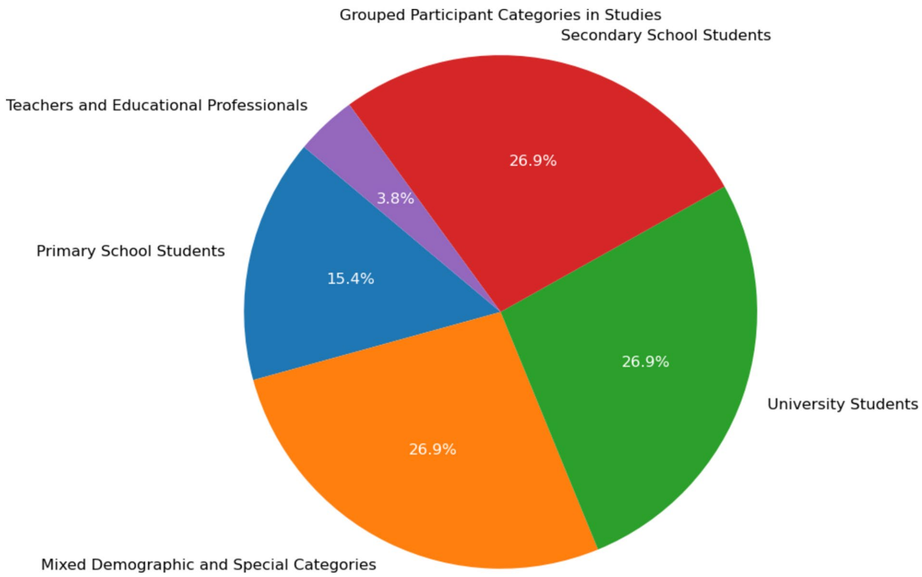

FIGURE 10
Pie chart showing the proportion of studies focusing on different grouped participant categories.

serious games to engage young learners in foundational subjects. At 3.8%, this is the smallest category, indicating a relatively lower focus on studies involving teachers and educational professionals. Their inclusion is crucial as they play a significant role in the implementation and success of serious games in educational settings. Remarkable observations were also detected:

- The low percentage of studies involving teachers and educational professionals suggests a gap in research. Future studies should involve these stakeholders more comprehensively to understand the practical implementation challenges and benefits from the educators' perspectives.
- The significant focus on university students and mixed demographics indicates that serious games are widely applied across diverse educational contexts. However, more tailored studies focusing on specific age groups or educational stages are needed to understand the unique impacts and adaptations required for different learners.
- A substantial portion of studies focusing on primary school students highlight the importance of early STEM education. Serious games can engage young learners, making complex subjects more accessible and enjoyable.

The significant interest in early STEM education through serious games suggests a promising avenue for future research to foster foundational skills and engagement from a young age. By exploring these diverse demographics, researchers can ensure that serious games are effectively tailored to meet the needs of all learners.

3.11 Generated data

To promote transparency and support further research, we have documented our data generation process at each stage of this systematic review. This comprehensive documentation ensures that our methods are not only transparent but also reproducible, allowing for rigorous scrutiny. For researchers interested in exploring our findings in greater detail or employing our dataset in future studies, we have made this information readily available. The complete dataset and an exhaustive description of our systematic review methodology can be accessed at the following link: https://doi.org/10.17605/OSF.IO/PTCQH.

4 Challenges of serious game in stem education

4.1 Challenges of serious game in STEM education

As noted, integrating serious games into STEM education offers significant potential, but also poses several challenges that need to be addressed to ensure their effective use (Supplementary Table S1). Here, we expose the key challenges associated with implementing serious games, as identified in our systematic review.

- High costs associated with the development and implementation of serious games present a significant barrier. Creating effective educational games requires investment in design, programming, and educational expertise. Additionally, the cost of hardware, software, and ongoing maintenance can be prohibitive, especially for underfunded schools.
- Technological limitations, such as inadequate access to necessary hardware and software, can hinder the use of serious games. Schools in rural or underfunded areas may struggle with limited internet bandwidth and outdated equipment, impeding the integration of advanced educational technologies.
- Effective use of serious games in the classroom requires teachers to be well-trained in both the technology and its pedagogical application. Resistance due to lack of familiarity or confidence in

using new technologies is common. Comprehensive professional development and support are essential to ensure teachers can effectively integrate serious games into their teaching strategies.
- Aligning serious game content with educational standards and learning objectives can be complex. Educators must balance traditional teaching methods with game-based learning to ensure that games complement rather than replace conventional instruction. This integration requires careful planning and flexibility within the curriculum.
- Assessing the educational impact of serious games presents a challenge. Traditional assessment methods may not capture the skills and knowledge gained through game-based learning. Developing new assessment tools that accurately measure the effectiveness of serious games is crucial.
- While serious games can boost engagement and motivation, not all students may respond positively. Differences in learning styles and prior gaming experience can influence how students interact with educational games. Ensuring inclusivity and accessibility is essential to maximize their impact.
- The educational value of serious games depends on the quality of their content. Games that prioritize entertainment over education can fail to achieve learning objectives. High standards in game design and development are necessary to ensure educational effectiveness.

4.2 Comparison with previous literature reviews

The current systematic review significantly advances the understanding of serious games in STEM education by providing a comprehensive analysis of their impact on learning outcomes, performance, and engagement. Compared to previous literature reviews (Sanmugam et al., 2015; Coelho et al., 2020; Urdanivia Alarcon et al., 2023; Esterhuizen et al., 2022; Pellas et al., 2021; Kalmpourtzis et al., 2020; Table 4), this review offers several novel insights and highlights important areas for further research and practical implementation. Unlike previous reviews that often focus on specific subjects or types of games, this review encompasses a wide range of serious games across various STEM subjects, including mathematics, physics, biology, chemistry, and engineering. This broad scope allows for a more comprehensive understanding of the impact of serious games. Earlier reviews, such as those by Sanmugam et al. (2015) and Coelho et al. (2020), addressed the challenges of implementing gamified activities, but this review provides a detailed analysis of specific barriers, including high development costs, technological limitations, and the need for better teacher training and curriculum integration.

Furthermore, this review places a strong emphasis on learning outcomes, performance, and engagement. It builds on findings from previous studies, such as those by Pellas et al. (2021), offering a nuanced understanding of how different game designs and educational contexts influence these key outcomes. Additionally, this review integrates findings across primary, secondary, and higher education, as well as professional training, offering a holistic view of the educational landscape. In comparison to Urdanavia et al. (2023), who analyzed instructional models and inquiry-based learning in secondary science education, this review incorporates findings from primary and higher education and focuses on various STEM subjects. It also supports the conclusions of Esterhuizen et al. (2022), who investigated the potential of digital serious games, emphasizing gamification principles, and extending the discussion to include practical challenges and broader educational contexts.

As noted, this review provides a comparative analysis of different game types and their impact on engagement and learning outcomes. Additionally, the study by Kalmpourtzis et al. (2020), which studied the impact of game-based learning courses on students' understanding of educational game design, highlights the importance of aligning learning objectives with game mechanics. This review offers further insights into the practical implementation of serious games in STEM education. Importantly, this review highlights the need for further research to address identified challenges and gaps in the literature. It emphasizes the importance of exploring new game designs, integrating serious games into curricula more effectively, and conducting longitudinal studies to assess the long-term impact of serious games on STEM education. By featuring these future research needs, the review paves the way for continued advancement in this field.

4.3 General recommendations for future research

Based on the findings and insights from our current systematic review, we offer the following recommendations for future research:

- The integration of serious games within STEM education highlights the need for a globally recognized framework that outlines essential elements of game-based learning within a learner-centric educational model. This framework should establish core standards and provide a cohesive understanding of how serious games can be effectively implemented to enhance STEM pedagogy. It must maintain flexibility to accommodate ongoing advancements in technology and evolving theories in educational psychology.
- Future research should aim to illuminate how serious games can support not only student engagement but also personalized learning pathways. By adapting educational experiences to meet the diverse needs and preferences of individual learners, serious games can offer tailored educational solutions that maximize learning outcomes.
- As serious games become increasingly prevalent in education, it is crucial to address accompanying ethical considerations and privacy concerns. Subsequent studies should thoroughly investigate these aspects, focusing particularly on the ethical use of data and the implications of employing serious games in student assessments and training. Ensuring that the adoption of serious games adheres to ethical standards and respects confidentiality is essential.
- A comprehensive evaluation of the various serious games currently used in STEM education is vital. Such assessments should determine the effectiveness of different platforms and applications in achieving specific educational goals and meeting user requirements. Establishing a repository of best practices and identifying the most impactful educational technologies will provide crucial guidance for educators and institutions. This resource will be fundamental for informed decision-making regarding the adoption of serious games in STEM curricula, ensuring these educational tools are utilized to their full potential to enrich STEM education.

TABLE 4 Comparison with previous review papers.

Reference	Technologies Used			Areas						Variable	Contribution to the knowledge	
	Immersive Technologies	Digital Games	Board Games	Mathematics	Physics	Biology	Chemistry	Engineer	Technology		Description	Impact
Sanmugam et al. (2015)	–	X	–	X	X	–	–	–	–	Engagement, cognitive impact, social impact, emotional impact	Role of gamification as an educational technology tool in engaging and motivating students based on an analysis review of several kinds of literature.	Gamified activities can enhance practical competencies, promote higher-order thinking skills, and improve student engagement and motivation. However, it also noted that the cognitive impact might not be significant compared to traditional methods, and there could be issues with technology implementation and teacher capability

(Continued)

TABLE 4 (Continued)

Reference	Technologies Used			Areas						Variable	Contribution to the knowledge	
	Immersive Technologies	Digital Games	Board Games	Mathematics	Physics	Biology	Chemistry	Engineer	Technology		Description	Impact
Coelho et al. (2020)	X	X	–	–	–	X	–	–	X	Engagement, knowledge retention, usability, awareness, user experience	Examines the impact of serious pervasive games on user engagement and learning, with a focus on environmental education and game-based learning.	Serious pervasive games can significantly enhance learning outcomes by increasing user engagement and knowledge retention
Urdanivia Alarcon et al. (2023)	–	X	–	X	X	–	–	–	X	Engagement, knowledge retention, scientific reasoning, problem-solving skills, student motivation, inquiry competence	Analyzes instructional models, subject areas, and developmental areas implemented by secondary school teachers in science education using inquiry-based learning (IBL).	Emphasizes the importance of continuous teacher training and the use of constructivist methods to improve student outcomes.

(Continued)

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TABLE 4 (Continued)

Reference	Technologies Used			Areas						Variable	Contribution to the knowledge	
	Immersive Technologies	Digital Games	Board Games	Mathematics	Physics	Biology	Chemistry	Engineer	Technology		Description	Impact
Esterhuizen et al. (2022)	–	X	–	–	–	–	–	–	X	Engagement, knowledge retention, reflection, feedback, story-based environment, structuring of content	Investigates the potential of using digital serious games in educational environments by integrating principles from gamification, ludology, and pedagogy.	The findings suggest that serious games designed with these principles can enhance engagement and knowledge retention, providing a structured and interactive learning experience.
Pellas et al. (2021)	X	X	–	–	–	–	–	–	X	Performance, engagement, knowledge retention, student motivation	Effectiveness of 3D virtual worlds in enhancing student engagement and participation across various learning subjects.	The use of 3DVWs positively affected students' learning outcomes, improving their achievements and motivation, particularly in subjects

(Continued)

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TABLE 4 (Continued)

Reference	Technologies Used			Areas						Variable	Contribution to the knowledge	
	Immersive Technologies	Digital Games	Board Games	Mathematics	Physics	Biology	Chemistry	Engineer	Technology		Description	Impact
Kalmpourtzis and Romero (2020)	–	X	–	–	–	–	–	–	X	Performance, engagement, knowledge retention, coherence between learning mechanics and game mechanics, learning objectives, assessment	Investigates the impact of a game-based learning course on students' understanding of designing educational games with constructive alignment	The course improved students' ability to align learning objectives with game mechanics, enhancing the educational effectiveness of their game designs.
This review	X	X	X	X	X	X	X	X	X	Learning outcomes, performance, and engagement	This systematic review explores the impact of serious games on performance, engagement, and learning outcomes. This review highlights the benefits, challenges, and effectiveness of integrating serious games into STEM curricula.	This review evidence the importance of further research to address these issues and provides valuable insights for educators, developers, and policymakers to effectively implement serious games in educational settings.

By addressing these recommendations, future research can build on the foundations laid by this systematic review and contribute to the development of more effective, ethical, and innovative serious games for STEM education. These efforts will help maximize the potential of serious games to enhance learning outcomes and engagement across diverse educational contexts.

4.4 Limitations and restrictions

This systematic review acknowledges certain limitations inherent to its scope and methodology. Given the rapid evolution and extensive literature on serious games in STEM education, there is a risk of inadvertently overlooking relevant studies. Precision in formulating search queries and selecting keywords was critical to ensuring the breadth of our review. Although the "snowballing" technique was instrumental in identifying key studies and terminology, some significant contributions may have been excluded due to constraints in scope and time.

Additionally, the review applied selective inclusion criteria, focusing on peer-reviewed journal articles and conference papers published in English. This language restriction likely resulted in the exclusion of valuable research conducted in other languages, which may have limited the global representation and diversity of perspectives. To partially address this, we prepared Supplementary Table S4, which lists 29 relevant studies published in languages other than English. This table provides a resource for future researchers to explore non-English contributions systematically and highlights the importance of considering multilingual sources.

Moreover, important findings in non-journal formats or less widely circulated publications may have been missed, potentially impacting the understanding of serious games' international application in STEM education. Future research should consider broadening inclusion criteria to incorporate studies in multiple languages and grey literature, such as dissertations and technical reports, which could offer a more comprehensive view of global advancements and applications of serious games in STEM education. This expanded approach would not only increase the generalizability of systematic review findings but also present a more inclusive picture of innovations and practices worldwide.

By addressing these limitations, future systematic reviews can provide a fuller understanding of the impact and potential of serious games in STEM education, ensuring that diverse perspectives and contributions are represented. This, in turn, can lead to more robust and inclusive educational strategies that make the most of serious games' potential.

4.5 Challenges of serious games implementation

While serious games offer promising benefits for STEM education, their practical implementation faces several significant challenges. A critical understanding of these limitations is essential for educators, policymakers, and developers aiming to integrate serious games effectively.

- The deployment of serious games often requires advanced technology, including high-quality devices, reliable internet access, and technical support. These requirements can be a barrier, particularly in underfunded schools or regions with limited resources, potentially leading to inequalities in access to these tools. Schools without the necessary infrastructure may struggle to implement serious games effectively, which could hinder the scalability and inclusivity of these educational innovations.
- Effective integration of serious games requires educators to have a solid understanding of both the technology and pedagogical strategies to incorporate games into the curriculum meaningfully. Many teachers may lack the necessary training, confidence, or time to fully utilize these tools, which can result in superficial or inconsistent use. Professional development programs specifically aimed at training educators in game-based learning are essential but often underfunded or unavailable.
- Another challenge is aligning serious games with existing curricula. Many games may not fully match curriculum standards or learning objectives, making it difficult for educators to justify their use within structured STEM courses. In some cases, serious games may emphasize engagement at the expense of educational depth, which could lead to gaps in student understanding. Ensuring that games are designed with curriculum requirements in mind is necessary for maximizing their educational impact.
- The development, maintenance, and implementation of serious games can be costly, involving both software and hardware expenses. These financial requirements can be prohibitive, particularly for public institutions with limited budgets. Additionally, ongoing costs for updates, technical support, and new resources may prevent sustainable use of these tools over time.
- While serious games are generally associated with increased student engagement, there is also a risk that students may focus more on gameplay mechanics than on learning objectives, potentially leading to distraction. Striking a balance between engaging gameplay and academic rigor is essential to ensure that students benefit educationally rather than merely engaging in game elements.
- Serious games often collect data on student performance and behavior to tailor learning experiences. However, this raises ethical concerns related to data privacy and security. Schools and educators must be cautious about the collection and use of student data, adhering to privacy standards to protect students' personal information. Additionally, educators and parents may have concerns about screen time, particularly for younger students, which needs to be carefully managed.

5 Conclusion

In summary, this systematic review aimed to explore the impact of serious games on performance, engagement, and learning outcomes in STEM education for students and professionals. By meticulously analyzing 31 studies published between 2010 and 2023, we have provided a comprehensive synthesis of the current state of research on serious games in STEM education. Our findings indicate that serious games positively impact learning outcomes, engagement, and performance in STEM education. The studies evaluated demonstrate that serious games can effectively enhance knowledge acquisition, retention, and application of skills in STEM subjects.

Additionally, the integration of serious games into curricula has been shown to increase student engagement, making learning more interactive and enjoyable.

The assessed studies encompassed diverse educational levels, from primary school to higher education and professional training, highlighting the broad applicability of serious games across different age groups and educational settings. This versatility confirms the potential of serious games to be widely adopted in various educational contexts. Despite the promising results, our review identified several challenges and limitations. High development costs and technological barriers remain significant obstacles to the effective implementation of serious games. There is also a critical need for comprehensive teacher training to ensure educators can effectively integrate serious games into their curricula. Additionally, ethical considerations and data privacy concerns must be addressed to ensure the responsible use of serious games in education.

To address these challenges, we recommend that future research focus on developing a globally recognized framework for serious games in STEM education, conducting longitudinal studies to assess long-term impacts, and exploring the application of serious games in diverse educational settings. Expanding future reviews to include studies published in multiple languages and grey literature will provide a more inclusive understanding of global advancements. Lastly, this review emphasizes the potential of serious games as powerful educational tools in STEM education. By enhancing learning outcomes, engagement, and performance, serious games offer innovative and effective strategies to support STEM education. Addressing the identified challenges and gaps in the current literature is essential for maximizing their impact and ensuring their successful integration into educational practices. This review contributes to the body of knowledge on serious games in education, highlighting their potential to transform STEM learning and providing a foundation for future research and practice in this field.

Author contributions

TT: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DV: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. PV: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. NC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. CV: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. SB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1432982/full#supplementary-material

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