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SURVEY

Advancing Engineering Education Through Serious Games: A Systematic Literature Review of Technological Innovation, Challenges, and Future Directions

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ABSTRACT The rapid evolution of engineering education has intensified the demand for instructional approaches that can effectively support experiential learning, complex problem solving, and student engagement beyond traditional lecture-based methods. In this context, serious games have emerged as a promising pedagogical paradigm, particularly when combined with emerging technologies such as artificial intelligence (AI) and immersive environments. This study presents a systematic literature review (SLR) of serious games in engineering education, synthesizing peer-reviewed research published between 2020 and 2025 and indexed in Scopus and IEEE Xplore. Following the PRISMA 2020 framework, 63 primary studies were rigorously selected and analyzed to identify dominant technological innovations, application domains, game genres, research methodologies, and implementation challenges. The findings indicate that web- and mobile-based serious games remain the most prevalent due to their accessibility and scalability, while immersive technologies especially Virtual Reality (VR) demonstrate strong potential for enhancing spatial understanding and experiential learning in complex engineering domains. However, the integration of AI-driven adaptivity remains limited, with only a small subset of studies employing machine learning or computer vision techniques for personalized learning support. Key challenges include high development and infrastructure costs, limited pedagogical alignment, inconsistent evaluation frameworks, and insufficient attention to long-term learning outcomes and soft skill development. This review contributes a comprehensive cross-disciplinary perspective on technological trends and research gaps, highlighting the need for pedagogically grounded, AI-enhanced, and scalable serious game frameworks to support sustainable innovation in engineering education.

INDEX TERMS Serious games, engineering education, virtual reality, artificial intelligence, adaptive learning, game-based learning.

I. INTRODUCTION

Engineering education is increasingly shaped by rapid technological advancement and the growing complexity of contemporary engineering practice. Modern engineering problems are rarely confined to a single discipline instead, they involve dynamic systems, multiple constraints, and context-dependent decision-making [1]. Consequently, conventional instructional approaches that rely primarily on lectures and predefined laboratory exercises often provide limited support for developing higher-order cognitive skills, problem-solving abilities, and practical competencies. Recent studies therefore emphasize the importance of learning models that actively engage students and promote experiential, problem-oriented,

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and student-centered learning within engineering education [2], [3], [4], [5]. In response to these demands, digital learning technologies have become integral components of modern engineering curricula. Interactive tools such as simulations and virtual laboratories are widely adopted to complement traditional instruction and enhance learning outcomes. Prior research indicates that these technologies can significantly improve students' conceptual understanding and engagement when they are meaningfully aligned with instructional design principles [6], [7]. Within this context, serious games have gained increasing attention due to their ability to integrate educational objectives with interactive gameplay. By embedding engineering concepts within contextualized tasks and challenges, serious games support experiential learning, iterative decision-making, and continuous feedback features that are particularly relevant for abstract, procedural, and systems-oriented engineering topics [8]. The pedagogical potential of serious games has been further expanded by advances in emerging technologies, particularly artificial intelligence (AI) and immersive environments. AI-based techniques enable learning systems to adapt to individual learners by analyzing interaction patterns, adjusting task difficulty, and delivering real-time, targeted feedback. When incorporated into serious games, AI supports adaptive scenarios, intelligent tutoring functions, and data-driven assessment, thereby enhancing personalization and learner engagement [8], [9], [10]. In parallel, immersive technologies namely virtual reality (VR), augmented reality (AR), and mixed reality (MR) enable learners to interact with simulated environments that represent complex, hazardous, or otherwise inaccessible engineering settings. VR- and MR-based serious games, in particular, provide high levels of immersion that allow students to explore spatially complex systems, manipulate virtual components, and engage in realistic engineering tasks without physical risk [11], [12]. Applications of immersive serious games have been reported across multiple engineering domains, including mechanical, electrical, construction, maritime, and energy engineering, highlighting their versatility for procedural training and spatial learning. Despite these promising developments, the integration of serious games into engineering education remains uneven. Reported challenges include high development and maintenance costs, limited institutional infrastructure, varying levels of instructor preparedness, and the absence of widely accepted pedagogical and evaluation frameworks. Moreover, many existing studies describe isolated implementations or small-scale pilot projects, which constrain broader adoption and limit insights into long-term effectiveness and scalability. Evaluation practices also vary substantially across studies, with no clear consensus on how learning outcomes, skill transfer, and sustained educational impact should be systematically assessed [13], [14], [15], [16].

These limitations indicate the need for more systematic and comprehensive research in this area. Although several review studies have examined serious games in education, many focus on a single technology, a specific engineering discipline, or general STEM contexts. Consequently, there is still a lack of cross-disciplinary reviews that jointly consider multiple technological developments such as AI-driven adaptivity and immersive environments within engineering education [17], [18], [19]. This paper presents a systematic literature review (SLR) on the use of serious games in engineering education. The objectives of this study are to identify the dominant technological approaches employed in serious games and to examine the challenges and opportunities associated with their implementation. By analyzing technological trends in relation to engineering domains, game characteristics, research methods, and evaluation strategies, this review provides an overview of the current research landscape and highlights directions for future work. Accordingly, the study is guided by the following research questions:

RQ1: Which technological approaches are most frequently applied in serious games for engineering education?

RQ2: What challenges and research opportunities are reported in the implementation of serious games in engineering education?

The remainder of this paper is structured as follows. Section II discusses related work and outlines existing limitations. Section III describes the systematic review methodology. Section IV presents the review results, which are discussed in Section V. Section VI concludes the paper and outlines implications for future research and practice.

II. RELATED WORK

In the past few years, serious games have attracted growing interest in engineering education, particularly as tools to support experiential and interactive learning. A number of studies have explored their benefits in promoting student engagement and improving conceptual understanding. However, despite these encouraging developments, several areas remain underexplored, especially in terms of how emerging technologies can enhance the depth and scalability of game-based learning. Moreover, questions around institutional readiness, long-term integration, and cross-disciplinary applicability continue to challenge their widespread adoption.

Castro et al. offered a systematic mapping study of game-based approaches in software engineering education [21]. Their work classifies different forms of game use, ranging from digital game-based learning to gamification, and sheds light on how these methods are currently applied. While insightful, the study stops short of discussing how AI could be used to tailor game experiences based on student learning patterns or how immersive environments might simulate real-world engineering problems, which are key aspects this review aims to address. Similarly, Rodriguez et al. examined the use of serious play to teach agile methods, compiling a range of best practices and evaluation models [22]. Yet, their focus remains within the confines of software engineering and doesn't extend to the broader field of engineering disciplines. Technologies like VR, MR, and AI-powered tutors, which have the potential to transform how engineering concepts are taught across disciplines, are notably absent from their discussion.

Zarate Perez et al. employed a science mapping approach to review two decades of digital game-based learning in engineering [23]. They identified growing interest in simulations and video-based games, but their analysis remains trend-focused. It offers limited insight into how recent innovations can be practically implemented in diverse educational settings. Other studies, like that of Sabri et al., provide a broader bibliometric perspective, charting the global growth of serious game publications [24]. While useful for understanding publication volume and topical focus, their study does not engage with the actual pedagogical or technological complexities faced by educators and developers. For example, it does not explore how digital twin technology could link simulated tasks with real-world system data to create deeper learning experiences. Giraldo et al. offer a more focused look at game-based learning in electrical and energy engineering [25]. Their findings underscore the value of simulation tools in reinforcing technical knowledge. However, like much of the existing literature, the study remains confined to one subfield. It does not explore how similar approaches might be adapted across other engineering domains, or how infrastructure and institutional support affect broader deployment.

Taken together, these studies point to several important research gaps. First, while immersive and game-based methods have shown clear promise, the role of AI in driving adaptive, personalized learning within serious games is still not well understood. Second, despite the growing interest in immersive technologies, tools such as digital twins and metaverses are still underutilized in current frameworks despite their great potential to create authentic real-world simulation environments. Third, many existing reviews focus on narrow domains or publication trends, without addressing cross-disciplinary integration, institutional adoption, or long-term pedagogical alignment. Recent review studies published in 2025 further demonstrate the growing academic interest in serious games and immersive technologies for education; however, their scope and analytical focus remain limited in several respects. For instance, recent reviews concentrate on virtual reality–based serious games, emphasizing immersion, usability, and user experience outcomes, while largely treating AI as a peripheral or supportive component rather than a core driver of adaptive learning [26]. Moreover, these reviews often restrict their analysis to specific technologies or learning outcomes, without systematically examining how AI-driven personalization, immersive environments, and emerging paradigms such as digital twins converge within engineering education contexts. In contrast to these technology-centric or domain-specific reviews, the present SLR adopts a broader, integrative perspective by jointly analyzing AI-enhanced adaptivity, immersive technologies (VR, AR, and MR), and their application across multiple engineering disciplines. This approach enables a more comprehensive understanding of how technological innovation, pedagogical alignment, and institutional constraints interact in shaping the effectiveness and scalability of serious games in engineering education.

This review aims to close those gaps by examining not only which technological innovations are being introduced into serious games, but also how they are being implemented or not implemented in real educational settings. By bringing together studies across engineering disciplines and highlighting both the technical and institutional barriers to adoption, this review offers a more complete picture of what is needed to scale serious games from pilot tools to integrated learning solutions.

III. RESEARCH STRATEGY

The study uses the SLR methodology, as it is one of the most robust approaches developed for the identification, evaluation, and systematic synthesis of existing research on a specific topic. The SLR methodology is more applicable in addressing the integration of AI into engineering education, as it is a complex research question and establishes a clear framework for systematic analysis of the existing literature. This helps to ensure that the findings are not only reliable but also comprehensive enough to base the continuation of knowledge, identifying gaps in existing research. The study follows the PRISMA framework to improve the quality and transparency of the review process. The PRISMA Guidelines are internationally recognized for their ability to improve rigor, reproducibility, and consistency in the systematic review process [27]. The process is well documented and reproducible. Therefore, the validity of the findings is improved by adhering to this framework. PRISMA organizes the review process into four stages that provide a systematic roadmap to improve and evaluate a series of studies.

A. ELIGIBILITY CRITERIA

In this study, we use several criteria that must be met to obtain eligible data, including:

- **Type of Study**: The study should be an empirical research (e.g., experimental study, case study) or a theoretical framework directly related to the application of serious games in engineering education.
- **Topic**: This study should address the profound role of play in improving engineering education, with a particular focus on educational methodologies, outcomes, challenges, and impacts on student learning in engineering disciplines.
- **Type of Participant**: Study participants must be engineering students in various subfields (e.g., mechanical, civil, electrical, and software engineering) or related educational professionals involved in teaching engineering courses.
- **Studies**: Both theoretical studies (conceptual applications of serious games) and empirical studies (quantitative or qualitative research studies) are included.

It provides a broad range of insights from basic theory to practical applications.
- **Language**: Only studies published in English are considered to ensure accessibility for an international audience.
- **Publication Status**: The study focuses on peer reviewed journal articles, conference proceedings, and book chapters published between 2020 and 2025 to capture the latest advances in the field.

This combination of inclusion criteria ensures that the review reflects a comprehensive spectrum of recent developments in the use of serious games in engineering education.

B. SEARCH AND SCREENING PROCESS

The search strategy we used in this study initially adopted a multi tier concept across academic databases and repositories to ensure extensive and complete literature searches. This systematic literature review employed a structured search across three major academic databases: Scopus and IEEE Xplore, selected for their comprehensive coverage of peer-reviewed research in engineering, computing, and educational technology. The search targeted studies addressing the application of serious games in engineering education. Where in the early stages of the search, the search is carried out using a key string.

"Serious AND Game AND Engineering AND Education AND Learning"

These queries were applied to the title, abstract, and keyword of the articles in the database to retrieve notes that directly address the intersection of serious game and engineering education. The records drawn in the initial phase of the search from SCOPUS (406) and IEEE (400), totaling 806 initial records. To address the differences in metadata standards across these various databases, we implemented a manual metadata harmonization process using spreadsheet tools. This step involved organizing all retrieved records into a unified format in Google Sheets, where attributes such as title, author, publication year, keywords, and source were standardized. Duplicate entries were identified and removed by comparing titles, DOIs, and author combinations. The primary goal of this harmonization was to ensure that all extracted data from different sources could be consistently compared and analyzed, thereby enhancing the accuracy and reliability of our findings.

Keyword normalization was also conducted manually through spreadsheet filtering and supported by basic Python scripting. This included grouping variations of key terms (e.g., "virtual reality" and "VR") and standardizing terminology across records. Using Python libraries such as pandas, we generated keyword frequency lists to identify high-frequency terms, which helped in aligning thematic trends across studies. The use of Python also allowed for the generation of term frequency visualizations and co-occurrence patterns through simple dataframes and plotting tools like matplotlib. This step was crucial for ensuring that our thematic analysis accurately reflected the underlying themes in the literature, rather than merely lexical variations. The process of selecting articles in this study was carried out systematically through several steps. From the initial search, 806 articles were obtained that reflect the development of the application of serious games in engineering education in various disciplines. To ensure that the literature reviewed is up to date and relevant, the selection was then focused on several stages to ensure that only the most relevant studies were considered.

Figure 1 illustrates the systematic flow of this selection process, starting from the initial identification of 806 articles from SCOPUS and IEEE. Prior to screening, 476 records were removed, consisting of duplicate entries, non-English publications, studies published outside the defined timeframe, and articles not relevant to engineering education. As a result, 330 records were retained for the screening stage. During the screening phase, 129 records were excluded because they focused on sectors outside engineering education, such as business or private industry. This process resulted in 201 reports being sought for retrieval. Of these, 56 reports could not be retrieved, leaving 145 reports for eligibility assessment. In the eligibility stage, 72 reports were excluded because they were review papers or did not directly address the application of serious games in engineering education, or lacked empirical or theoretical contributions. Consequently, a total of 63 studies satisfied all inclusion criteria and were included in the final review. These selected studies, which are comprehensively listed in Table 1, were subsequently analyzed in depth to examine their implementation fields, game types, and research subjects, as well as to understand the methodologies employed, implementation challenges encountered, and their impact on learning outcomes within engineering education. This rigorous and transparent selection procedure ensures that the review is grounded in high-quality primary studies and provides a robust foundation for analyzing trends, methodological practices, and research gaps in serious game–based engineering education.

C. CODING AND DATA EXTRACTION

After selecting 63 articles, coding and data extraction were carried out intensively to identify the main points to be analyzed in this study. To ensure rigor and objectivity, the process involved two independent coders. We employed a systematic thematic analysis approach, which included several stages: familiarization with the data, initial coding of relevant information, actively searching for overarching themes, reviewing and refining these themes, and finally defining and clearly naming them. To assess inter-rater reliability (IRR), both coders independently coded approximately 20% of the included studies.

Agreement was evaluated using Cohen's Kappa, yielding a value of $\kappa = 0.79$, which indicates substantial agreement. Percentage agreement across all coding categories exceeded 85%. Any discrepancies were resolved through consensus

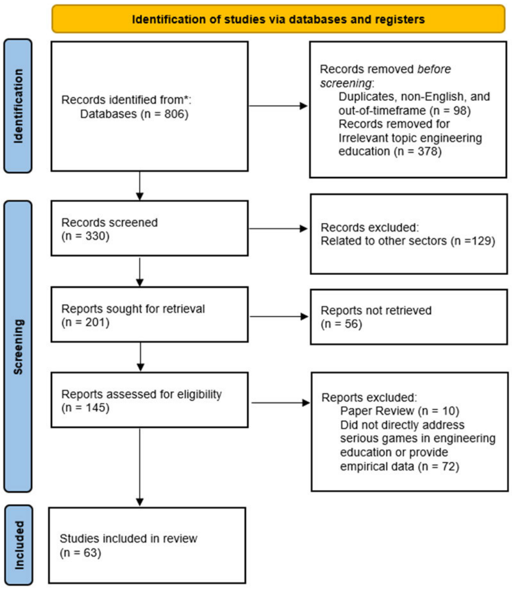

FIGURE 1. PRISMA 2020 flow diagram.

meetings, and all decisions were documented in a coding log to ensure transparency and reproducibility.

Investigator bias mitigation during data interpretation was addressed through several strategies. The involvement of two independent coders helped reduce individual bias by comparing perspectives and reaching consensus. Furthermore, we implemented researcher triangulation by engaging in in-depth discussions among the research team to validate findings and interpretations. This ensured that identified patterns and relationships between themes genuinely emerged from the data and were not influenced by pre-conceived notions. Thematic saturation was determined iteratively throughout the coding process. We continued to code articles until no new themes or categories emerged from the data, and existing themes were fully developed and interconnected. This approach ensured that sufficient data had been collected to draw comprehensive and credible conclusions from the reviewed literature. To make it easier to manage data, Google Sheets organizes articles based on various factors, such as the type of serious game used for example, simulations, role playing, or VR based games. In addition, the educational impact of these games is analyzed based on their contribution to learning outcomes, such as increased student engagement, technical skills development, and the acquisition of new knowledge. The study also classifies the research methodology, including experimental designs, surveys, and case studies. Finally, data on the target population is recorded in detail, covering the academic level and discipline of the research participants, such as undergraduate mechanical engineering students. The extracted data is then stored in CSV format and analyzed using Python libraries, such as Matplotlib and WordCloud, through the Google Colab platform. This visualization process allows for identifying patterns related to the most frequently used research methods, the types of serious games that are most widely applied, and the dominant educational impact in various studies. To ensure a more systematic classification of data, a coding scheme was developed so that each article can be categorized based on its characteristics, such as title, author, year of publication, research method, journal where the article was published, as well as the educational sector in which the research focused. This process is carried out in a flexible and exploratory manner, where new categories are added if studies are found that do not fully match the initial classification. This coding approach is designed to provide a comprehensive overview of the trends and patterns emerging in the serious game related literature in engineering education. For example, the impact of games on learning outcomes is categorized to identify their specific effects on students' skills and understanding. At the same time, classifying target populations helps uncover the academic disciplines that most adopt these methods. With a structured data management system, this study can draw more meaningful conclusions about the role of serious games in engineering education. In addition, additional tools such as word frequency analysis and word clouds are used to highlight key concepts and trends that often appear in the studies that have been studied.

D. GENERAL RESULT

Based on Figure 2, the publication trend on serious games in engineering education demonstrates a significant upward trajectory over time, particularly in the most recent year. Early publications were relatively limited, with four papers published in 2020 (6%), marking the initial stage of academic exploration of serious games in engineering contexts. The number of studies gradually increased in 2021 (8%) and 2022 (11%), reflecting growing scholarly attention during the post-pandemic digital transformation period.

Although a slight decrease is observed in 2023 (6%) and a moderate recovery in 2024 (10%), a substantial surge occurs in 2025, which dominates the distribution with 37 papers (59%). This sharp increase indicates an accelerating and sustained research focus on serious games in engineering education. The dominance of recent publications suggests growing technological maturity, wider pedagogical acceptance, and stronger institutional support for game-based learning initiatives.

The distribution of publications across major publishers indicates that research on serious games in engineering education is disseminated through a diverse range of academic outlets, with several dominant publishers contributing significantly to the field, as shown in Figure 3. Several publishers dominate the field, with ASEE, MDPI, and IEEE being the three most influential publishers in research on serious gaming and AI in engineering education. Other publishers, such as Springer Science and Business Media, Taylor & Francis, and the European Society of Engineering Education, also published three papers. Meanwhile, other major publishers such as John Wiley, Elsevier, and Virginia Polytechnic Institute each have one publication in the database. This

TABLE 1. List of serious game references for engineering education.

Ref	Implementation Field	Type of Games	Research Subject
[1]	Civil Engineering	Simulation	Climate Change Decision-Making
[2]	Civil Engineering	Strategy (Board Game)	Sustainable Building
[3]	Software Engineering	Turn-based Strategy	Exploratory Software Testing
[4]	Industrial Engineering	Simulation	Logistics Skill Development
[8]	Industrial Engineering	Simulation	Supply Chain Decision-Making
[9]	Computer Science	Simulation	Personalized Learning
[14]	Engineering (General)	Simulation	Learning Effectiveness
[18]	Electrical Engineering	Simulation (VR)	Wind Power Education
[19]	Maritime Engineering	Simulation (VR)	Technology Acceptance
[29]	Engineering Education	Simulation	Technology Acceptance Model
[31]	Software Engineering	Group Dynamic Game	Agile Project Management
[32]	Industrial Engineering	Simulation	Competitive ETO Market
[33]	Maritime Engineering	Simulation (VR)	Immersion Profiling
[34]	Electrical Engineering	Puzzle (Escape Room)	Digital Electronics
[35]	Chemical Engineering	Simulation	Vapour–Liquid Equilibrium
[36]	Electrical Engineering	Simulation (VR)	Electrical Circuits
[37]	Industrial Engineering	Simulation	Supply Chain Education
[38]	Software Engineering	Role-play (VR)	Scrum / Agile
[39]	Engineering Education	Simulation	Learning Feedback Impact
[40]	Software Engineering	Simulation	Video vs Game-Based Learning
[41]	Electrical Engineering	Educational Game	Basic Electronics
[42]	Software Engineering	Puzzle / Simulation	Code Review Practice
[43]	Industrial Engineering	Simulation (VR)	Remote Learning Assistant
[44]	Industrial Engineering	Simulation	Agile Hardware Development
[45]	Civil Engineering	Mixed Reality Simulation	Construction Sensing
[46]	Mechanical Engineering	Simulation	Statics & Dynamics
[47]	Maritime Engineering	Simulation	Maritime Economics
[48]	Engineering Education	Strategy	Student Performance vs Perception
[50]	Engineering Education	Serious Game	Digital Competence Assessment
[51]	Software Engineering	Role-play	Requirements Engineering (ISO 29148)
[52]	Software Engineering	Puzzle	Code Review
[53]	Software Engineering	Role-play	Software Estimation
[54]	Engineering Education	Gamified GBL	Employability Skills
[55]	Computer Science	Adventure	Cyber Security
[56]	Engineering Education	AI-based Tutoring	Intelligent Tutoring Systems
[57]	Engineering Education	Gamification	Blended Engineering Learning
[58]	Mechanical Engineering	Simulation (VR)	Active Thermography
[59]	Industrial Engineering	Simulation	Production & Logistics
[60]	Chemical Engineering	Gamified Learning	Laboratory Safety
[61]	Engineering Education	Cooperative Game	Transferable Skills
[62]	Computer Science	2D Platformer	C++ Programming
[63]	Computer Science	Gamified Learning System	Basic Programming Concepts
[64]	Software Engineering	Mystery / Role-play	Stakeholder Identification
[65]	Computer Graphics / Engineering	Inclusive Game	Accessibility & Prosthetics
[66]	Software Engineering	Platform Architecture	Serious Game Framework
[67]	Software Engineering	Strategy / Puzzle	White-box Testing
[68]	Computer Science	Simulation	Programming with Scaffolding
[69]	Education	Gamification	Student Motivation
[70]	Civil Engineering	Scoping Review	Gamification in Construction **(Review)**
[71]	Games Engineering	XR Interaction Study	XR Learning Evaluation
[72]	Engineering Education	Bibliometric Study	Serious Games Trends **(Review)**
[73]	Software Engineering	Systematic Review	Serious Games in SE **(Review)**
[74]	Software Engineering	Role-play	Requirements Ambiguity
[75]	Software Engineering	Narrative / Sci-Fi	Unit Testing & Debugging
[76]	Software Engineering	Simulation	Software Measurement (ISO 15939)
[77]	Industrial Engineering	Simulation	Supply Chain Integration
[78]	Industrial Engineering	Simulation (VR)	Bullwhip Effect
[79]	Marine Electrical Engineering	3D Simulation	Electrical Fault Troubleshooting
[80]	Engineering Project Management	Role-play	Empathy & Soft Skills
[81]	Software Engineering	Gamified Simulation	Software Process Quality
[82]	Systems Engineering	Team-Based Game	Intro to Systems Engineering
[83]	Civil Engineering	Hands-on Simulation	Lean Construction
[84]	Engineering Education	Role-Playing Game	Novelty Effect & Gaming Experience

distribution shows that research in this area is not only centered on a single publisher but has received widespread attention from various academic institutions and leading publishers. This reflects the growing global interest in exploring

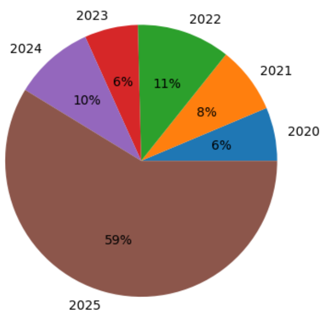

FIGURE 2. Distribution of record by year of publication.

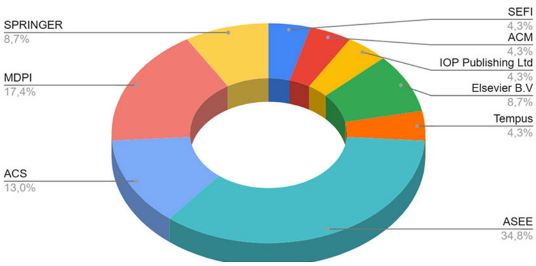

FIGURE 3. Distribution of record by field and journal of publication.

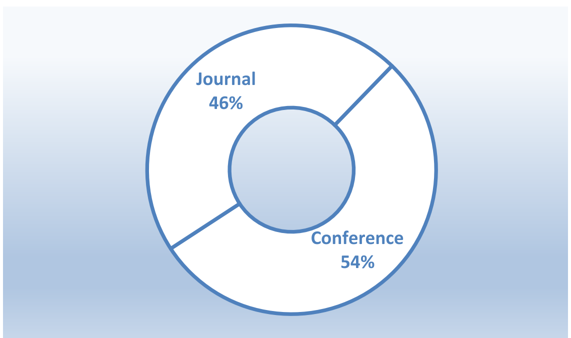

FIGURE 4. Distribution of record by type of publication.

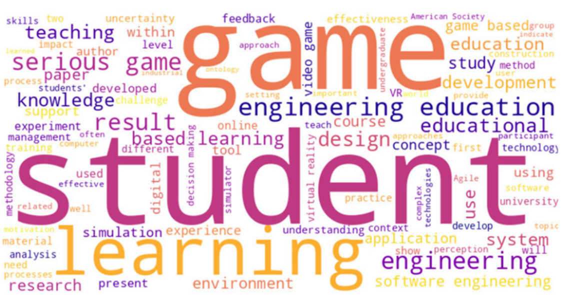

FIGURE 5. Word Frequency analysis.

the integration of serious gaming technology and AI in engineering education, which has the potential to revolutionize the approach to learning in the future.

The distribution of publication types shows that conference proceedings are still the main platform for disseminating research on serious games in engineering education. As seen in Figure 4, 54% studies were published in the form of conference proceedings, reflecting the preference of academics to share initial findings and spark academic discussion in scientific forums. In contrast, the other 46% studies were published as journal articles, which showed that more mature, peer reviewed research was more likely to be published in scientific journals. The excellence of conference proceedings as a publication medium lies in its speed in disseminating the latest research results and providing opportunities for researchers to get direct feedback from the academic and industry communities. On the other hand, publications in scientific journals offer more in depth analysis as well as more rigorous methodologies, making them a more comprehensive source of reference in understanding the profound role of play in engineering education.

E. DATA COLLECTION AND ANALYSIS PROCESS

In synthesizing data from the various selected studies, we applied a systematic analysis approach that began with identifying key themes in the application of AI for engineering education. Each publication is meticulously coded to highlight key aspects such as the application of AI technology, education regulations, and challenges in the implementation process. This thematic analysis allows us to craft a narrative that illustrates how AI has been used diversely in the context of engineering education.

The analysis process is carried out through several stages. First, each study is classified based on key themes identified previously, such as the application of AI technology, regulatory challenges, and the effectiveness of serious game-based learning methods. After that, patterns and relationships between various themes are analyzed to identify trends emerging from the literature studied. Bibliometric analysis was then used to visualize the relationship between the key terms often appearing in this study. This approach provides a thorough insight into how AI and serious games are evolving in engineering education without relying on meta analysis based statistical methods.

An updated word frequency analysis was conducted on the abstracts of 63 selected papers focusing on serious games in engineering education. The most dominant terms identified include "games" (134 occurrences), "students" (97 occurrences), and "learning" (91 occurrences). These results reinforce a central theme in the literature, namely the extensive use of game-based learning to enhance students' learning experiences, particularly within educational and engineering contexts. The high frequency of the term "engineering education" (90 occurrences) further confirms the dominance of this approach in the field. Additionally, pedagogical aspects are strongly emphasized, as reflected by the frequent appearance of the terms "education" (86 occurrences) and "teaching" (23 occurrences). The term

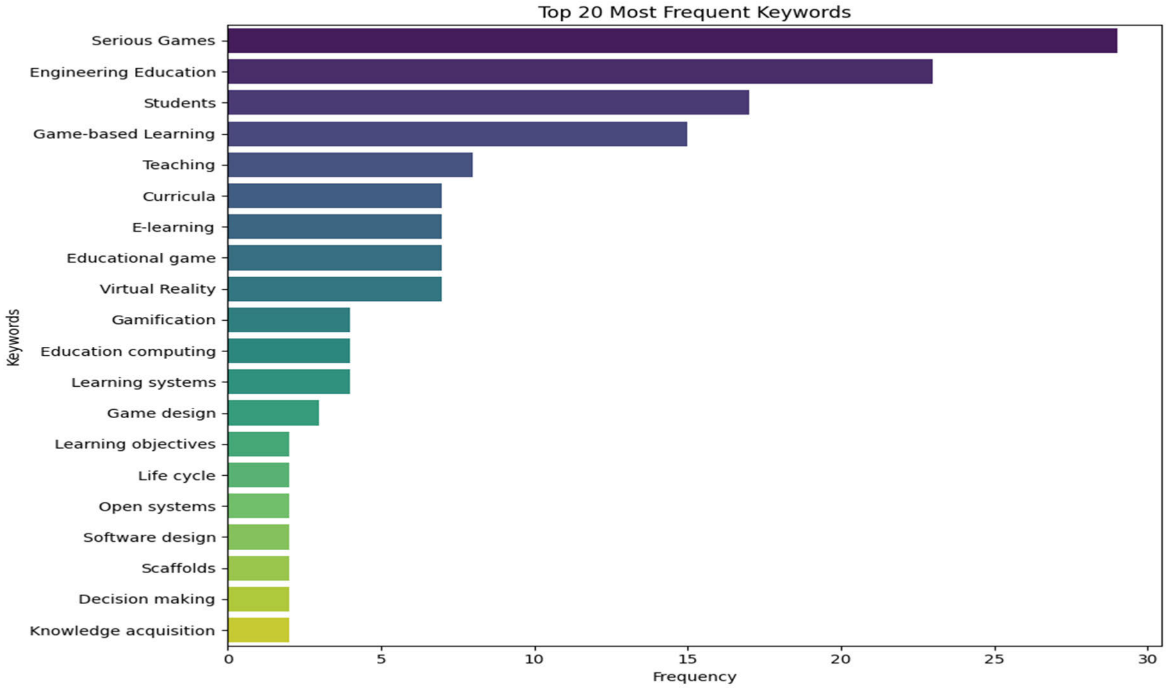

FIGURE 6. Distribution of record by keyword of publication.

"serious games" (39 occurrences) highlights the deliberate design of game environments aimed not only at entertainment but also at achieving specific educational objectives. Moreover, the presence of terms such as "software" (28 occurrences) and "development" (22 occurrences) indicates a recurring focus on technical implementation and iterative tool creation. Technological innovation also emerges as a key theme, with "virtual reality" appearing 25 times, signaling the increasing integration of immersive technologies in educational simulations, as illustrated in Figure 5.

An examination of keyword distributions provides deeper insight into how research themes are organized and emphasized across the literature. As illustrated in Figure 6, the keyword "serious games" (29 occurrences) emerges as the most dominant concept, followed by "engineering education" (23 occurrences) and "students" (17 occurrences), highlighting the centrality of learner-focused serious game applications within engineering curricula. Pedagogically driven terms such as "game-based learning" (15 occurrences) and "teaching" (8 occurrences) further reinforce the instructional motivations underlying these studies. At the curricular and delivery levels, the presence of keywords including "curricula" (7 occurrences) and "e-learning" (7 occurrences) indicates increasing efforts to formally embed serious games into structured educational frameworks. Moreover, the repeated appearance of "educational game" (7 occurrences) and "virtual reality" (7 occurrences) reflects a growing interest in immersive and technology-enhanced learning environments. Collectively, these patterns point toward a clear transformation in engineering education research, moving away from traditional, instructor-centered models toward more interactive, experiential, and digitally mediated learning ecosystems.

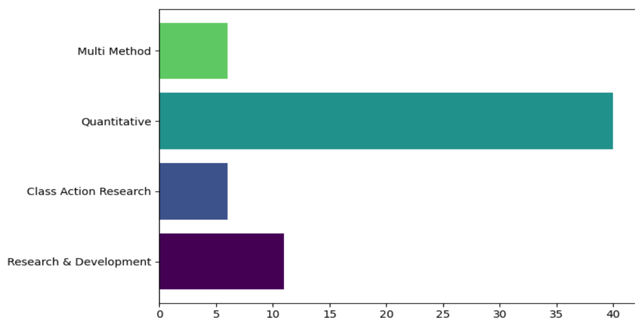

FIGURE 7. Distribution of research types.

This analysis shows that serious play, immersive technology, and game-based approaches are increasingly becoming part of modern engineering education strategies. By integrating interactive digital tools into learning, these studies show how technology can support a more dynamic, engaging, and effective learning experience for engineering students. After selecting relevant publications, each article is critically reviewed to understand how the technology is implemented, the regulations followed, and the challenges faced during implementation. This in depth analysis aims to provide a more holistic insight into the effectiveness of serious gaming in engineering education and identify opportunities and challenges in the future application of this technology.

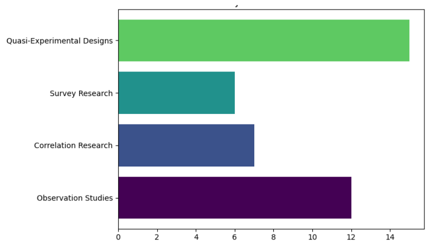

FIGURE 8. **Quantitative research type.**

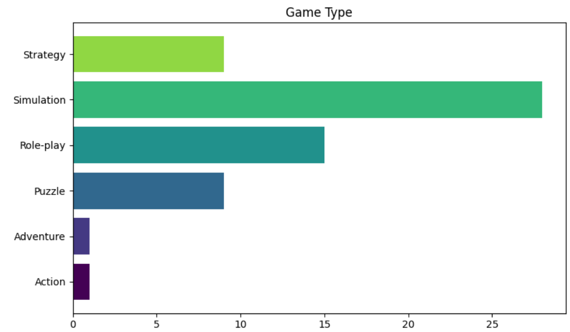

FIGURE 9. **Serious game genre distribution.**

IV. RESULT

Serious games have become an integral part of engineering education innovation, with a variety of research methods being used to evaluate their effectiveness. This chapter presents research results categorized based on the type of research, subject of study, disciplines involved, and the genre of games used. With a more in depth analysis, this chapter aims to identify key trends in the application of serious games to engineering education and how these technologies contribute to more interactive and effective learning.

A. RESEARCH TYPES

An analysis of methodological approaches reveals a clear preference for empirically measurable research designs in serious game studies within engineering education. As summarized in Figure 7, quantitative research overwhelmingly dominates the field, accounting for 40 studies, which reflects a strong reliance on outcome-driven evaluation frameworks emphasizing performance metrics and learning gains. Research and Development (R&D) approaches follow with 11 studies, indicating sustained interest in the iterative design and validation of serious game systems. Classroom Action Research and multi-method designs, each represented by 6 studies, suggest emerging efforts to contextualize serious game interventions within authentic classroom environments while combining multiple analytical perspectives. Despite the presence of mixed-method approaches, the complete absence of purely qualitative studies is particularly noteworthy. Qualitative inquiry has been widely recognized for its capacity to uncover nuanced learning processes, contextual influences, and stakeholder perceptions that are often overlooked by quantitative metrics alone [28]. The limited incorporation of qualitative perspectives therefore points to a methodological gap in current research, suggesting opportunities for future studies to enrich the understanding of learner experiences, engagement dynamics, and pedagogical effectiveness beyond numerical performance indicators.

A more granular view of the quantitative paradigm further highlights methodological diversity within this dominant research category. As depicted in Figure 8, quasi-experimental designs constitute the largest share (15 studies), underscoring the emphasis on causal inference through controlled comparisons between experimental and control groups. Observational studies (12 studies) represent another substantial portion, frequently leveraging in-game analytics such as player behavior patterns, decision-making trajectories, and alignment between simulated and real-world conditions. Correlational (7 studies) and survey-based approaches (6 studies) complement these designs, collectively indicating a balanced use of statistical methods to examine relationships, perceptions, and learning outcomes. Nonetheless, the prominence of quasi-experimental designs reinforces the prevailing objective of validating the instructional effectiveness of serious games in engineering education.

B. RESEARCH SUBJECT

The distribution of research subjects across educational levels reveals a strong concentration on undergraduate learners, who account for the majority of studies (43 studies), as illustrated in Figure 9. This focus reflects the central role of undergraduate education within engineering curricula, where serious games are most frequently employed to support foundational knowledge acquisition and applied skill development. Graduate-level research is comparatively limited, with only 6 studies targeting master's students, while 9 studies involve multiple educational levels, indicating attempts to design adaptable game-based learning systems applicable to diverse learner profiles. A smaller number of studies address professional workers (3 studies), highlighting an emerging recognition of serious games as tools for lifelong learning and professional upskilling in rapidly evolving engineering domains. Notably, only a single study focuses on senior high school students, suggesting that pre-university applications of serious games in engineering-related contexts remain significantly underexplored.

C. FIELDS OF STUDY

An examination of disciplinary coverage indicates that serious game research is unevenly distributed across engineering fields. As shown in Figure 10, Computer Science emerges as the most represented field with 15 studies, followed by General Engineering (10 studies) and Industrial Engineering (9 studies). This dominance is largely attributable to the strong alignment between serious game development and computational skill sets, as many studies involve in-house game design and software implementation. Other disciplines represented include Civil Engineering (7 studies), Electrical Engineering (6 studies), Mechanical Engineering (6 studies),

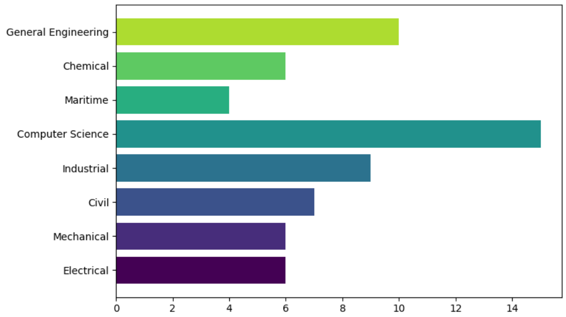

FIGURE 10. Distribution of studies across engineering disciplines.

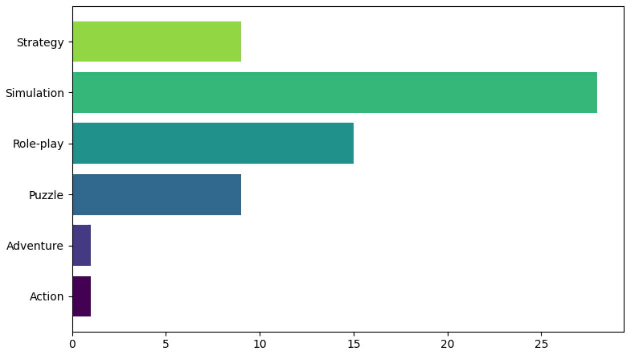

FIGURE 11. Distribution of game type.

Chemical Engineering (6 studies), and Maritime Engineering (4 studies). The presence of general engineering studies suggests that several serious games are designed around cross-disciplinary subjects such as production systems or statistics that are applicable across multiple engineering domains. This is due to the existence of several similar subject subjects in all engineering disciplines such as production process [14] and statistics [48].

D. GENRE

An analysis of game genres employed in engineering education highlights a clear preference for formats that support experiential and systems-based learning. As illustrated in Figure 11, simulation games dominate the landscape with 28 studies, followed by role-play games with 15 studies. These genres are particularly well suited to engineering education, as they support experiential learning, system-level thinking, and decision-making in realistic contexts. Simulation games typically provide learners with high degrees of control and flexibility, such as managing industrial processes or transportation systems [30], [31]. In contrast, role-play games immerse learners in predefined professional roles such as software engineers or project managers allowing them to experience domain-specific responsibilities and workflows [32], [33]. Other genres include puzzle games and strategy games, each with 9 studies, while action and adventure games are minimally represented, with one study each. Although less frequently used, these alternative genres may serve as complementary tools to enhance engagement and motivation when integrated with more structured game mechanics.

V. DISCUSSION

A. RQ1: THE RELEVANT TECHNOLOGICAL INNOVATIONS

Based on the analysis of the reviewed articles, technological innovations in serious games for engineering education can be categorized into three major types: immersive technologies, web/mobile based platforms, and AI enhanced applications. Among these, in Table 2, VR stands out as a prominent immersive tool, applied in at least 9 of the studies, accounting for approximately 14.3% of the reviewed literature. Table 3, these VR based games are primarily deployed in disciplines such as mechanical engineering, electrical engineering, industrial engineering, and software engineering, and are particularly effective in conveying complex spatial or dynamic concepts, such as thermography, electrical circuits, and maritime systems. The high level of immersion, interaction, and experiential learning enabled by VR allows learners to engage with abstract technical content in 3D environments, fostering deeper conceptual understanding and motivation. However, the implementation of VR faces challenges, notably the need for expensive hardware, potential user discomfort (e.g., motion sickness), and limited accessibility in low resource educational settings. Additionally, the requirement for higher technical literacy among educators and students can act as a barrier to adoption.

Mixed Reality (MR), although represented in only one study (1.6%), demonstrates the unique potential of combining physical and digital elements in real time, utilizing advanced technologies such as computer vision and eye tracking. In a civil engineering context focused on construction, MR was used to provide contextualized simulations, supporting highly situated learning through sensor integration. The application of computer vision allowed the game to respond to users' gaze and physical orientation, creating a dynamic feedback loop. However, MR remains at a nascent stage, facing similar constraints as VR in terms of hardware cost and complexity, and lacks standardized frameworks for its pedagogical integration.

In contrast, Web and Mobile platforms are the most frequently employed technologies, appearing in over 49% of the reviewed papers, highlighting their dominance in current engineering education practices. These platforms are celebrated for their high accessibility, cost efficiency, and ease of deployment across diverse learning environments, making them ideal for self directed learning and massive distribution. Games in this category span disciplines such as electrical and mechanical engineering and often include simulation, role playing, or quiz based genres. Nevertheless, web/mobile games tend to lack the immersive realism and sensorimotor fidelity necessary for effectively teaching physical manipulation skills or spatial reasoning. As a result, their pedagogical strength is often confined to conceptual knowledge and procedural learning.

TABLE 2. Technological innovations.

Technological Innovation	Number	Strengths	Weaknesses
Virtual Reality	9 (14.3%)	Enhances immersion and user interaction. Highly effective for practical or spatial subjects such as thermography and electrical circuits. Helps visualize abstract or difficult-to-demonstrate concepts in 3D.	Requires specialized hardware (e.g., VR headsets), which can be expensive. May cause motion sickness for some users. Also demands higher technical literacy.
Mixed Reality	1 (1.6%)	Combines real and virtual worlds in real-time. Enables contextual learning through advanced sensor integration like eye-tracking and computer vision.	High hardware costs and limited availability. Still in early stages of adoption and lacks standardized pedagogical frameworks.
Web/Mobile	31 (49,2%)	Easily accessible on various devices. Lower development and deployment costs. Ideal for self-paced learning and scalable distribution.	Less immersive than VR/MR. Limited interactivity and realism. Not suitable for teaching spatial or sensorimotor skills in high fidelity.

TABLE 3. Immersive technologies.

Ref	Technological Innovation	Subject	Discipline	AI
[10]	Mixed Reality	building Construction	Civil Engineering	Computer Vision
[17]	Virtual Reality	Software Engineering	Computer Science	-
[20]	Virtual Reality	Electrical Circuits	Electrical Engineering	-
[28]	Virtual Reality	Power	Electrical Engineering	-
[31]	Virtual Reality	Thermography	Mechanical Engineering	-
[35]	Virtual Reality	Industrial Engineering	Industrial Engineering	Machine Learning
[38]	Virtual Reality	Maritime Engineering	Mechanical Engineering	-
[67]	Virtual Reality	Student Profiling	Maritime Engineering	Machine Learning
[71]	Virtual Reality	Bullwhip Effect in Supply Chain	Industrial Engineering	-

TABLE 4. Integration artificial intelligents.

Ref	AI Category	Method	Platform	Genre	Engineering Discipline
[36]	Machine Learning	Reinforcement Learning	Web App or PC App	Role-play	Electrical Engineering
[47]	Machine Learning	Reinforcement Learning	Virtual Reality	Simulation	Industrial Engineering
[67]	Machine Learning	KNN	Virtual Reality	Simulation	Maritime Engineering
[52]	Computer Vision	Eye Tracking	Mixed Reality	Simulation	Civil Engineering

With regard to AI-enhanced serious games, Table 4 indicates that AI integration remains relatively limited. A total of four studies explicitly report the use of AI components, including three studies employing machine learning techniques one of which applies a k-nearest neighbor (KNN) algorithm and one study utilizing computer vision. These AI-driven approaches are primarily used to support adaptive learning mechanisms, such as dynamically adjusting gameplay difficulty, predicting learner performance, or personalizing in-game assistance based on user behavior. For example, machine learning techniques, including KNN, were applied in an industrial engineering simulation to adapt learning pathways according to player performance patterns, while computer vision was used to enable gaze tracking in MR environments to enhance contextual awareness. Notably, no studies employed deep learning or natural language processing (NLP), despite their strong potential to enable intelligent tutoring, conversational feedback, and advanced learner modeling. This absence highlights a significant research gap and opportunity for future innovation. Taken together, immersive technologies such as VR and MR offer strong experiential and representational affordances but remain limited by financial and logistical constraints. Web and mobile platforms provide scalable and accessible solutions but face pedagogical limitations in realism and interactivity. AI-enhanced serious games present a promising avenue for personalization and adaptivity; however, their adoption is still minimal and methodologically narrow. Future research should therefore emphasize pedagogically grounded, AI-driven personalization strategies while ensuring contextual alignment with engineering learning objectives.

B. RQ2: THE CHALLENGES AND PROSPECTS FOR FURTHER RESEARCH OF SERIOUS GAMES IN ENGINEERING EDUCATION

In addressing Research Question 2 (RQ2), the discussion reveals a multifaceted array of challenges and prospects that must be considered when advancing the role of serious games in engineering education. This section synthesizes findings from ten critical thematic categories, drawing on evidence from international Scopus indexed studies to identify obstacles, innovations, and future research directions.

Each category not only identifies the barriers faced but also provides detailed implications and potential future directions, thus strengthening the empirical grounding and generalizability of this SLR.

Table 5 show Challenge and Finding Research of Serious Games in Engineering Education. The first major challenge centers on the abstraction and conceptual complexity of engineering content. Topics such as thermodynamics, digital logic, and circuit analysis are often difficult for students to visualize and internalize through traditional teaching approaches. Serious games offer the promise of transforming these abstract ideas into interactive visual simulations that enable concrete understanding. For example, escape rooms and VR based simulations have shown efficacy in enhancing conceptual understanding. Study Towards Teaching Digital Electronics addresses the difficulty in understanding digital logic an abstract concept that is often unappealing to beginners. Escape rooms are used as a scenario based approach to contextualize and challenge learning [34]. This approach is particularly effective in enhancing engagement and cognition because students must actively solve problems. Study 2DVLE: Simulation Game for Vapour Liquid Equilibrium, addresses the visualization challenges in thermodynamic systems, one of the most abstract engineering concepts. By simulating liquid vapor equilibrium, the game provides an experiential medium that brings students closer to real system dynamics [35]. Research VR for Electrical Circuits, addresses boredom in circuit analysis learning. VR is used to transform boring material into an immersive learning experience. This study shows that hands on experience through manipulation of virtual objects increases participation and understanding of electric current flow [36].

Second, interdisciplinary integration remains a pressing concern. While engineering problems are inherently multidisciplinary, many curricula remain siloed. Games offer flexible environments that can bridge this divide. Studies demonstrate that serious games can contextualize cross domain concepts such as maritime economics and hardware software development. However, content depth and gameplay balance remain challenges, especially in maintaining both educational integrity and student engagement within multicontextual scenarios. This issue is further illustrated in several studies. For instance, study Serious Game for Maritime Economics and Technology, highlights interdisciplinary challenges arising from the gap in understanding between economics and engineering. The game in question brings both domains together within a realistic maritime context, promoting transversal skills and systemic thinking. Yet, it requires deeper evaluation regarding the balance between the two disciplines and the assessment of conceptual mastery [37]. Similarly, study Agile Hardware Simulator, extends agile concepts traditionally rooted in software engineering into the hardware and industrial engineering space via simulation based learning. This showcases the adaptability of agile methodologies but also raises questions about curriculum readiness and cross contextual effectiveness [38]. In another case, research Game for ISO 29148 Requirements Engineering, tackles the rigidity of formal standards like ISO, which are often perceived as abstract and disconnected from practice. Through a task based serious game, students internalize standards more naturally, suggesting a viable path to overcoming resistance to regulatory content. Nonetheless, challenges remain in evaluating long-term compliance and real-world transfer [13].

The technological accessibility, particularly concerning the use of immersive technologies such as VR and MR. While these tools can significantly enhance spatial reasoning and conceptual engagement, their broader adoption is often hindered by high hardware costs, infrastructural limitations, and lack of educator readiness. Studies have shown promising results in terms of student motivation and comprehension, but challenges persist in ensuring institutional readiness and equitable access to compatible hardware. The demand for cost effective and scalable immersive platforms is especially critical in low resource educational environments.

These challenges are further explored in several studies. Game Gamification in Blended Engineering Education examined students' readiness for blended learning through VR based gamification, which successfully increased engagement. However, it also exposed limitations in infrastructure readiness from both institutional and student perspectives, emphasizing the need for greater technology inclusivity in under resourced campuses [39]. In study Scrum VR for Learning Agile, a VR simulation was used to immerse students in the roles of a Scrum team within an Agile framework. While the experience mimicked real life scenarios, it remains unclear whether students developed a deep understanding of Scrum principles or merely acted out predefined roles [40]. Meanwhile, study VR Game for Wind Power offered a creative solution to the lack of access to physical laboratories. By utilizing Unity, students built and tested wind turbine scenarios in a virtual environment, enhancing ownership and engagement. Yet, despite overcoming some infrastructural issues, concerns about scalability and the consistent availability of instructional guidance still need to be addressed [41].

Despite the growing adoption of serious games in engineering education, a significant challenge lies in the lack of pedagogical alignment and consistent evaluation frameworks. Many of these games are not grounded in established instructional design theories, such as Bloom's taxonomy or formative assessment models, which limits their effectiveness in supporting structured learning outcomes. Moreover, current evaluation methods are fragmented, with minimal consensus on how to measure critical aspects such as long-term knowledge retention, skill acquisition, and behavioral transfer, thereby hindering the scalability and reproducibility of game-based interventions across different educational contexts. To address this, recent studies have introduced more structured approaches. For example, the study on Game Design Patterns for Software Engineering presents an integrated instructional design framework that combines pedagogical theory with reusable game design elements, offering a replicable and consistent structure that

TABLE 5. Design-oriented challenges in the development and implementation of serious games for engineering education.

Ref	Challenge	Finding
[16]	Teaching formal engineering standards	Targeted game facilitates learning of ISO standards, increases procedural comprehension
[22]	Lack of structured methodology	Game design patterns aligned with Learning-Teaching Framework enhance curricular coherence
[17]	Teaching Agile traditionally	VR simulation improves comprehension of Scrum with procedural fidelity
[11]	Agile methods in hardware domains	Simulator effectively introduces Agile to engineering hardware with industry-aligned feedback
[24]	Teamwork and leadership	Game supports development of non-technical skills in authentic task settings
[20]	Unengaging circuit analysis	VR increases engagement, supports experiential learning of current flow
[18]	Abstract logic concepts	Escape rooms improve conceptual understanding through scenario-based play
[28]	Inaccessible wind lab experiences	Students develop Unity-based VR wind lab to simulate inaccessible physical infrastructure
[30]	Student readiness for blended learning	VR-based gamification increases motivation and course preparedness
[33]	High custom game cost	Commercial games can be modified for logistics and teamwork, reducing development time and cost
[14]	Teaching cross-disciplinary topics	Game improves inter-field engagement and understanding using economic-engineering fusion
[13]	Varied attitudes by background	Mixed-methods study highlights diversity of student experiences and adaptation preferences
[36]	Safety training seen as boring	JiTT and Kahoot! enhance engagement and safety knowledge with active recall strategies
[19]	Visualizing thermodynamic systems	VLE game enhances learning via active simulation of phase behavior
[15]	Teaching uncertainty and adaptive logic	Game helps grasp strategic responses in uncertain conditions, reflecting real-world unpredictability
[42]	Low correlation between perception/performance	Experience more predictive than subjective perception
[6]	Large-scale evaluation complexities	Demographics significantly influence effectiveness, suggesting need for stratified analysis

aligns gameplay with educational objectives [42]. Similarly, the JiTT Game for Lab Safety utilizes Just in Time Teaching (JiTT) methods and gamified tools like Kahoot to improve engagement in laboratory safety training. While it effectively boosts student attention, it falls short of providing robust evidence for the transfer of safe practices to real laboratory settings, which should be the ultimate indicator of its success [43]. Furthermore, a large scale study titled Evaluation of Serious Games reveals that the perceived effectiveness and impact of educational games are significantly shaped by learner demographics such as gender and professional background. This underscores the importance of employing data driven evaluation strategies to ensure equitable access, inclusivity, and responsiveness to diverse learner profiles in game-based learning environments [40].

Table 6 summarizes key prospects and future research directions for serious games in engineering education, as gleaned from the reviewed studies, highlighting emerging opportunities related to pedagogical advancements, technological scalability, and methodological maturity. These prospects include the integration of serious games for soft skills development, inclusive and culturally responsive design, large-scale and longitudinal evaluation frameworks, cost-effective implementation models, and the increasing role of AI-based adaptive learning. Taken together, these directions indicate a strategic shift from exploratory implementation to a sustainable, data-driven, and competency-oriented serious games ecosystem in engineering education. Implementing serious games in engineering education lies in the development and evaluation of soft skills, such as teamwork, leadership, adaptability, and decision making. While technical competence remains foundational, the engineering profession increasingly demands these non technical competencies, which are often difficult to cultivate through traditional classroom methods. Serious games offer immersive, socially complex scenarios that can simulate real-world interactions and enhance social emotional learning. However, the field still lacks standardized metrics to evaluate the growth of these competencies effectively. Additionally, the theoretical underpinnings such as the application of social learning theory and experiential learning require more rigorous integration and assessment. One relevant study, Employability Skills via Serious Games, designed its game environment specifically to promote soft skills, particularly teamwork and leadership. This reflects a growing recognition of industry relevant competencies, yet the absence of robust quantitative methods to measure skill development remains a methodological limitation [44]. In a different context, Decision Making under Uncertainty focuses on training students to navigate ambiguity and make adaptive decisions, mirroring the complexities of real-world engineering scenarios and strengthening students' resilience. Nevertheless, the link between this general decision making training and more discipline specific technical decision making remains insufficiently defined [45]. Lastly, the use of commercial off the shelf (COTS) games, such as Factorio, in the study COTS Game for Production and Logistics, demonstrates a cost effective and scalable approach to technical education. This strategy creatively leverages existing gaming platforms to teach logistics and production systems, but it introduces new concerns regarding ethical and legal issues related to licensing, as well as the challenge of maintaining educational rigor within inherently entertainment focused game environments [46].

In addition to technical and pedagogical challenges, diversity and inclusion remain pressing concerns in the design of serious games for engineering education. Students bring a wide range of cultural, academic, and gender identities

TABLE 6. Empirical evaluation and contextual adaptation challenges in serious games research for engineering learning.

Ref	Challenge	Finding
[41]	Varied attitudes by background	Mixed-methods study highlights diversity of student experiences and adaptation preferences
[43]	Low correlation between perception/performance	Experience more predictive than subjective perception
[44]	Evaluation across media types	Game more effective for engagement and knowledge retention
[16]	Dry and formal subject matter	Game increases understanding of requirements engineering through application-focused gameplay
[36]	Boring safety training	Gamification raises student attention and retention, improves compliance awareness
[33]	High development cost	Modifying commercial games is viable for resource-limited institutions
[28]	Expensive turbine labs	Student-built VR simulations substitute unavailable physical labs
[45]	Varied competency needs	

into the learning environment, each shaping how they interact with educational games and absorb knowledge. While several studies highlight that experiential engagement during gameplay is a stronger predictor of learning outcomes than students' initial perceptions or attitudes, inclusive design strategies are still underdeveloped. There is a growing need to embed culturally responsive frameworks and accessibility features that can accommodate diverse learning preferences and backgrounds. For instance, the study Perceptions of Engineering Software utilized a mixed methods approach to explore how students' cultural and academic backgrounds influence their perception of engineering learning tools. This research is significant in uncovering variability in learner responses that cannot be captured by one size fits all design strategies, thereby reinforcing the call for more cognitively and culturally inclusive game development. However, it stops short of explicitly linking these perceptions to measurable learning performance, leaving a critical gap in understanding how inclusivity affects outcomes [47]. Complementing this, the study Perception vs. Performance Evaluation challenges the assumption that students' initial perceptions of a game are directly correlated with their eventual learning success. Instead, it reveals that the immersive, real time gameplay experience exerts a greater influence on cognition and engagement than pre existing attitudes. This underscores the importance of behavioral and experience based evaluation approaches rather than relying solely on attitudinal surveys. Together, these studies emphasize that inclusive game design must move beyond surface level adaptations, incorporating deeper experiential elements that are responsive to learner diversity and capable of producing equitable learning outcomes across varied populations [48].

Evaluation and validation scalability constitute another crucial challenge in the adoption of serious games for engineering education. Despite promising results in small scale trials, many educational games lack rigorous validation across larger and more demographically diverse populations, which undermines the generalizability of findings. Most current evaluations are confined to limited sample sizes or conducted within narrowly defined institutional or cultural contexts, making it difficult to draw broad conclusions about effectiveness. To establish empirical legitimacy, there is an urgent need for comparative studies that include control groups, longitudinal tracking, and multi dimensional metrics capable of capturing not only learning outcomes but also motivation, engagement, and behavioral change over time. The study Video-based vs. game-based Learning offers an illustrative example by directly comparing traditional video instruction with game-based learning. The results indicate that games outperform videos in enhancing knowledge retention and student motivation marking a significant validation of the potential pedagogical superiority of game-based approaches. However, the authors also acknowledge the possible influence of the novelty effect, where learners' enthusiasm may stem from exposure to a new format rather than the inherent effectiveness of the game itself. This highlights the need for longitudinal research to assess whether the observed benefits are sustainable over time and across varying educational settings. Without such validation, the scalability and long-term adoption of serious games will remain limited, particularly in formal academic curricula that demand strong evidence of efficacy [29].

Furthermore, standards and regulatory education presents a distinct pedagogical challenge due to the inherently formal, text heavy, and often disengaging nature of its content. Topics such as ISO standards, requirements engineering, and lab safety are essential to engineering practice but are typically delivered through passive, documentation heavy instruction. Serious games offer a compelling alternative by transforming abstract standards into interactive, context rich learning experiences. Emerging studies have demonstrated the potential of simulation based and quiz driven game formats particularly VR and Just in Time Teaching (JiTT) to enhance comprehension and engagement with regulatory content. One notable example is the study on a Game for ISO 29148, which focuses on requirements engineering, a traditionally dry topic. Through simulation and hands on task based gameplay, students reported increased clarity and contextual understanding of formal standards. This case illustrates the pedagogical benefit of converting dense technical documentation into experiential practice, although the study stops short of assessing whether this understanding translates into workplace behavior or long-term compliance [49]. Similarly, the JiTT for Safety study integrates gamified quizzes like

Kahoot into safety training, resulting in higher levels of engagement and immediate awareness of safety principles. While this approach effectively transforms a mundane topic into an active learning experience, it raises critical questions about learning retention and behavioral transfer specifically, whether enhanced knowledge actually leads to fewer safety incidents in practice. Together, these studies underscore the transformative potential of serious games in regulatory education but also highlight the pressing need for rigorous, longitudinal evaluation to validate sustained impact beyond initial classroom contexts [50].

Infrastructure and cost related barriers continue to be a central concern in the implementation of serious games within engineering education. The development of sophisticated, custom designed educational games often requires substantial technical expertise, hardware infrastructure, and financial investment resources that many institutions, particularly in developing regions, may lack. In response, several studies have explored low cost alternatives, including open source game platforms, do it yourself (DIY) virtual reality solutions, and modifications of commercial off the shelf (COTS) games. While these approaches show promise in lowering entry barriers, questions remain regarding their sustainability, scalability, and long-term cost effectiveness. For example, the study COTS Game for Logistics demonstrates a pragmatic solution by adapting commercial games like Factorio for educational purposes, enabling institutions with limited funding to deliver engaging, systems based instruction. Although this approach yields positive outcomes, it introduces new complications related to licensing restrictions, content alignment, and limited flexibility in game design. Moreover, comprehensive cost benefit analyses comparing COTS adaptations to open source or custom built platforms are still lacking [13]. In contrast, the VR for Wind Power study highlights a student driven innovation, where learners created their own virtual lab simulations to compensate for the lack of physical infrastructure specifically, unavailable wind turbine laboratories. This DIY VR initiative not only circumvented infrastructural constraints but also enhanced student ownership and engagement through active content creation. These examples underscore that while financial and technical limitations remain significant obstacles, they can be partially mitigated through creative use of existing technologies and collaborative, resource sharing approaches. However, broader institutional strategies and empirical studies are needed to validate the cost effectiveness and pedagogical consistency of such models over time [43].

Lastly, the emergence of adaptive design powered by AI represents a critical frontier in the evolution of serious games for engineering education. The promise of personalized learning pathways, enabled through AI driven feedback loops, real time analytics, and content adjustment mechanisms, holds significant potential for enhancing learner engagement and achievement. However, this domain remains underexplored, particularly in engineering contexts where competencies and learner needs are highly diverse. Ethical considerations related to data usage, transparency, and learner autonomy further complicate implementation. The study Employability Skills via Serious Games, already noted for its contribution to soft skill development, also underscores the importance of adaptivity in game design. It highlights how learners possess varied competency profiles and therefore benefit from systems that tailor progression paths to individual strengths and weaknesses [46]. This insight lays a foundational argument for the integration of AI and learning analytics to support competency based education within game environments. Similarly, Perception vs. Performance reinforces the idea that personalized, experiential gameplay rather than uniform design or initial learner attitudes plays a decisive role in knowledge acquisition and performance outcomes [41]. The study suggests that static, one size fits all game designs may significantly limit learning impact, thereby reinforcing the urgency of developing responsive, data informed educational games that adapt to real time student performance. Together, these findings point to a future in which AI driven adaptivity becomes not just an enhancement, but a pedagogical necessity in serious game design.

VI. CONCLUSION

This systematic literature review provides a comprehensive synthesis of recent advances in the use of serious games within engineering education, with particular emphasis on technological innovations, implementation challenges, and future research directions. Based on the analysis of 63 peer-reviewed studies published between 2020 and 2025, the findings confirm that serious games have become an increasingly relevant instructional approach for supporting experiential, student-centered, and problem-oriented learning in diverse engineering disciplines. Web- and mobile-based serious games currently dominate the research landscape due to their accessibility, scalability, and relatively low implementation cost, while immersive technologies especially VR demonstrate strong potential for enhancing spatial reasoning, procedural understanding, and engagement in complex and abstract engineering topics.

Despite these promising developments, the review reveals several critical limitations that constrain the broader adoption and long-term impact of serious games in engineering education. First, the integration of artificial intelligence remains limited and methodologically narrow, with only a small number of studies employing machine learning or computer vision to support adaptive learning and personalization. Advanced AI approaches such as deep learning, natural language processing, and learning analytics are largely absent, representing a substantial research gap. Second, many serious game implementations lack explicit alignment with established pedagogical frameworks, resulting in fragmented evaluation practices and limited evidence regarding long-term knowledge retention, skill transfer, and behavioral change. Third, high development costs, infrastructure constraints, and uneven institutional readiness continue to hinder the scalability and sustainability of immersive and AI-enhanced serious games, particularly in resource-constrained educational contexts.

This review contributes to the existing body of knowledge by offering a cross-disciplinary perspective that jointly examines immersive technologies, AI-enhanced adaptivity, and game design characteristics within engineering education. By systematically identifying technological trends, methodological patterns, and persistent challenges, the study highlights the need for future research to move beyond technology-driven novelty toward pedagogically grounded, learner-centered, and ethically responsible serious game frameworks. Future work should prioritize the integration of AI-driven personalization, standardized evaluation metrics, and inclusive design principles, as well as longitudinal and large-scale empirical validation. Ultimately, the effective adoption of serious games in engineering education depends on their integration into coherent institutional ecosystems that align technological innovation with sound educational theory and the evolving competency demands of modern engineering practice.

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