

## Emerging Trends in Virtual Simulation for Education: A Systematic Review of Technology–Pedagogy Alignment

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### Article Info

### Abstract

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Virtual simulation has become a transformative approach in education, particularly in contexts that require practical, skill-oriented learning. This systematic review examines emerging trends in virtual simulation for education by synthesizing evidence on educational technologies and instructional design approaches applied in virtual laboratory environments. Guided by the PRISMA protocol and the PSALSAR framework, 20 peer-reviewed journal articles published between 2020 and 2024 were systematically selected and analyzed. The results indicate a growing emphasis on virtual laboratories and immersive technologies, especially virtual and augmented reality, to support hands-on learning across science, engineering, medical, and vocational education. These technologies are predominantly implemented through learner-centered instructional designs, including experiential, inquiry-based, and constructivist approaches, which facilitate active engagement, repeated practice, and meaningful knowledge construction. While immersive and simulation-based technologies dominate current implementations, the integration of AI-supported and analytics-driven systems remains limited, suggesting an emerging area for future development. This review contributes a synthesized conceptual framework that illustrates how virtual simulation technologies are pedagogically operationalized through instructional design themes to produce meaningful learning outcomes. By integrating technological and pedagogical perspectives, the findings provide a structured foundation to inform evidence-based instructional design, implementation, and future research on virtual simulation-based education.

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## Introduction

The rapid advancement of digital technologies has significantly transformed educational practices, particularly in domains that require hands-on experimentation and skill development (Johnson et al., 2023; Thompson et al., 2023). Among these innovations, virtual simulation has emerged as a powerful educational approach, enabling learners to engage with complex, hazardous, or resource-intensive tasks within safe, repeatable, and flexible digital environments (Mariscal et al., 2020; Peterson & Zhang, 2024). The increasing adoption of virtual simulation in education has been driven by advances in immersive technologies, such as virtual reality (VR) and augmented reality (AR), alongside the integration of artificial intelligence (AI), cloud computing, and learning management systems (Kim & Park, 2024; Wang & Liu, 2024). These developments have expanded opportunities for experiential and practice-based learning across disciplines, including science, engineering, medicine, and vocational education (Barrow et al., 2024; Corbi et al., 2020).

Virtual simulation gained further prominence during the global shift toward remote and blended learning, highlighting its potential to address limitations associated with physical laboratories, such as high costs, safety concerns, limited access, and geographical constraints (Karara et al., 2021; Bunse et al., 2023). Prior studies have reported that virtual laboratories and simulation-based environments can support learner engagement, conceptual understanding, and skill acquisition by allowing repeated practice and immediate feedback without the risks inherent in real-world experimentation (Anderson & Kim, 2023; Lee et al., 2024). Consequently, virtual simulation is increasingly viewed not only as an alternative to traditional laboratory instruction but also as a complementary pedagogical strategy capable of enhancing instructional flexibility and learning scalability (Papadimitropoulos et al., 2021; Santyadiputra et al., 2024).

Despite its growing adoption, the educational effectiveness of virtual simulation does not depend solely on technological sophistication. Research consistently emphasizes that learning outcomes are strongly influenced by how simulation technologies are embedded within instructional design (Chen et al., 2023; Rodriguez-Martinez, 2024). Learner-centered strategies, including inquiry-based learning, experiential learning, gamification, and collaborative activities, have been identified as critical factors in leveraging the affordances of virtual environments (Rebecca et al., 2021; Serrano-Ausejo & Mårell-Olsson, 2024). When instructional design is poorly aligned with technological capabilities, even highly immersive systems may fail to achieve meaningful learning outcomes, underscoring the importance of pedagogical alignment in simulation-based learning environments (Byukusenge et al., 2023; Aldosari et al., 2022).

A substantial body of research has investigated virtual simulation technologies in isolation, focusing on specific tools such as VR, AR, or virtual laboratories, or evaluating learning outcomes within particular disciplines (Kim & Park, 2024; Kulkarni & Harne, 2024). Parallel strands of literature have explored instructional design approaches suitable for technology-enhanced learning environments, including constructivist, experiential, and inquiry-based frameworks (Huang et al., 2024; Yu et al., 2024). However, existing reviews often emphasize either technological trends or pedagogical practices without systematically synthesizing the relationship between educational technologies and instructional design approaches across contexts (Johnson et al., 2023; Peterson &

Zhang, 2024). As a result, there remains limited consolidated evidence on how different types of virtual simulation technologies are pedagogically operationalized and aligned with learning theories across diverse educational settings.

Moreover, prior reviews frequently adopt descriptive perspectives, reporting technology frequencies or summarizing outcomes without offering integrative frameworks to guide instructional design and implementation (Thompson et al., 2023; Martinez et al., 2024). This lack of synthesis poses challenges for educators, instructional designers, and policymakers who seek evidence-based guidance on selecting and designing virtual simulation environments that are both pedagogically sound and technologically appropriate (Wilson et al., 2023). Given the rapid pace of innovation in immersive and intelligent educational technologies, an updated and analytically grounded synthesis is necessary to capture emerging trends and inform future practice.

To address these gaps, the present study conducts a systematic review of research published between 2020 and 2024 to examine emerging trends in virtual simulation for education. Guided by the PRISMA protocol and the PSALSAR approach (Mengist et al., 2020), this review analyzes peer-reviewed journal articles to (1) identify trends in virtual simulation research related to skill development, (2) examine the types of educational technologies employed in virtual laboratories, and (3) synthesize the learning theories and instructional design approaches underpinning their implementation. By integrating technological and pedagogical perspectives, this review aims to provide a coherent synthesis that supports evidence-based instructional design, informs educational practice, and highlights directions for future research in virtual simulation-based learning.

## Literature Review

### Conceptualizing Virtual Simulation in Education

Virtual simulation has become a core modality in technology-enhanced education, enabling learners to engage with complex, hazardous, or resource-intensive tasks in safe, repeatable environments. Recent scholarship frames virtual simulation not merely as a digital substitute for physical practice, but as a pedagogical space where interactivity, feedback, and authenticity can be designed to support conceptual understanding and procedural fluency (Johnson et al., 2023; Thompson et al., 2023). This shift has been accelerated by rapid advances in immersive interfaces and intelligent systems, positioning virtual simulation as a strategic approach to skill development across science, engineering, medicine, and vocational contexts.

### Technological Trajectories: From Virtual Labs to Immersive and Intelligent Systems

The technological evolution of virtual simulation can be characterized as a progression from conventional screen-based simulations and virtual laboratories to immersive, data-driven learning systems. First, virtual labs and simulation platforms have expanded access to experimentation and practice, particularly for remote and blended learning contexts, with reported advantages in scalability and cost-efficiency (Peterson & Zhang, 2024). Second, immersive technologies such as virtual reality (VR) and augmented reality (AR) have increased the fidelity of learning experiences by supporting spatial visualization, embodied interaction, and realistic scenario rehearsal

(Kim & Park, 2024; Davidson & Roberts, 2024). Third, the integration of artificial intelligence (AI) and real-time analytics has begun to enable personalization, adaptive feedback, and learning support aligned with individual learner characteristics (Wang & Liu, 2024; Martinez et al., 2024). Collectively, these trajectories indicate that technological innovation is reshaping not only the form of simulations but also the instructional possibilities within virtual learning environments.

### **Instructional Design as the Determinant of Learning Value**

Although technological sophistication is often highlighted, the educational value of virtual simulation is largely determined by instructional design choices. Contemporary design discourse emphasizes learner-centered approaches, meaningful interaction, and structured learning sequences rather than technology features alone (Chen et al., 2023). Effective virtual simulation design typically includes (a) explicit learning outcomes and alignment with tasks, (b) guided inquiry or scaffolded exploration, (c) formative feedback and assessment mechanisms, and (d) opportunities for collaboration and reflection (Rodriguez-Martinez, 2024). In this view, virtual simulation functions as an instructional system: its effectiveness depends on how learning activities, supports, and evaluations are orchestrated to leverage the affordances of virtual environments.

### **Learning-Theoretical Foundations Supporting Virtual Simulation**

Multiple learning theories have been used to justify and design virtual simulation experiences. Constructivist perspectives support simulations that enable learners to construct understanding through exploration, experimentation, and reflection actively. Experiential learning and activity-based approaches are commonly invoked to explain learning gains when simulations provide authentic tasks, iterative practice, and feedback loops. Cognitive and cognitive-load perspectives highlight the importance of managing information complexity, sequencing, and visualization to avoid overload while supporting comprehension. Theoretically grounded design is therefore essential for translating immersive and interactive technologies into measurable learning outcomes (Anderson & Kim, 2023; Lee et al., 2024). However, the literature also suggests that theory is often referenced at a high level, with limited operationalization into explicit design principles, leaving a gap in evidence-based alignment between learning theories and simulation design features.

### **Evidence on Learning Outcomes and Implementation Constraints**

Evidence indicates that virtual simulation can enhance learning outcomes, particularly for applied competencies and problem-solving in domains requiring practice-based learning (Anderson & Kim, 2023; Lee et al., 2024). Reported benefits include risk-free rehearsal, improved engagement, and opportunities for repeated practice. Nonetheless, implementation barriers remain substantial. Financial constraints, infrastructure readiness, and instructor professional development are repeatedly identified as persistent challenges that may limit scalability and sustainability (Peterson & Zhang, 2024; Wilson et al., 2023). These constraints highlight that successful adoption requires not only technical procurement but also institutional capacity-building, pedagogical training, and inclusive design considerations.

## Synthesis Gap and Rationale for the Present Review

Despite growing scholarship, prior work has tended to emphasize either (a) technological innovation (e.g., VR/AR/AI features) or (b) pedagogical approaches (e.g., inquiry-based, active learning) in isolation. Consequently, a critical gap remains in systematically synthesizing how educational technologies used in virtual simulation align with instructional design approaches and learning-theoretical rationales, particularly in the context of virtual laboratories across disciplines and educational levels. Addressing this gap is important because misalignment between technology affordances and instructional design may reduce effectiveness and limit transfer to practice. Therefore, the present systematic review examines emerging trends in virtual simulation for education by mapping educational technologies and instructional design approaches, with the aim of informing evidence-based development, implementation, and future research directions.

## Method

The research employs a systematic review methodology to investigate the growth trends of Virtual Simulation technology in the development of comprehensive learner outcomes, alongside the design of instructional practices tailored to this technology's capabilities. The methodological framework follows the PSALSAR approach (Protocol, Search, Appraisal, Synthesis, Analysis, Report) proposed by Mengist et al. (2020). Furthermore, the study adheres to the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) for the systematic identification, screening, and selection of literature.

Figure 1 presents the systematic process of identifying, screening, and selecting journal articles using the PRISMA 2020 protocol. The steps include initial identification of records from databases (ERIC, ACM Digital Library, ScienceDirect, and Scopus), removal of ineligible and duplicate articles, screening for relevance, and final eligibility assessment. After thorough appraisal and quality assessment, 20 studies were ultimately included in the review.

## Protocol Stage

The first stage involved developing a protocol, which entailed defining the research scope, formulating key research questions, and establishing the review's boundaries. The primary focus was on the growth trends of Virtual Simulation technology and the theories and instructional design employed in virtual laboratories. The research aimed to address the following questions:

RQ1. What is the trend of their growth in Virtual Simulation research for developing hard skills?

RQ2: Which technologies have been used for virtual labs?

RQ3. What learning theories and instructional design features have been applied in virtual laboratories?

To ensure a focused investigation, the study's scope was limited to journal articles published between 2020 and 2024, with an emphasis on sources available in ERIC, ScienceDirect, ACM Digital Library, and Scopus.

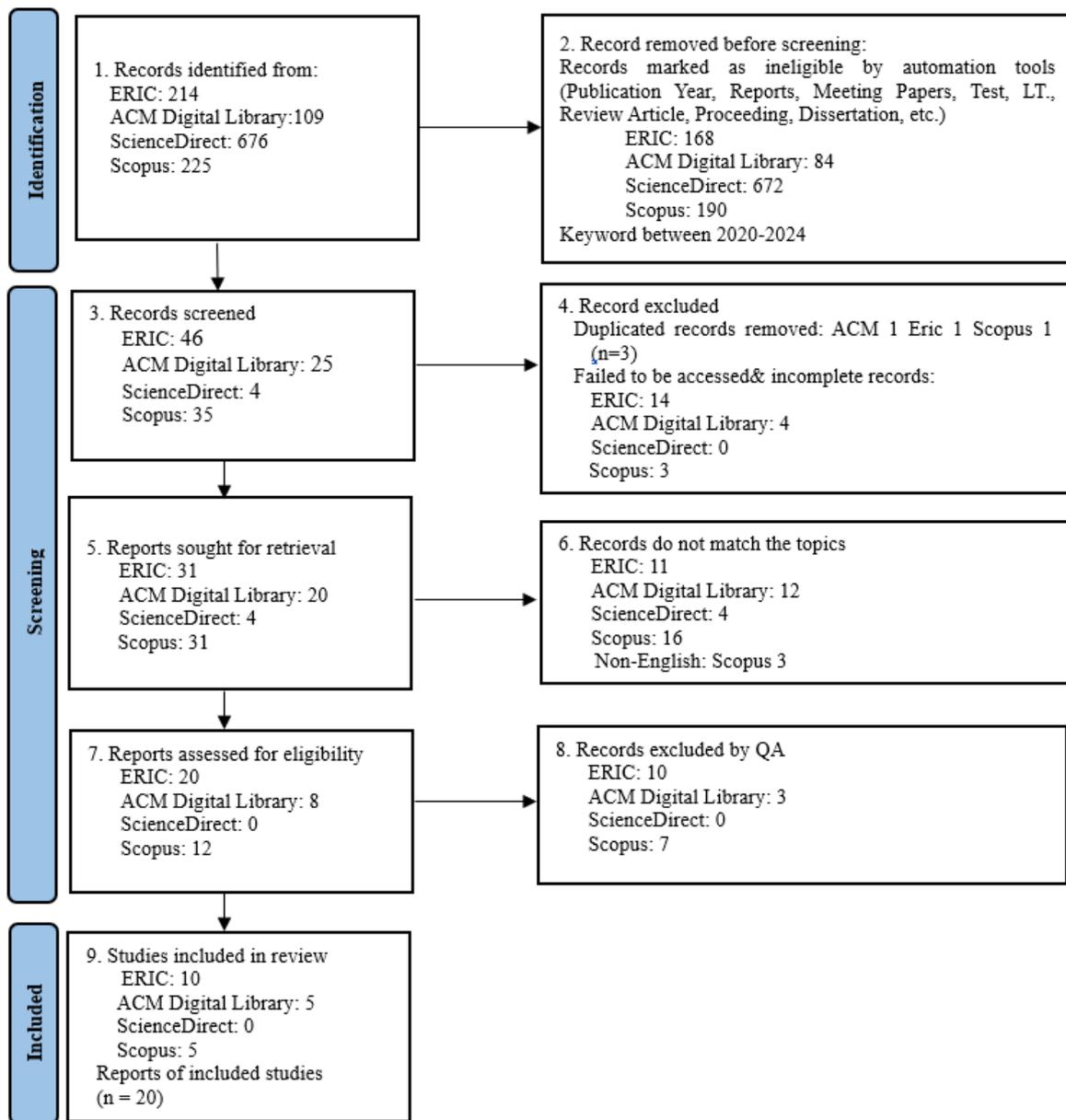


Figure 1. Result of Article Search Using PRISMA 2020

**Search Stage**

The literature search process meticulously identified and refined key terms during the search phase. The primary keywords included “simulation,” “virtual labs,” and “technology,” alongside related terms outlined in Table 1. These terms were systematically adapted to align with each database's search algorithm to optimize the retrieval of relevant scholarly sources.

Table 2 summarizes the search results for the selected keywords across three databases: ERIC, ScienceDirect, and ACM Digital Library. Among these, ScienceDirect produced the most articles, totaling 676, followed by Scopus with 225, ERIC with 214, and ACM Digital Library with 109. These findings highlight the extensive availability of literature and emphasize the importance of systematic screening in the review process.

Table 1. Keywords and Their Derivatives in Journal Article Searches

Main Keywords	Derivative Keywords
simulation	Simulation, Virtual simulations
virtual labs	Virtual simulations lab, Virtual laboratory
technology	Virtual Labs & Simulations, Simulation Technology, Virtual & Augmented Reality (VR/AR), Cloud Computing, Artificial Intelligence & Machine Learning (AI/ML), Learning Management Systems (LMS) & E-learning, Communication & Collaboration Tools, 3D Modeling & Game Engines, Visualization & Digital Content Creation, Gesture-Based & Interactive Technologies

Table 2. Search Journal Articles by Keyword

Database	Search keywords	Results
ERIC	"simulation" AND "virtual labs" AND "technology"	214
ScienceDirect	"simulation" AND "virtual labs" AND "technology"	676
ACM Digital Library	"simulation" AND "virtual labs" AND "technology"	109
Scopus	"simulation" AND "virtual labs" AND "technology"	225

### Appraisal Stage

The appraisal stage involved rigorous screening to ensure the inclusion of high-quality and relevant articles. Table 3 outlines the criteria used to include or exclude studies. Inclusion criteria focused on peer-reviewed articles discussing Virtual simulation contexts, published within the defined timeframe, and accessible in full text. Articles were excluded if they were duplicates, inaccessible, or irrelevant to the research focus.

Table 3. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Journal articles on the topic of Technologies Virtual Simulations in Education	Journal articles that cannot be accessed
Journal articles published on ERIC, ScienceDirect, ACM Digital Library, Scopus.	Duplicate journal articles (previously found)
Journal articles published in 2020 – 2024	Journal articles that are not complete (not full text) Journal articles in the form of literature reviews, books, and websites

The inspection stage of appraisal incorporates both quality and literature evaluation. Rechecking the inclusion and exclusion criteria constitutes a component of the literature appraisal process. The two assessments that make up the quality assessment are as follows:

QA1: Does the journal article discuss using Technologies Virtual Simulations in Education?

QA2: Is the journal article in the form of Classroom Action Research, or contains classroom

experiments?

## **Synthesis and Analysis**

The synthesis stage consisted of extracting and classifying data from the selected journal articles, which were then organized into tables. The analysis stage involved evaluating the synthesized data, extracting meaningful information, and summarizing the selected journal articles. At this stage, the research questions formulated would be answered.

## **Reporting Stage**

In the reporting stage, the findings of the systematic review were organized and presented in alignment with the research questions and the adopted synthesis framework. The results were reported using descriptive statistics, tabular summaries, and thematic categorization to ensure transparency and traceability between the reviewed studies and the synthesized outcomes.

Specifically, publication trends and research contexts were reported to address RQ1, highlighting patterns in the adoption of virtual simulation for skill-oriented learning across educational domains. To address RQ2, the educational technologies employed in virtual laboratory environments were systematically categorized and summarized, with Tables 4 and 5 presenting the distribution of technology types and their application contexts. For RQ3, learning theories and instructional design approaches were synthesized and reported thematically, as presented in Tables 6 and 7, illustrating recurring pedagogical patterns across the reviewed studies.

In addition, a conceptual framework was developed during the reporting stage to integrate the synthesized findings. This framework visually represents the relationships between virtual simulation technologies, instructional design themes, and reported learning outcomes, providing a coherent summary of the review results. The reporting approach ensures that all findings are directly derived from the reviewed evidence and are consistently aligned with the objectives and scope of this systematic review.

## **Results**

This section presents the synthesized results of the systematic review based on the analysis of 20 peer-reviewed journal articles published between 2020 and 2024. The findings are organized in alignment with the three research questions, focusing on (1) research trends in virtual simulation for skill development, (2) educational technologies used in virtual laboratories, and (3) learning theories and instructional design approaches underpinning their implementation.

### **Trends in Virtual Simulation Research for Skill Development (RQ1)**

The analysis reveals a clear upward trend in virtual simulation research related to skill development between 2020

and 2024. As illustrated in Figures 2 and 3, scholarly output increased steadily over the review period, with a notable rise after 2022 and a peak in 2024, accounting for 30% of the total publications. This growth indicates growing academic interest in leveraging virtual simulation to support practical, hands-on learning, particularly in contexts where physical laboratories are constrained by cost, safety, or accessibility.

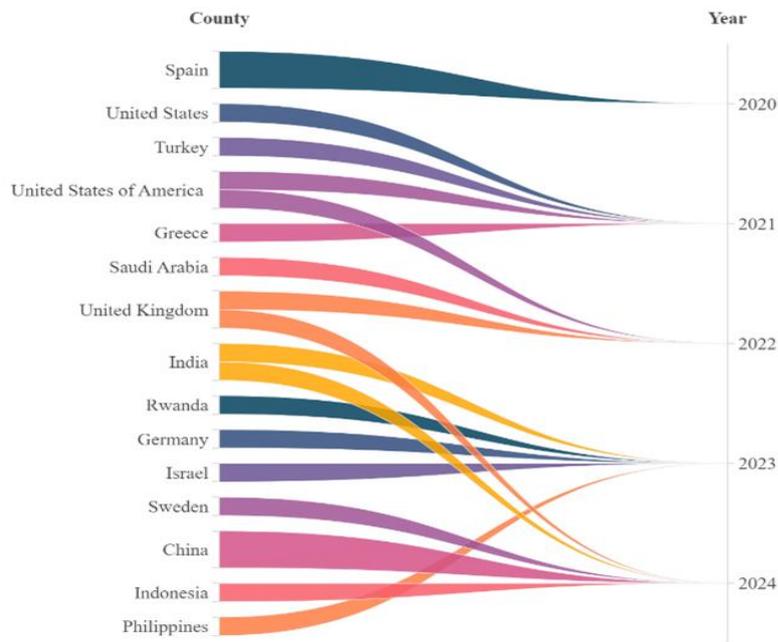


Figure 2. The Publication of Articles from Each Country between 2020 to 2024

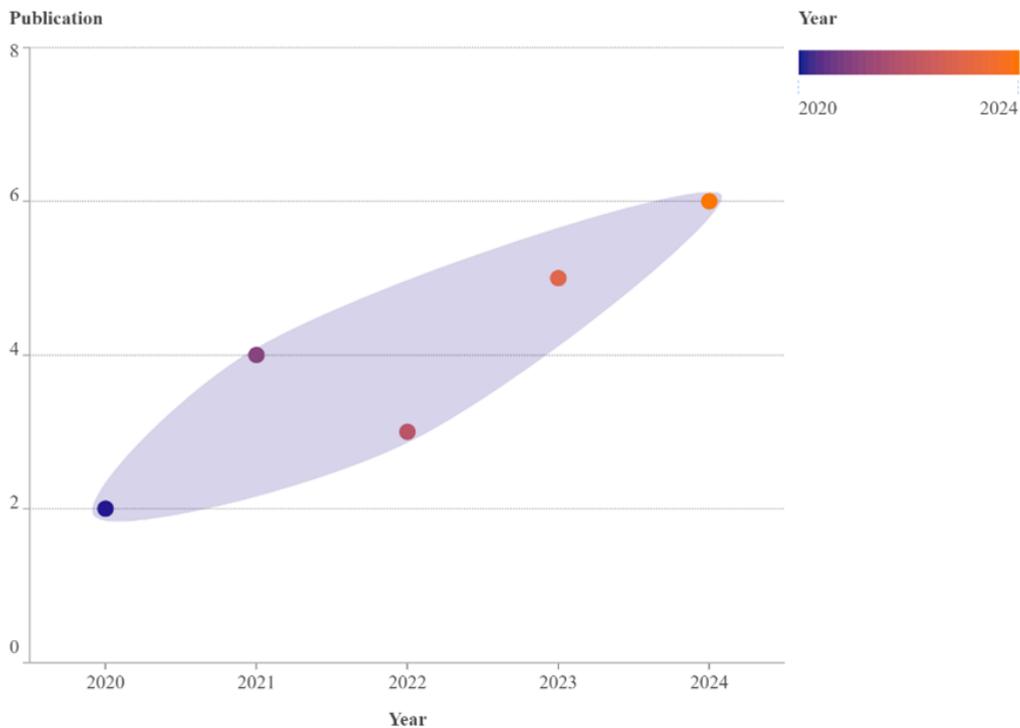


Figure 3. The Number of Articles Published between 2020 and 2024

Geographically, research activity was distributed across multiple regions, with higher publication frequencies observed in technologically advanced countries such as the United States, the United Kingdom, and several European nations. At the same time, emerging contributions from developing regions highlight the growing global relevance of virtual simulation as a scalable educational solution. Across contexts, the dominant focus of the reviewed studies was the development of practical or hard skills, including laboratory procedures, technical operations, and applied problem-solving. These findings suggest that virtual simulation research has increasingly shifted from conceptual demonstrations toward skill-oriented and performance-based learning outcomes.

### Educational Technologies Used in Virtual Laboratories (RQ2)

The reviewed studies employed a diverse range of educational technologies to support the implementation of virtual laboratories. As summarized in Tables 4 and 5 and visualized in Figure 4, Virtual Labs and Simulations and Virtual and Augmented Reality (VR/AR) emerged as the most prevalent technology categories, each accounting for 24% of total usage. These technologies were commonly applied in science, engineering, medical, and vocational education to facilitate interactive experimentation and immersive learning experiences.

Simulation-based technologies, including virtual simulations and domain-specific simulation software, represented 12% of the reviewed implementations. Cloud computing and infrastructure-related technologies accounted for 14%, reflecting the growing role of scalable platforms, virtualization, and remote access in supporting virtual laboratory environments. Learning management systems (LMS) and e-learning tools, as well as communication and collaboration technologies, were used less frequently but played supportive roles in structuring learning activities and enabling remote collaboration.

Advanced technologies such as artificial intelligence, learning analytics, and 3D modeling engines were comparatively underrepresented, indicating that most implementations prioritized experiential access and visualization over adaptive or data-driven instructional features. Overall, the results demonstrate that current virtual laboratory practices are predominantly grounded in immersive and simulation-based technologies, with emerging but limited integration of intelligent and analytics-driven systems.

Table 4. Technology Utilized in Virtual Labs

ID	Author	Type of Technology	Key Features	Education level
P1	Aridan N., 2024	1. VR 2. AR	1. Photogrammetry-based 3D brain models enhance neuroanatomical education. 2. A custom-built virtual laboratory facilitates interactive learning. 3. Evaluation results indicate improved spatial comprehension and learning satisfaction	Medical and Neuroscience students

ID	Author	Type of Technology	Key Features	Education level
P2	Rebecca M., 2021	1. VR 2. Virtual lab simulations.	1. Virtual reality (VR)-based glove hygiene education enhances lab safety awareness 2. A collaborative initiative among chemistry, computer science, and library faculty 3. Evaluation results indicate improved user navigation and engagement	Undergraduate, students first-year chemistry
P3	Yildirim, F.S., 2021	1. Virtual laboratory 2. Virtual simulations.	1. Virtual lab applications in science education 2. Virtual labs enhance students' interest and motivation	Secondary school, eighth-grade students
P4	Karara AH., 2021	1. Blackboard Collaborate Ultra® for live sessions. 2. Labster® science lab simulations. 3. Sniffy the Virtual Rat® simulations. 4. Virtual Interactive Clean Room®	1. Virtual format adapted due to COVID-19 pandemic. 2. Social media for community building among	high school
P5	Kabilan J., 2023	1. Google Sites 2. Virtual labs. 3. Digital curation tools.	1. Google Sites is utilized for virtual lab creation. 2. Curates digital resources relevant to biochemistry topics. 3. Facilitates access from multiple devices (PC, mobile)	higher education
P6	Alfredo C., 2023	1. Digital modular distance learning (DMDL). 2. Free messaging platforms. 3. Virtual simulations lab	1. The study investigates distance learning modalities in physics education 2. Pretest-posttest and repeated measures research designs are utilized. 3. Findings highlight the effectiveness of virtual and physical labs	Senior High School (SHS) students in STEM strand

ID	Author	Type of Technology	Key Features	Education level
P7	Barrow, J., 2024	1. VR 2. Visualization tools 3. Simulations	1. Utilizes Virtual Reality for biochemistry education 2. Participants engage in a virtual lab environment, electrodermal activity sensors. 3. Supports immersive and interactive learning experiences, MetaQuest2 headset	University biochemistry students
P8	Serrano-Ausejo., 2024	1.VR 2.AR	1.Utilizes VR and AR technologies for teaching stereochemistry. 2. Focuses on immersive learning experiences in K–12 education.	Grade 8 students K-12 education
P9	Papadimitropoulos, N., 2021	1. Virtual Chemistry Labs	1. Integration of Technology in Chemistry Education 2. Interactive and Adaptive Learning 3.Accessibility and Cost-Effectiveness	3rd grade of Junior High school
P10	Byukusenge, C., 2023	1. Virtual labs	1.Technology-Enhanced Learning of Nerve Cells 2.Effectiveness of Instructional Approach 3.Implications for Education	secondary school students
P11	Villanueva, A., 2022	1. Tangible Augmented Reality (TAR) technology is utilized.	1. Remote Collaboration and Hands-on Learning 2. Enhanced User Experience 3. Empathetic Collaboration	undergraduate students
P12	Bunse, C., 2023	1. Distance labs 2. Centralized infrastructure 3. Virtualization 4. Scalable and portable technology	1. Remote and Scalable Learning 2. Support for Engineering Courses 3. Infrastructure and Maintenance	engineering education
P13	Alharbi, A. 2022	1. Web-based Integrated 2. E-learning tools	1. Support for Multiple Languages and Collaboration 2 Code Management 3. Mobile Access and Limitations	undergraduate first-year computer science students.

ID	Author	Type of Technology	Key Features	Education level
		1. VR 2. Simulations.	1. Immersive Virtual Reality and Remote Access 2. Cost and Space Efficiency 3. Realistic Simulations	higher education.
P15	Huang, G., 2024	1. VR 2. Unreal Engine 4 3.3DsMax 4. Interactive human-machine	1. Immersive Learning with Virtual Reality 2. Integration with Teaching Models 3. Virtual Laboratory for Practical Learning	junior high school education level
P16	Aldosari, S. S., 2022	1. Gesture-based technology 2. Virtual simulation	1. Virtual Simulation and Molecular Visualization 2. Interactive Learning Tools 3. Exam Preparation and Performance Tracking	secondary school education.
P17	Mariscal, G., 2020	1.VR	1. Virtual Reality for Medical Training 2. Evaluation and Comparison 3. Safety and Emergency Response	higher education
P18	Corbi, A., 2020	1. Virtual engineering labs. 2. Container technology. 3. Cloud 4. Simulation	1. Scientific Simulations and Modern Computing 2. Engagement and Learning Tools 3. Physics and Engineering Applications	engineering undergraduates' education
P19	Kulkarni, R., 2024	1.AR 2. Virtual engineering labs 3. Mixed and Augmented Reality Studio (MARS)	1. Interactive Learning with AR 2. Performance and Motivation 3. Real-Time Tracking and Model Access	engineering education.
P20	Santyadi Putra, G. S., 2024	1. Vilanets 2. Simulation 3. Moodle 4. Google Cloud 5. Videos and Cisco Packet Tracer files.	1. Integration of VLEs and Virtual Labs 2. Collaborative and Cloud-Based Learning 3. Structured Learning and Complex Objectives	higher education students.

Table 5. Classification of Technologies Used in Virtual Labs

Technology Category	Item	Count	Percentage
Virtual Labs & Simulations	Virtual engineering labs	2	24.00%
	Labster Virtual Simulations labs	2	
	Virtual Chemistry Labs	2	
	Virtual Interactive Clean Room®	1	
	Virtual labs	1	
	Virtual labs Simulations	2	
	Remote laboratories	1	
	Virtual and Remote Laboratories,	1	
Simulation Technology	Simulation	3	12.00%
	Virtual simulations	2	
	Sniffy the Virtual Rat® simulations	1	
Virtual & Augmented Reality (VR/AR)	VR	6	24.00%
	AR	3	
	Tangible Augmented Reality (TAR)	1	
	Mixed and Augmented Reality Studio (MARS)	1	
	Vilanets	1	
Cloud Computing & Infrastructure	Cloud	1	14.00%
	Google Cloud	1	
	Container technology	1	
	Centralized infrastructure	1	
	Virtualization	1	
	Scalable and portable technology	1	
	Web-based Integrated	1	
Learning Management	Moodle	2	6.00%
	Blackboard Collaborate Ultra	1	
Systems (LMS) & E-learning	E-learning tools	1	4.00%
	Digital modular distance learning (DMDL)	1	
Communication & Collaboration Tools	Free messaging platforms	1	4.00%
	Google Sites	1	
3D Modeling & Game Engines	Unreal Engine 4	1	2.00%
Visualization & Digital Content Creation	Visualization tools	1	6.00%
	Videos and Cisco Packet Tracer files	1	
	Digital curation tools	1	
Gesture-Based & Interactive Technologies	Gesture-based technology	1	4.00%
	Interactive human-machine	1	

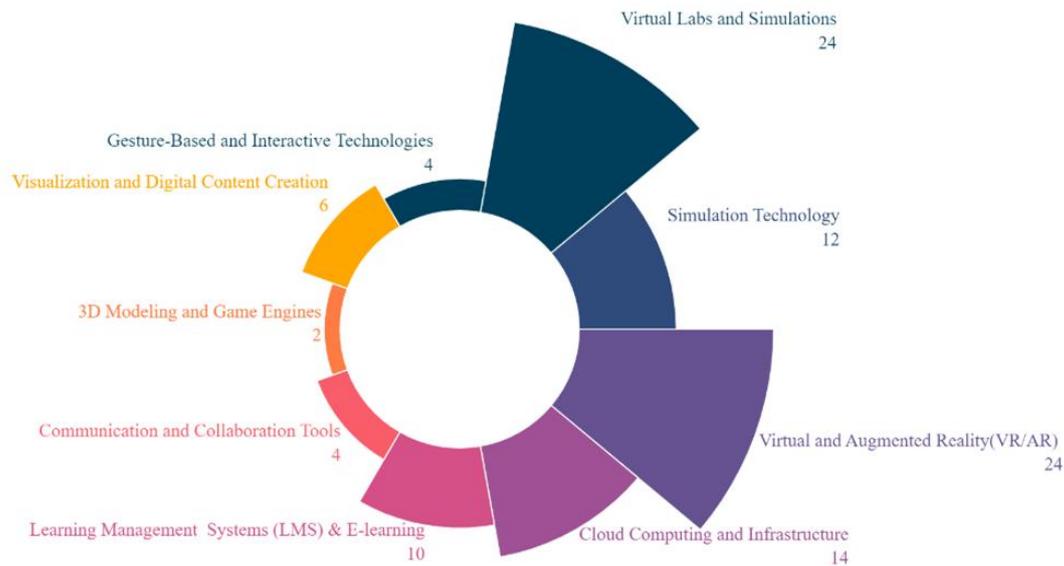


Figure 4. Percentage of Technology Category from 2020 to 2024

### Learning Theories and Instructional Design Approaches in Virtual Laboratories (RQ3)

Analysis of instructional design practices revealed strong alignment with learner-centered and activity-oriented pedagogical frameworks. As presented in Tables 6 and 7, constructivist, experiential, and inquiry-based learning approaches were the most frequently reported theoretical foundations across the reviewed studies. These approaches emphasized active engagement, exploration, and problem-solving within virtual laboratory environments.

Instructional design strategies commonly incorporate guided inquiry, self-directed learning, gamification elements, and collaborative tasks. Assessment practices primarily relied on formative mechanisms, including pre- and post-tests, task-based evaluations, and iterative feedback loops. However, explicit integration of advanced assessment analytics and adaptive feedback systems was limited, suggesting an emphasis on traditional evaluation methods adapted to virtual contexts rather than fully data-driven assessment models.

The relationship between instructional design and technology use also revealed consistent patterns. VR and AR technologies were frequently associated with experiential and immersive learning designs, particularly in higher education and medical contexts. In contrast, conventional virtual laboratories were more commonly paired with inquiry-based and scaffolded instructional approaches in secondary and undergraduate education. These patterns indicate that both technological affordances and educational levels influenced instructional design choices.

Consistent with the synthesized themes presented in Table 7, the reviewed studies demonstrated recurring instructional design patterns, including instructional design adaptation, active and inquiry-based learning, assessment and feedback, gamification and interactive learning, and collaboration and remote learning. Instructional design adaptation was reflected in pre-planning strategies, accessibility considerations, and

structured communication to support virtual learning environments. Assessment and feedback practices primarily involved formative approaches such as pre- and post-tests and iterative task-based evaluations, while gamification and interactive learning strategies were employed to enhance learner engagement through immersive and interactive modules. These themes collectively illustrate how instructional design practices were systematically aligned with virtual simulation technologies across educational contexts.

Table 6. Relationship Between Instructional Design and Virtual Labs

ID	Learning theory	Virtual laboratory	Instructional Design
P1	1. VR and Neuroanatomy Learning 2. Enhanced Spatial Understanding 3. Improved Exam Performance	1. Custom-Built Virtual Laboratory 2. Immersive Learning with VR 3. Enhanced Learning Outcomes	1. Neuroanatomy using Virtual Reality (VR) to enhance learning. 2. Self-Guided Learning in Virtual Lab 3. Assessment through Exams
P2	1. VR for Active Learning in Lab Safety 2. Enhancing Glove Hygiene Awareness 3. Promoting Engagement and Interaction	1. VR Laboratory Application for Chemistry Education 2. Realistic Lab Experience 3. Glove Hygiene Training and Immersive Technology	1. Active Learning 2. Familiarization with Lab Settings 3. Safety and Compliance Focus
P3	1. Constructivist Approach in Education 2. Virtual Laboratories for Meaningful Learning 3. Technology-Supported Learning	1. Safe Experimentation in Virtual Laboratories 2. Enhancing Academic Success and Motivation 3. Understanding Complex Physics Concepts	Virtual laboratory applications in science education.
P4	1. Lab Simulations for Experiential Learning 2. Interactive, Gamified Virtual Labs 3. Engagement through Social Media	1. Transition to Virtual Format 2. Use of Labster® for Interactive Simulations 3. Simulated On-Campus Lab Experiences	1. Adaptation of instructional design for virtual learning 2. Evaluation design with process and outcome data 4. Hands-on training in drug discovery and biomedical research 5. Use of lab simulation software
P5	1. Effective Online Teaching-Learning	1. Remote-Controlled Simulations	1. Adaptation of instructional design for

ID	Learning theory	Virtual laboratory	Instructional Design
	2. Google Sites for Collaborative Learning 3. Virtual Curation Lab for Student Engagement	2. Web-Based Digital Learning 3. Feasibility and Accessibility	virtual curation labs 2. Importance of pre-planning 3. Accessibility of digital resources 4. Clear communication of objectives
P6	1. Metacognition's Influence 2. Distance Learning 3. Modalities Study Focus on Metacognition	1. Improved Learning with Virtual Labs 2. Better Achievement with Virtual Labs 3. Complementary Role of Labs	1. Inquiry-based learning 2. Static PDFs for learning modules 3. Challenge prompts 4. guided learning Comprehensive module content
P7	1. VR for Biochemical Understanding 2. Hierarchical and Dynamic Learning Structure 3. Challenges in Biochemical Pathways	1. VR Visualization Model for Biochemistry 2. Immersive 3D Learning 3. Improved Learning in Virtual Labs	1. VR-based learning environment 2. Interactive virtual lab experience 3. Mixed-methodology approach
P8	1. Activity Theory in Learning 2. Exploring VR and AR in Education 3. Student Challenges in Virtual Learning	1. Effectiveness of Virtual Labs 2. Motivation and Understanding 3. Positive Learning Outcomes	1. Collaboration 2. VR and AR technologies 3. Gamification and iterative testing
P9	1. Cognitive Load and Neural Mirroring 2. Declarative Knowledge Acquisition 3. Learning Gains from Arduino and Virtual Labs	1. Alternatives to Real Labs 2. Impact on Chemistry Knowledge 3. Integration with Arduino Experiments	1. Digital Application (DA) for teaching Chemistry 2. Learning path and guidance 3. Course objectives and concept maps
P10	1. Cognitive Theory Application 2. Effective Learning Tools 3. Deep Learning Promotion	1. Virtual labs Enhanced Understanding 2. Improved Performance 3. Independent Learning	1. Technology-enhanced instruction 2. Effective selection and integration of tools
P11	1. The study emphasizes hands-on learning in laboratory-based classes.	1. Virtual labs lower costs and enhance academic performance. 2. They facilitate distance	1. Enabling Complex and Flexible STEM Environments

ID	Learning theory	Virtual laboratory	Instructional Design
	2. Instructors noted a better understanding through scientific experimentation. 3. Students preferred flexible setups for exploring experiments.	learning and promote health and safety. 3. Virtual labs support various subjects like chemistry and physics, providing hands-on learning through augmented reality and haptic feedback.	2. Remote Collaboration and Engagement 3. Facilitating Hands-on, Practical Learning
P12	1. Promotes self-organized learning and practical experience 2. Enhances learning flexibility 3. Bridges theory with real-world problem-solving	1. High-fidelity digital replication 2. Preparation through virtual twins 3. Standardization in engineering education	1. Study Design and Grouping 2. Compares two teaching methods: distance lab versus traditional lab. 3. Assessment and Feedback
P13	1. Integration of theory and practice 2. Bridging theory and practice 3. Hands-on programming experience	1. Transition to virtual laboratories 2. Overcoming physical limitations 3. Positive student experiences and effectiveness	1. web-based 2. Traditionally conducted in computer labs. 2. Virtual Lab Framework and Technology 3. Collaborative and Remote Learning
P14	1. Enhancing distance and blended learning. 2. Interactive and immersive learning 3. Limitations of traditional methods	1. High simulation and open accessibility 2. Support for distance and blended learning 3. Immersive and interactive learning	1. Use of digital twin technology and simulation 2. collaborative and remote experiments
P15	1. Enhanced immersive and interactive learning 2. Deeper learning engagement 3. Support for constructivist learning	1. Enhanced learning through immersion 2. Observation beyond traditional limits 3. Improved understanding of abstract concepts	1. BOPPPS model 2. Combines experiments and theories for comprehensive learning 3. Assessment through pre- and post-tests
P16	1. Exploration of experiential learning 2. Comparison of learning outcomes 3. Better understanding of the proposed system	1. Virtual chemistry lab for experimentation 2. Safety in virtual labs 3. Integration of virtual simulation and molecular visualization	1. Combines virtual simulation and molecular visualization, utilizing a Leap Motion controller to enhance interactive learning experiences.

ID	Learning theory	Virtual laboratory	Instructional Design
		4. Positive student attitudes	2. Pre-test and Post-test Design 3. Interactive and immersive learning environment
P17	1. Clear learning outcomes in instructional design 2. Enhancement through virtual reality 3. Simulation-based training for skill development 4. Feedback promoting critical thinking	1. UE Risk Simulator for laboratory training 2. Safe simulation of laboratory accidents 3. Enhancing learning in lab work courses 4. Learning safety and basic operations	VR and other immersive technologies
P18	1. Novel virtual lab for teaching x-ray basics 2. Combining science and modern computing 3. Motivation through practical applications 4. Focus on distance learning for adult learners	1. Novel virtual lab for teaching X-ray basics 2. Enhancing physics learning for engineering students 3. Utilizing cloud and computing techniques 4. Engaging and successful pedagogy	Virtual Laboratories
P19	1. Optimizing educational outcomes with digital tools 2. Enhancing engagement through AR technology 3. UTAUT2 framework for assessing AR labs 4. Improved visualization and interaction with e-learning	1. Virtual AR laboratory for engineering education 2. Improved learning experiences in engineering labs 3. Integration of geo-location for interactivity 4. Boosting student engagement 4. Facilitating knowledge acquisition without physical labs	1. AR tools 2. UTAUT2 model for evaluating adaptability.
P20	1. Enhancing practical skills and problem-solving 2. Bridging theory and practice 3. Immersive learning with Vilanets	1. Utilizing Unetlab for virtual functions 2. Enhanced compatibility with networking vendors 3. Better preparation for practical exercises 4. Improved learning outcomes with Vilanets	Advanced Virtual Learning Environments

Table 7. Synthesized Instructional Design Themes and Learning Approaches in Virtual Simulation

Main Instructional Design Themes	Publication ID	Author(s) and Year
Virtual Reality (VR) and Augmented Reality (AR) in Education: Enhancing learning through immersive technologies such as VR, AR, and digital twins	P1	Aridan et al., 2024
	P7	Barrow et al., 2024
	P8	Serrano-Ausejo & Mårell-Olsson, 2024
	P16	Aldosari et al., 2022
	P17	Mariscal et al., 2020
	P19	Kulkarni & Harne, 2024
	P20	Santyadi Putra et al., 2024
Virtual Laboratories: Applications of virtual laboratories in science education, including remote and collaborative experiments	P3	Yildirim, 2021
	P4	Karara et al., 2021
	P11	Villanueva et al., 2022
	P13	Alharbi, 2022
	P14	Yu et al., 2024
	P18	Corbi et al., 2020
Instructional Design Adaptation: Adapting instructional methods for virtual learning, including pre-planning, accessibility, and clear communication	P4	Karara et al., 2021
	P5	Kabilan, 2023
	P10	Byukusenge et al., 2023
	P15	Huang et al., 2024
Active and Inquiry-Based Learning: Promoting engagement through active learning, inquiry-based methods, and challenge prompts	P2	Rebecca et al., 2021
	P6	Alfredo et al., 2023
	P12	Bunse et al., 2023
Assessment and Feedback: Evaluating learning through exams, pre-/post-tests, and iterative testing	P1	Aridan et al., 2024
	P12	Bunse et al., 2023
	P15	Huang et al., 2024
	P16	Aldosari et al., 2022

Main Instructional Design Themes	Publication ID	Author(s) and Year
Collaboration and Remote Learning: Facilitating remote collaboration and hands-on learning in STEM environments	P8	Serrano-Ausejo & Mårell-Olsson, 2024
	P11	Villanueva et al., 2022
	P13	Alharbi, 2022
	P14	Yu et al., 2024
Gamification and Interactive Learning: Using gamification, interactive modules, and immersive environments to enhance engagement	P8	Serrano-Ausejo & Mårell-Olsson, 2024
	P16	Aldosari et al., 2022
	P19	Kulkarni & Harne, 2024
Technology Integration: Effective selection and integration of tools such as simulation software, gesture-based controllers, and AR tools	P4	Karara et al., 2021
	P10	Byukusenge et al., 2023
	P16	Aldosari et al., 2022
	P19	Kulkarni & Harne, 2024

### Cross-Pattern Synthesis of Technologies and Instructional Design

Cross-analysis of the reviewed studies highlights several dominant and underrepresented patterns in virtual simulation research. Dominant trends include the widespread use of immersive technologies for enhancing engagement and spatial understanding, as well as the application of inquiry-based and experiential pedagogies to support skill acquisition. Conversely, underrepresented areas include the use of artificial intelligence for adaptive learning, the integration of learning analytics for real-time assessment, and systematic consideration of accessibility and equity in virtual laboratory design. Additionally, contextual patterns emerged across educational levels. Higher education and professional training contexts tended to adopt advanced immersive technologies, whereas secondary and K–12 settings favored cost-effective virtual laboratories and simulation tools. These findings suggest that contextual constraints, including infrastructure readiness, learner characteristics, and institutional capacity, shape technological and instructional design decisions.

### Conceptual Synthesis of Virtual Simulation, Instructional Design, and Learning Outcomes

Figure 5 presents a conceptual framework derived from the synthesis of instructional design themes and learning approaches identified across the reviewed studies. The framework illustrates the structured relationship between categories of virtual simulation technologies, instructional design themes, and observed learning outcomes in educational contexts.

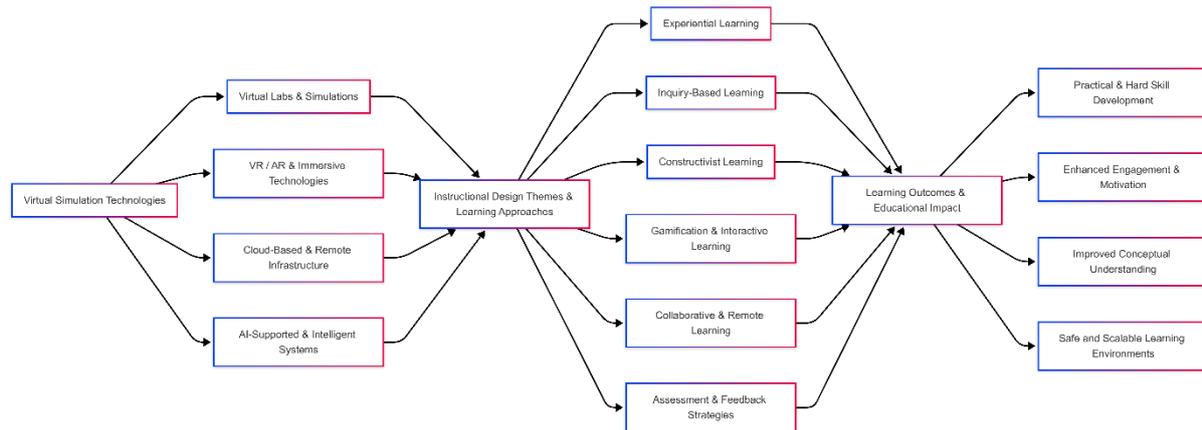


Figure 5. Conceptual Framework Illustrating the Alignment between Virtual Simulation Technologies, Instructional Design Themes, and Learning Outcomes in Education

At the technological level, the reviewed studies predominantly employed four categories of virtual simulation technologies: virtual laboratories and simulation platforms; immersive technologies such as virtual and augmented reality (VR/AR); cloud- and remote-based infrastructures; and emerging AI-supported systems. These technologies served as foundational enablers, providing learners with access to interactive, scalable, and immersive learning environments. Virtual laboratories and simulation platforms were most frequently associated with structured experimentation and procedural practice, while VR/AR technologies emphasized spatial visualization and immersive interaction.

At the instructional design level, the synthesis revealed that technological affordances were operationalized through recurring instructional design themes and learning approaches. These included experiential learning, inquiry-based learning, constructivist learning, gamification and interactive learning, collaborative and remote learning, and assessment and feedback strategies. Experiential and inquiry-based learning approaches were most commonly aligned with immersive and simulation-based technologies, supporting active exploration and hands-on practice. Constructivist learning approaches emphasized learner autonomy and knowledge construction within virtual environments, while gamification and interactive strategies enhanced engagement and sustained participation. Collaborative and remote learning approaches leveraged cloud-based infrastructure to facilitate learner interaction, and assessment strategies primarily focused on formative evaluations embedded within virtual tasks.

At the outcome level, the framework synthesizes learning outcomes reported across the reviewed studies. The most frequently observed outcomes included the development of practical and hard skills, enhanced learner engagement and motivation, improved conceptual understanding, and the provision of safe and scalable learning environments. These outcomes were consistently associated with instructional designs that aligned technological capabilities with learner-centered and activity-oriented pedagogical approaches. The framework highlights that learning outcomes emerged not from the use of technology alone, but from the systematic integration of instructional design strategies within virtual simulation environments.

Overall, the conceptual framework represents a synthesized model of how virtual simulation technologies are pedagogically enacted through instructional design themes to produce educational outcomes. This synthesis provides a structured representation of patterns identified across the reviewed studies and serves as an integrative summary of the empirical results reported in this systematic review.

## Conclusion

This systematic review demonstrates that the educational effectiveness of virtual simulation is determined not by technological sophistication alone, but by the alignment between educational technologies and instructional design approaches (Chen et al., 2023; Rodriguez-Martinez, 2024). The synthesized results indicate that immersive technologies, particularly virtual and augmented reality, are most effective when integrated with experiential, inquiry-based, and constructivist learning approaches, which emphasize active engagement and knowledge construction (Mariscal et al., 2020; Serrano-Ausejo & Mårell-Olsson, 2024).

The predominance of virtual laboratories and VR/AR applications across the reviewed studies reflects a strong focus on practical and hard-skill development, especially in science, engineering, and medical education (Barrow et al., 2024; Corbi et al., 2020). These findings are consistent with prior evidence showing that simulation-based environments support skill acquisition through repeated practice and risk-free experimentation (Anderson & Kim, 2023; Lee et al., 2024). However, the limited presence of AI-supported and analytics-driven systems suggests that most current implementations prioritize immersion and accessibility rather than adaptive personalization (Wang & Liu, 2024; Martinez et al., 2024).

The conceptual framework proposed in this study synthesizes these patterns by illustrating how virtual simulation technologies are pedagogically operationalized through instructional design themes to generate meaningful learning outcomes. This integrative perspective contributes a structured lens for understanding technology–pedagogy alignment in virtual simulation-based education and supports evidence-informed design and future research directions (Johnson et al., 2023; Peterson & Zhang, 2024).

This systematic review synthesized recent research on virtual simulation in education to examine how educational technologies are aligned with instructional design approaches across diverse learning contexts. The findings indicate that virtual laboratories and immersive technologies, particularly VR and AR, are predominantly used to support practical, skills-oriented learning. At the same time, learner-centered instructional designs such as experiential, inquiry-based, and constructivist approaches play a critical role in transforming technological affordances into meaningful educational outcomes. The conceptual framework developed in this study offers a synthesized perspective by illustrating the structured relationships among virtual simulation technologies, instructional design themes, and learning outcomes, thereby providing an integrative lens for understanding technology–pedagogy alignment in virtual simulation-based education. This contribution aligns with broader trends in the field that emphasize aligning technological innovation with pedagogical design to enhance the effectiveness and scalability of educational simulations (Johnson et al., 2023).

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