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Evolution of Simulation-Driven Science Education: Three Decades of Scholarly Patterns and Research Dynamics (1996–2025)

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Abstract

This study maps the global landscape of simulation-based science education (SBSE) research to identify publication trends, influential contributors, collaboration patterns, and future research opportunities. A bibliometric analysis was conducted on 4,489 Scopus-indexed publications published between 1996 and August 25, 2025, using VOSviewer and Biblioshiny; therefore, 2025 should be interpreted as a partial year. The results indicate sustained growth in the literature, with a marked increase during 2020–2024 that may be associated with the expansion of virtual and augmented reality (VR/AR), online learning, and post-pandemic pedagogical adaptation. Keyword evolution suggests a shift from conventional computer-based simulation toward more immersive and data-informed approaches, including machine learning, learning analytics, and adaptive learning systems. The United States and China produced the largest publication outputs, while Indonesia recorded the highest proportion of international collaboration among the top 10 most productive countries (29%). Overall, the findings highlight the growing importance of cross-border collaboration, sound instructional design, and the ethical integration of intelligent technologies in advancing SBSE research and supporting more inclusive and adaptive science learning environments.

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INTRODUCTION

Science education continues to transform in line with the development of increasingly sophisticated digital technology (Ahmad & Prasetyo, 2023; Wulansari et al., 2025). In recent decades, simulation has become an innovative approach widely used to enhance the effectiveness of science learning (Ben Ouahi et al., 2022; Pang et al., 2024). Through simulation, students can gain a more interactive and contextual learning experience that is closer to real-world situations without incurring direct risks (Lord et al., 2025). This makes simulations not only a visualization tool but also a means of building a deeper understanding of concepts (Korkut & Surer, 2023), improving problem-solving skills (Simanjuntak et al., 2021), and fostering critical thinking skills (Astuti et al., 2020). The emergence of new technologies such as virtual reality (VR), augmented reality (AR), mixed reality, and machine learning further enriches the potential application of simulations in science learning (Supurwoko et al., 2025; Zainuddin et al., 2025). In addition, the growing use of online learning environments, distance learning systems, virtual laboratories, and

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digital platforms has expanded the role of simulation in science education, making it increasingly relevant in both classroom-based and technology-mediated instruction. Thus, research on simulation-based science education (SBSE) has become an increasingly relevant area of study, not only for pedagogical innovation but also to support the readiness of the younger generation to face the challenges of the 21st century.

While the potential of simulation in science education is enormous, existing research reflects diverse dynamics, with different foci, approaches, and outcomes. Some studies emphasize the use of simulation to improve understanding of abstract scientific concepts (AlGerafi et al., 2023; Hernandez-de-Menendez et al., 2020; Liu et al., 2020). However, the challenge lies in ensuring that simulation has a meaningful and sustained impact on learning outcomes, rather than being perceived as a temporary technological innovation. Additionally, there are considerable differences in the use of simulation across countries and institutions, particularly in infrastructure, educator readiness, and policy support (Al-Maskari et al., 2024; Brenya, 2024; Campos et al., 2020; McGarr, 2021). These differences are also increasingly important in online and digitally mediated learning settings, where effective implementation often depends on access to virtual labs, digital infrastructure, and platform-supported learning. This highlights the complexity of the field and signals the need for a more comprehensive understanding of how research themes evolve, what factors are most influential, and the extent to which global collaboration has shaped SBSE research.

Although several studies have reviewed the use of simulation in education (Azhari et al., 2024; Banda & Nzabahimana, 2021; Chernikova et al., 2020; Pellas et al., 2021), most of them focus on specific domains, particularly medical and nursing education (Koukourikos et al., 2021; Sezgin & Bektas, 2023; Shorey & Ng, 2021). Likewise, existing bibliometric studies have largely concentrated on narrower areas such as nursing simulation, medical simulation, virtual simulation, or technology-specific strands of educational research (Ba et al., 2025; Chen et al., 2024; Mun et al., 2025; Sun et al., 2024). By contrast, bibliometric evidence on simulation-based science education remains limited, particularly regarding global publication trends, patterns of cross-country collaboration, and long-term thematic evolution. Therefore, this study contributes by mapping the development of simulation-based science education research within this more specific educational scope.

The main objective of this study is to conduct a bibliometric analysis of international publications in the field of SBSE. This analysis aims to understand the dynamics of research development, identify influential actors, and reveal opportunities for innovation in this field. More specifically, this study focuses on answering the following three research questions:

RQ1: How have the main research themes in SBSE developed over time?
RQ2: What aspects of the literature are most influential in the field of SBSE?
RQ3: What are the challenges and directions for the development of SBSE based on research trends?

The significance of this study lies in its contribution to a comprehensive understanding of the SBSE research landscape. First, the results of bibliometric mapping can help researchers and academics identify trends, current keywords, and themes that have the potential to become state-of-the-art. Second, information about influential authors, journals, institutions, and countries enables the establishment of more effective global collaboration. Third, the results of this study can inform educators and curriculum developers in designing simulation-based learning strategies that are more innovative, relevant, and responsive to the needs of the 21st century. Thus, this study not only fills the gap in the literature related to the global map of simulation-based research but also provides a scientific basis for strengthening the quality of science education through the integration of more adaptive and collaborative digital technologies.

METHOD

This study employed bibliometric analysis to describe research trends and characteristics of a group of publications (Amiruddin et al., 2025; Donthu et al., 2021). In addition, bibliometric analysis is an approach that has great potential in identifying research trends, collaboration patterns, and knowledge maps in a particular field (Pessin et al., 2022; Yan & Zhiping, 2023). Bibliometric analysis can be used to display a structural overview of SBSE. To improve

methodological transparency and reproducibility, the bibliometric workflow in this study covered three main stages: literature retrieval, screening and eligibility assessment, and bibliometric mapping and performance analysis. The search and selection process was reported using the PRISMA 2020 framework (Page et al., 2021), while VOSviewer and Biblioshiny were used to analyze the retrieved records.

Literature Search and Selection

Scopus was chosen as the primary database for this study due to its comprehensive and up-to-date coverage of peer-reviewed literature (Malinowska et al., 2024). As one of the largest and most widely recognized databases, Scopus indexes a vast range of articles, research topics, and books in the fields of education and science (Pranckutė, 2021; Singh et al., 2021). It provides access to a high-quality selection of sources subject to rigorous peer review, ensuring the reliability and academic credibility of the data used in this bibliometric analysis. Moreover, Scopus offers robust tools for citation analysis and bibliometric visualization, making it an ideal choice for conducting large-scale systematic reviews and research mapping.

Search Strategy and Eligibility Criteria.

The literature search was conducted in Scopus on August 25, 2025. To ensure transparency and reproducibility, the exact query used was: TITLE-ABS-KEY ((simulat OR "augmented reality" OR "virtual reality") AND (educat OR teaching OR learning) AND (science)). The search was limited to records indexed between 1996 and August 25, 2025; therefore, publication counts for 2025 should be considered partial. Additional filters restricted the results to journal articles in English with final publication status and available abstracts, as specified in the query. Duplicate records were removed by cross-checking titles, authors, publication years, DOIs, and source titles. The search terms and Boolean operators used to construct the query are summarized in Table 1.

Table 1. Summary of Search Item and Operator Boolean (TITLE-ABS-KEY)

"OR"	Simulation	Education	Science
OR	simulat*	educat*	science
OR	augmented reality	teaching	
OR	Virtual reality	learning	

The identification, screening, eligibility, and inclusion steps were reported using a PRISMA 2020 flow diagram (figure 1) (Page et al., 2021).

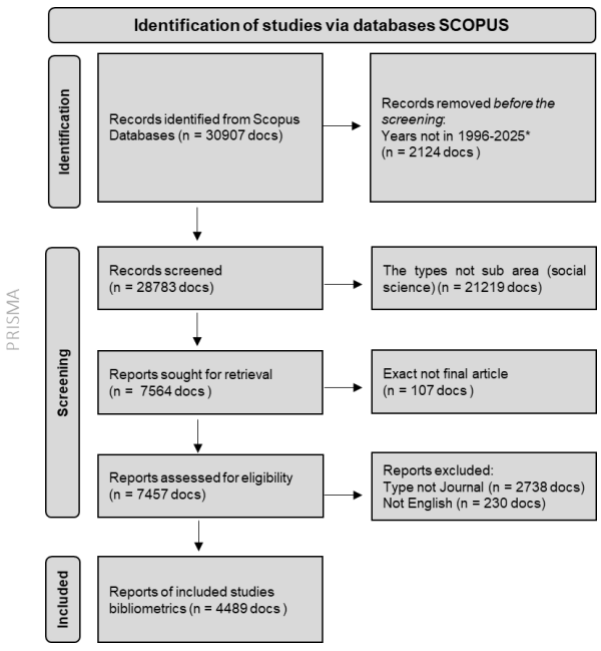

Figure 1. Flow Chart of The Article Election Process

In line with Figure 1, the initial Scopus search identified 30,907 records. Before screening, 2,124 records outside the 1996–August 25, 2025 range were removed, leaving 28,783 records for screening. At the screening stage, 21,219 records were excluded because they did not match the selected subject-area criterion, resulting in 7,564 reports sought for retrieval. A further 107 records were excluded because they did not meet the final-publication requirement, leaving 7,457 reports assessed for eligibility. At the eligibility stage, 2,738 records were excluded because they were not journal articles, and 230 were excluded because they were not in English. The final dataset, therefore, comprised 4,489 publications included in the bibliometric analysis. Because the search was conducted in a single database, duplicate checking functioned as a quality-control step during screening rather than as a separately reported PRISMA category.

Data Processing and Analysis

Data were retrieved from Scopus and exported in CSV, BibTeX, and RIS formats. The RIS file was analyzed using VOSviewer version 1.6.20, whereas the BibTeX file was processed using Biblioshiny in the bibliometrix package. CSV files were used only for data cleaning and tabulation in Microsoft Excel. In VOSviewer, co-occurrence mapping of author keywords was performed using the full-counting method and association-strength normalization, with the minimum occurrence threshold set at 5. The map was generated using the default VOSviewer clustering settings with a resolution value of 1.00. Only items meeting the threshold were included in the final visualization, and closely related terms were manually reviewed to improve consistency (van Eck & Waltman, 2010; Van Eck & Waltman, 2017; Waltman, 2016). In Biblioshiny, bibliometric performance and science-mapping analyses were conducted to identify the most productive authors, sources, institutions, countries, citation patterns, collaboration networks, and thematic evolution of the dataset.

In practical terms, VOSviewer was used primarily for network visualization, especially keyword co-occurrence mapping, whereas Biblioshiny was used for descriptive bibliometric performance analysis and thematic mapping. The extracted metadata included publication titles, author names, publication years, journals, keywords, affiliations, countries, and citation counts. These metadata were then used to generate analyses of publication trends, leading authors, source journals, institutional affiliations, country contributions, collaboration structures, and thematic development across the dataset. This combined workflow allowed the study to integrate transparent record selection with reproducible bibliometric mapping and descriptive analysis.

RESULTS AND DISCUSSION

Main Research Themes in Simulation-Based Science Education

Annual Publication 1996 – 2025

Figure 2 presents the annual publication trend from 1996 to August 25, 2025, showing the gradual expansion of research in simulation-based education over time. Between 1996 and approximately 2005, the number of publications remained low and relatively stable, suggesting an early exploratory phase. From 2006 to 2015, publication output increased gradually, indicating growing scholarly attention to the field. A more pronounced increase was observed during 2016–2020, followed by rapid growth in 2021–2024. In 2024, publication output reached its highest annual level (527 documents). By contrast, the lower count recorded for 2025 (370 documents) should be interpreted with caution because 2025 represents a partial year of Scopus indexing rather than a confirmed decline in research activity. Overall, the publication trend indicates sustained and accelerating growth, especially after 2020, while recent-year comparisons involving 2025 should be treated cautiously.

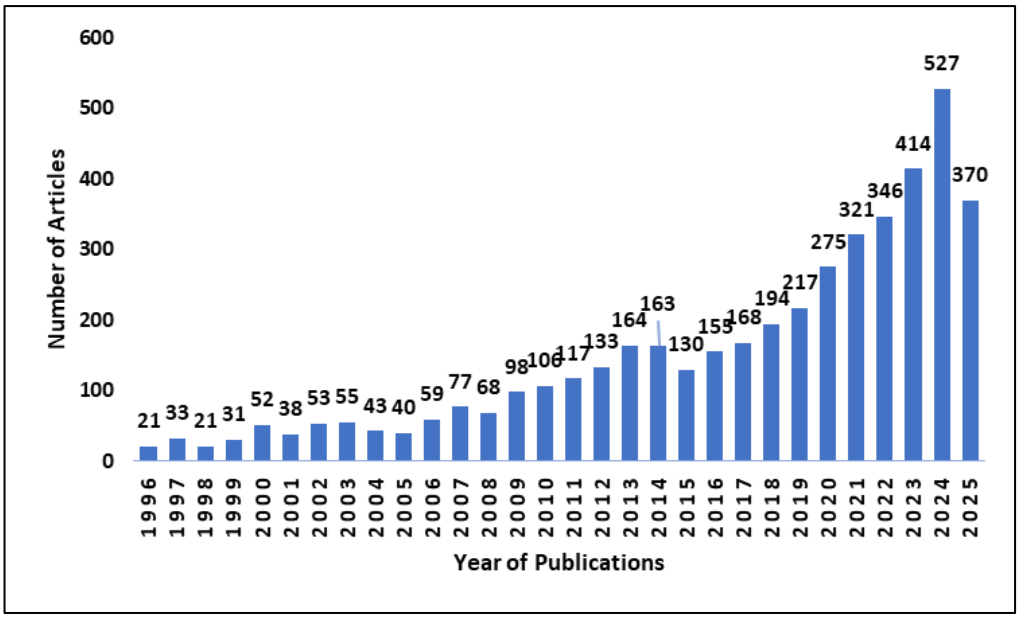

Figure 2. Distribution of Articles on SBSE

Keyword Trends

Figure 3 presents the distribution of core keywords in simulation-based education research through a keyword co-occurrence network generated in VOSviewer. In this map, larger nodes represent more frequently occurring keywords, while links indicate co-occurrence relationships among terms. The most prominent keywords include "human," "education," "simulation," "learning," and "teaching," suggesting that these concepts form the main conceptual core of the literature. Other frequently connected terms, such as "students," "virtual reality," "augmented reality," "e-learning," and "computer simulation," indicate the strong technological orientation of the field. The presence of health-related terms, including "clinical competence," "nursing education," and "simulation training," further shows that the corpus extends beyond science education in the narrow sense and includes substantial work from medical and nursing education. At the same time, terms such as "science education" and "science learning" remain visible within the broader education-related network, indicating that science education is one important strand within the larger simulation-based education literature. Emerging terms such as "machine learning," "gamification," and "mixed reality" suggest continuing thematic expansion in the field.

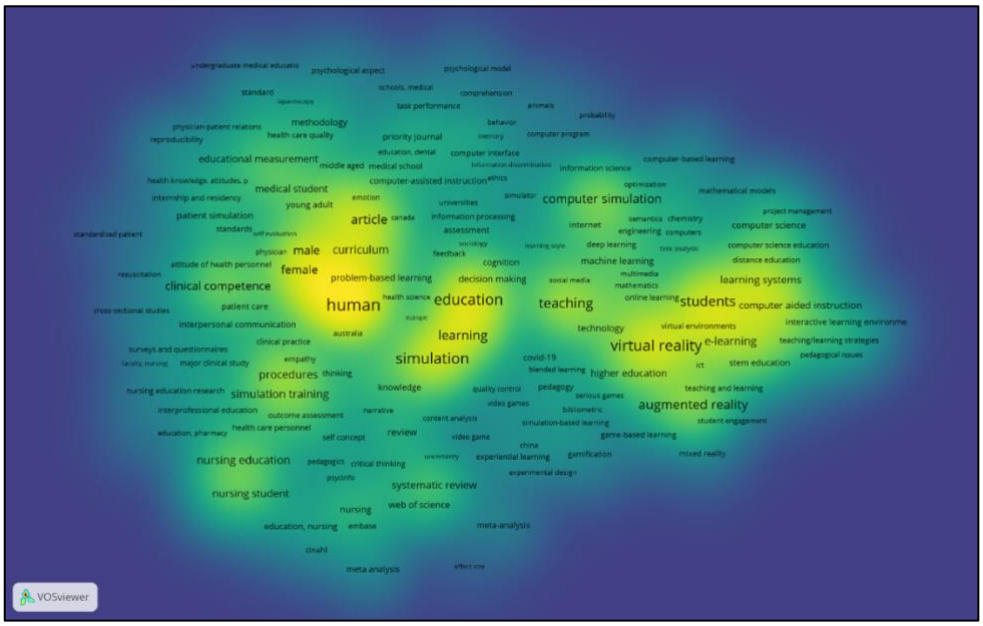

Figure 3. Distribution of Core Keywords

Interpreted more critically, the keyword pattern suggests that the retrieved corpus is not organized around technology alone, but around the interaction between pedagogy, learner engagement, and digital mediation. The prominence of terms such as "education," "learning," "teaching," and "students" indicates that simulation is primarily discussed as an instructional approach rather than merely as a technological artifact. At the same time, the visibility of "virtual reality," "augmented reality," "e-learning," and "machine learning" suggests that recent research is increasingly concerned with how simulation can support more interactive, adaptive, and technology-enhanced learning environments. This pattern is consistent with constructivist and inquiry-oriented perspectives in science education, in which learners benefit from opportunities to explore phenomena, manipulate variables, and construct understanding through active engagement rather than passive reception (Banda & Nzabahimana, 2021; Chernikova et al., 2020; Ben Ouahi et al., 2022; Pang et al., 2024). Thus, the keyword map not only identifies prominent topics but also indicates that the field is shifting toward more learner-centered and digitally mediated forms of science learning.

Thematic Evolutions

Figure 4 illustrates the thematic evolution of research from 1996 to August 25, 2025, linking the main keywords that emerged across successive periods. The time slices used in this analysis (1996–2005, 2006–2010, 2011–2014, 2015–2020, and 2021–August 25, 2025) were defined heuristically to reflect differences in publication density across the dataset. Broader early periods were used because publication output was relatively sparse, whereas shorter and more recent periods were used to capture the faster thematic diversification observed in later years. Accordingly, these intervals should be interpreted as analytical segments rather than equal temporal units. This segmentation allows the thematic evolution map to display clearer transitions in the literature, including the increasing prominence of virtual reality, augmented reality, and other digital learning technologies over time. However, because the final period includes 2025 as a partial year, themes appearing in the last slice should be interpreted with caution. Overall, the figure suggests a gradual shift from foundational simulation and learning topics toward more technology-oriented and interdisciplinary themes in the later stages of the literature.

In interpretive terms, the thematic progression suggests that the field has moved from using simulation mainly as a representational or supportive classroom tool toward framing it as part of broader learning-system design. The early emphasis on "computer simulation," "human," and "students" reflects an initial concern with instructional use and learner interaction. The later emergence of themes such as "learning systems," "hands-on learning/manipulatives," "professional development," and "virtual reality" indicates that simulation research increasingly intersects with questions of pedagogy, curriculum design, and experiential learning. This transition is educationally meaningful because it reflects a shift from content delivery toward more active, exploratory, and student-centered learning arrangements.

The cross-theme connections also suggest that immersive technologies are becoming embedded within wider instructional frameworks rather than operating as isolated innovations. In particular, the connections among "virtual reality," "learning systems," and student-related terms imply that technological development is being accompanied by greater attention to engagement, interaction, and contextualized learning. From an educational-theory perspective, this pattern is compatible with constructivist and inquiry-based views of science learning, where the value of simulation lies in enabling experimentation, visualization, and guided meaning making. Accordingly, the thematic evolution shown in Figure 4 should be read not simply as technological change, but as evidence of a broader pedagogical reorientation in the field.

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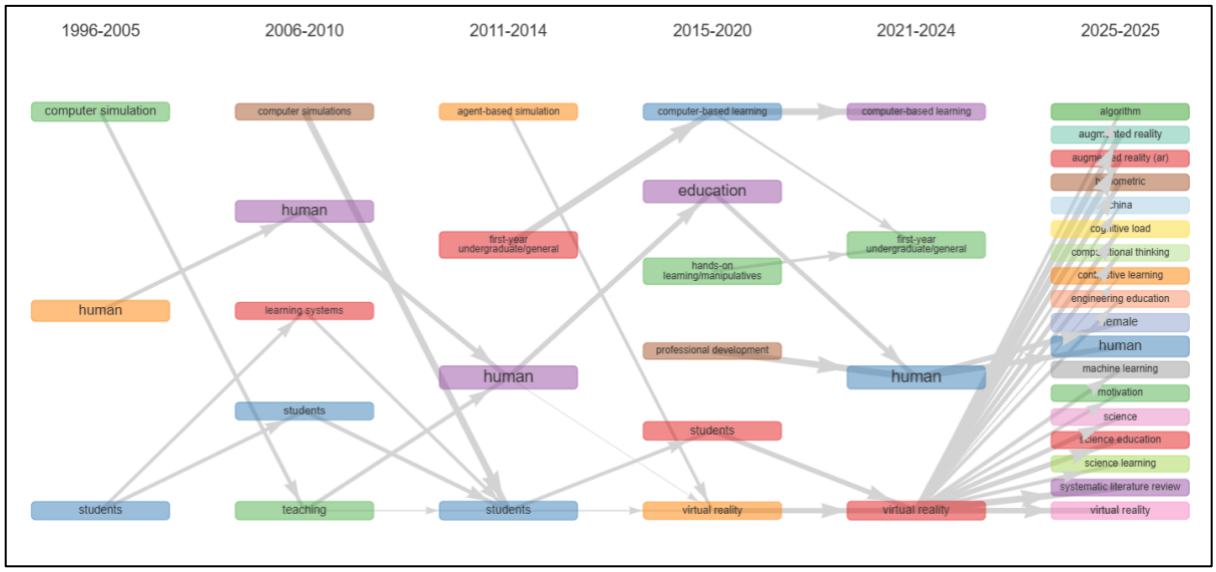

Figure 4. Thematic Evolution on SBSE

Furthermore, during the 2021–2024 period, major themes remained focused on "computer-based learning," "human," and "virtual reality," indicating continued attention to the role of technology in learning. When the 2024–2025 period is viewed cautiously, the thematic map suggests the growing visibility of terms such as "augmented reality," "machine learning," "computational thinking," "engineering education," and "systematic literature review," together with topics related to "cognitive load," "motivation," and gender. Because 2025 is a partial year, these more recent thematic signals should be interpreted as provisional rather than definitive. Overall, the findings point to increasing thematic diversification, with the literature expanding from core technology-use themes toward evaluation, psychological dimensions, equity-related concerns, and more advanced digital approaches in simulation-based education research.

Influential Aspects of Literature

Top Authors

Table 2 presents a list of the most influential authors in SBSE research, measured through bibliometric indicators such as h-index, g-index, m-index, total citations (TC), number of publications (NP), and publication year start (PYS). MAGANA AJ holds a significant position with an h-index of 12 and consistent productivity since 2012, despite a relatively lower total citation count (376) compared to others. TSAI C-C demonstrates strong citation impact with 1,253 citations since 2001, although the m-index (0.44) suggests that this influence has accumulated over a longer period. HWANG G-J stands out with 1,882 citations and an h-index of 10 since 2012, reflecting high productivity and substantial citation impact within a relatively short timeframe. MAYER RE emerges as the most highly cited author in terms of total citations (2,907), despite having only 10 publications, indicating strong scholarly visibility and citation impact.

Table 2. List of Top 10 Authors

Author	Scopus ID	H_index	G_index	M_index	TC	NP	PYS
MAGANA AJ	25655033800	12	17	0.857	376	17	2012
TSAI C-C	7404967011	11	16	0.44	1253	16	2001
HWANG G-J	7202677655	10	16	0.714	1882	16	2012
MAYER RE	7403065717	10	10	0.417	2907	10	2002
XIE C	41461929600	10	13	0.714	492	13	2012
CHEN C-H	57216232433	9	12	0.563	674	12	2010
LINDGREN R	25621716400	9	16	0.529	1074	16	2009
HWANG F-K	7102829007	8	9	0.348	298	9	2003
KLOPFER E	6603369467	8	8	0.364	756	8	2004
MAKRANSKY G	50361371800	8	8	1	2006	8	2018

TC = total citation, NP = number of publications, PYS = publication year start

Taken together, Table 2 suggests that intellectual leadership in the field is distributed across both long-established scholars and more recent high-output contributors. Authors such as XIE C, CHEN C-H, and LINDGREN R appear to occupy important middle positions between foundational influence and ongoing productivity, while authors such as MAKRANSKY G indicate the emergence of more recent but rapidly visible contributors. This combination is characteristic of a maturing field: senior authors provide conceptual continuity, whereas newer contributors help expand thematic diversity and methodological innovation. Therefore, the author profile in Table 2 points not only to individual visibility, but also to a dynamic and evolving structure of scholarly leadership.

The Most Impactful Source

Table 3 presents the ten most influential publication sources in simulation-based education research. The leading sources include journals from science education, educational technology, and health professions education. For example, the *Journal of Science Education and Technology* and *Computers & Education* represent strong contributions from science and technology-enhanced learning, whereas *BMC Medical Education* and *Nurse Education Today* indicate substantial representation from medical and nursing education. This source profile confirms that the dataset is not limited to science education in a narrow sense, but rather reflects a broader interdisciplinary body of simulation-based education research. Therefore, the source distribution is more appropriately interpreted within the scope of simulation-based education than simulation-based science education.

Table 3. Top 10 Influential Sources

Sources	Articles
Journal of Science Education and Technology	139
Computers & Education	136
BMC Medical Education	108
Nurse Education Today	95
Education and Information Technologies	83
Journal of Chemical Education	83
Clinical Simulation in Nursing	82
Computer Applications in Engineering Education	73
Education Sciences	71
Sustainability (Switzerland)	62

Top Affiliations

Figure 5 depicts the distribution of publications by institutional affiliations in simulation-based education research. The University of California system appears first with 106 documents; however, this figure may represent an aggregated count across multiple University of California campuses rather than a single campus-level entity. It is followed by Purdue University (98

documents) and National Taiwan Normal University (86 documents), both of which make substantial contributions to the literature. Stanford University also ranks prominently with 62 documents. Other institutions, including the University of Florida (56 documents), Indiana University (55 documents), the University of Toronto (54 documents), the University of Calgary (50 documents), National Central University (50 documents), and Arizona State University (49 documents), also show notable research output. Overall, Figure 5 indicates broad international institutional participation, with a strong concentration of highly productive affiliations in the United States. These affiliation counts should be interpreted in light of possible institution-level aggregation in the source metadata.

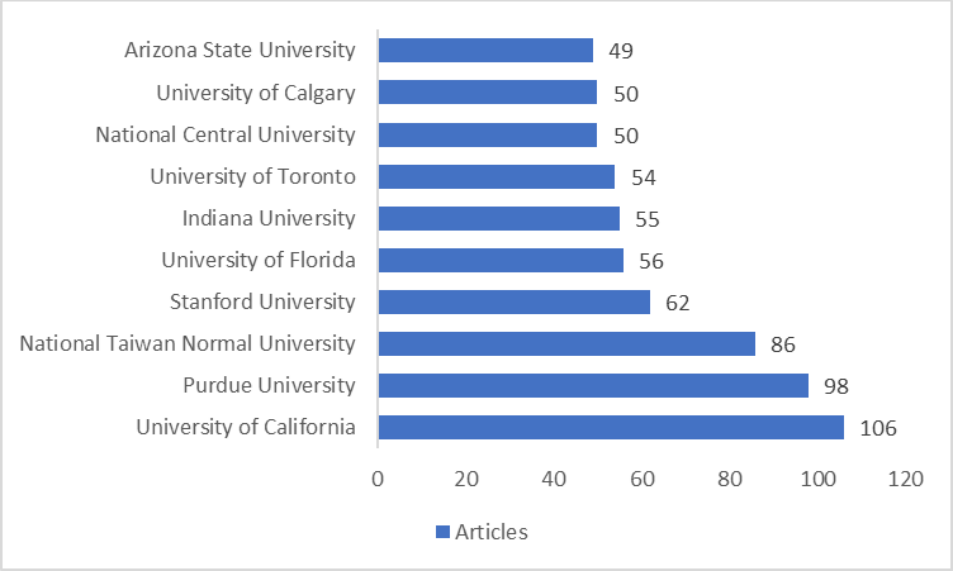

Figure 5. Publications by Affiliations

Most Productive Countries and Collaborations

Table 4 presents the countries with the highest productivity and collaboration in SBSE research. The United States dominates with 1229 documents (27.4%), most of which are domestic publications (SCP = 1118), but it also shows 111 international collaborative documents (MCP = 111). China ranks second with 310 documents (6.9%), of which 14.8% are from cross-country collaborations, indicating openness to global networks. The United Kingdom (199 articles) and Canada (134 documents) stand out with high proportions of international collaboration (MCP = 21.6%), while Germany (119 documents) and Brazil (60 documents) show even higher collaboration percentages, at 23.5% and 23.3%, respectively. Australia (152 documents) and Spain (134 documents) also play important roles with stable contributions and moderate levels of collaboration.

Table 4. Countries With the Most Productive and Collaborative

Country	Articles	Articles %	SCP	MCP	MCP %
USA	1229	27.4	1118	111	9
CHINA	310	6.9	264	46	14.8
UNITED KINGDOM	199	4.4	156	43	21.6
AUSTRALIA	152	3.4	126	26	17.1
CANADA	134	3	105	29	21.6
SPAIN	134	3	115	19	14.2
TURKEY	131	2.9	121	10	7.6
GERMANY	119	2.7	91	28	23.5
INDONESIA	62	1.4	44	18	29
BRAZIL	60	1.3	46	14	23.3

Note: SCP = Single country publications; MCP = multi-country publications

Additionally, Indonesia ranks among the top ten with 62 articles and a relatively high proportion of international collaboration (29%), the highest among all listed countries. This reflects Indonesia's growing integration into the global research network, with an increasing number of researchers engaging in cross-country partnerships. In contrast, Turkey (131 articles) shows a predominance of domestic publications, with a significantly lower rate of international collaboration (7.6%), indicating that its research activities are more internally focused. These data highlight a broader trend: while the United States leads in total publication output, European and Asian countries, such as Indonesia, are increasingly active in establishing international collaborations. Indonesia's relatively high international collaboration rate suggests that, despite its smaller publication output, it is strategically positioning itself in the global research landscape, facilitating the exchange of knowledge and expertise that is vital for its academic development. This trend underscores the importance of global connectivity, especially for developing nations like Indonesia, where international collaborations may play a key role in boosting research quality and visibility on the world stage.

Challenges and Future Directions of Simulation-Based Science Education Based on Research Trends

Thematic Development

Figure 6 presents a Sankey diagram linking research keywords (ID), influential authors (AU), and countries of origin (AU_CO). Rather than indicating causal influence, the diagram should be interpreted as a relational overview of how core themes, visible scholars, and national publication bases are connected within the retrieved corpus. The concentration of flows around a relatively small number of authors suggests that thematic visibility in the field is partly shaped by agenda-setting actors who connect recurring topics such as "students," "education," "teaching," "human," and "computer simulation" to broader international publication networks. The strong representation of the United States and China also indicates that these countries function not only as high-output contributors but also as important hubs in the circulation of dominant research themes. At the same time, the presence of Australia, Brazil, Canada, the United Kingdom, and Spain shows that the field develops through distributed, although unequal, international participation.

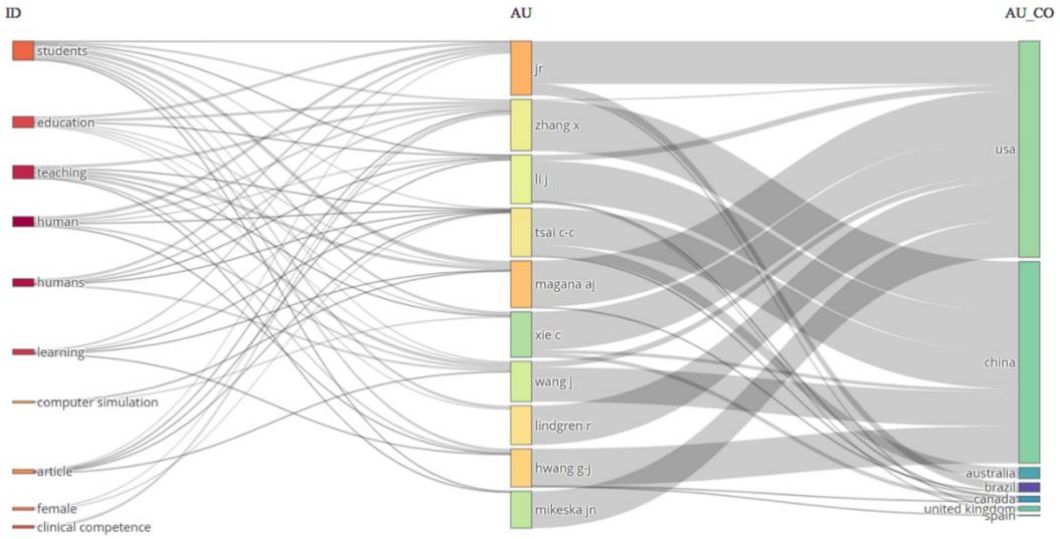

Figure 6. Three Developments using Sankey Diagram

Thematic Map

Figure 7 adds a strategic layer to this interpretation by showing how themes differ in centrality and density. The placement of "education," "human," and "simulation" in the motor-theme quadrant indicates that the field remains anchored in pedagogical application, learner interaction, and simulation as an instructional medium. Themes such as "students," "augmented reality," and "e-learning" appear close to this core, suggesting that technology adoption is

increasingly discussed through the lens of participation and engagement rather than through technology alone. Meanwhile, "virtual reality," "machine learning," and "motivation" appear as basic themes, meaning that they are already relevant to the field but still require stronger conceptual consolidation. The niche placement of "hands-on learning/manipulatives" and "laboratory instruction" indicates that laboratory-oriented and experiential strands remain important, although they are more specialized. The position of "professional development" in the emerging or declining quadrant may also signal a gap between rapid technological innovation and sustained attention to teacher capacity-building.

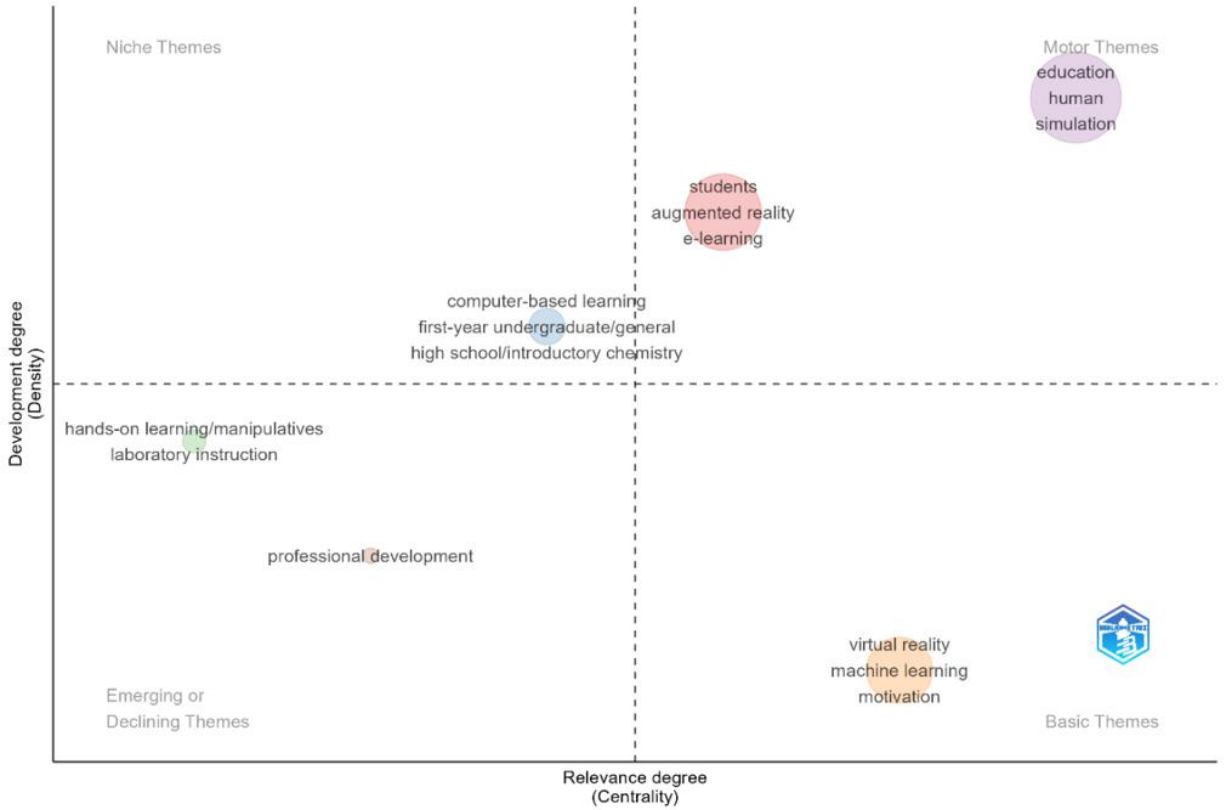

Figure 7. Thematic Map

Furthermore, in the central area of the map, terms such as "computer-based learning", "first-year undergraduate/general", and "high school/introductory chemistry" occupy transitional positions, indicating that these themes have moderate relevance and may either strengthen or decline depending on future research developments. Overall, this thematic map illustrates the dynamics of simulation-based education research, emphasizing the integration of digital technologies (e.g., AR, VR, e-learning, machine learning), a strong focus on student engagement and conceptual learning, as well as the potential re-emergence of more contextual traditional themes, such as laboratory practice.

Discussion

This study provides a bibliometric overview of 4,489 publications to examine the development of simulation-based science education (SBSE) from its early stages to the present. Overall, the findings show not only sustained publication growth but also shifts in thematic priorities, influential contributors, institutional concentration, and international collaboration. Taken together, these patterns suggest that SBSE has developed from a relatively specialized instructional topic into a broader and increasingly interconnected research area. At the same time, the source profile and keyword structure indicate that the retrieved corpus overlaps with the wider simulation-based education literature, including contributions from medical, nursing, and technology-enhanced learning contexts. Therefore, the findings should be interpreted as

representing SBSE within a broader interdisciplinary simulation-related landscape rather than as a completely isolated science education domain.

Main Research Themes in Simulation-Based Science Education

The results indicate that SBSE has experienced sustained expansion over the last three decades, with a particularly strong increase after 2020. Rather than interpreting this pattern as direct proof of a single cause, it is more defensible to read it as being associated with the wider integration of digital technologies, online learning environments, and immersive tools into science instruction (Amankwah-Amoah et al., 2021; Zhao et al., 2023; Samala et al., 2025). In educational terms, this development is important because it reflects growing interest in learning environments that allow students to explore phenomena actively, visualize abstract concepts, manipulate variables, and engage with science content in more interactive ways. This interpretation is consistent with constructivist and inquiry-oriented perspectives, in which simulations are valuable not merely as technological media but as tools that support active knowledge construction, guided exploration, and conceptual understanding. The lower publication count recorded for 2025 should also be interpreted cautiously because 2025 represents a partial year of indexing rather than a confirmed decline in research activity.

The keyword results reinforce this interpretation. The prominence of terms such as "education," "learning," "teaching," "students," and "simulation" indicates that the literature is anchored in pedagogical concerns rather than in technology alone. Meanwhile, the growing visibility of "virtual reality," "augmented reality," "e-learning," "machine learning," and related terms suggests that the field is increasingly oriented toward more immersive, adaptive, and digitally mediated forms of learning (Lu et al., 2021; Maltseva & Batagelj, 2020; Wang & Chai, 2018). These keywords are not only descriptors of topic popularity, but also signals of how the field is evolving conceptually. As noted in bibliometric scholarship, keyword structures help reveal both dominant themes and emerging lines of inquiry (Aria & Cuccurullo, 2017; Donthu et al., 2021). In this study, the thematic progression from "computer simulation," "human," and "students" toward terms such as "virtual reality," "machine learning," "gamification," and "computational thinking" suggests that SBSE is gradually shifting from conventional computer-assisted instruction toward more interactive and intelligent learning ecosystems (Bai et al., 2021; Zhao et al., 2021). Importantly (Sampagnaro, 2023; Weismayer & Pezenka, 2017), this transition does not imply that foundational themes have disappeared; rather, it suggests a layering process in which established pedagogical concerns remain central while newer digital approaches are added to the field's conceptual repertoire (Lee et al., 2021; Lee & Hwang, 2022; Singh-Pillay, 2024; Cabanes et al., 2024; Ghanbaripour et al., 2024).

Emerging Cross-Theme Relationships

An important implication of the thematic evolution is that advanced technologies are increasingly being connected to broader instructional frameworks rather than treated as stand-alone innovations. The co-occurrence of terms such as "machine learning," "adaptive learning systems," "virtual reality," and learner-related concepts suggests that current research is moving toward a more integrated view of simulation, one that combines technological sophistication with personalization, engagement, and learning support. This is educationally meaningful because it reflects a shift from using simulations mainly as representational tools toward using them as components of wider learning-system design. From a theoretical perspective, this trend is compatible with constructivist and inquiry-based science education, where digital tools become pedagogically valuable when they support experimentation, reflection, scaffolding, and student-centered meaning making. Thus, the emerging cross-theme relations in SBSE should be interpreted not only as evidence of technological novelty but also as signs of pedagogical reorientation toward more adaptive, exploratory, and context-sensitive science learning environments.

Influential Aspects of the Literature

Bibliometric analysis identified several key actors shaping the intellectual landscape of simulation-based education research. At the author level, Magana A.J. (n = 17), Hwang G.J. (n = 16), and Tsai C.C. (n = 16) stand out in terms of publication output and citation-based influence (see

Table 2). These findings indicate that a relatively small group of highly productive authors contributes substantially to the development of the field. The results also reveal collaboration structures and centers of knowledge production, which are common dimensions examined in bibliometric studies. Overall, this pattern highlights the importance of scholarly collaboration in strengthening the visibility and development of the field.

Taken together, the author profile suggests that intellectual leadership in the field is distributed across both long-established scholars and more recent high-output contributors. This pattern is characteristic of a maturing research area: senior authors provide conceptual continuity, while newer contributors help expand thematic diversity and methodological innovation. At the same time, the concentration of visibility in a limited number of authors and institutions suggests that agenda-setting power may remain unevenly distributed. In practical terms, this means that dominant conceptual vocabularies and methodological preferences may be shaped disproportionately by a relatively small number of productive networks. The source distribution supports this interpretation, as it shows that SBSE is not confined to a single disciplinary venue but is published across science education, educational technology, and health-related outlets. This broad source profile confirms that the field develops through cross-disciplinary exchanges, although it also requires careful interpretation of scope.

International Collaboration and Global Impact

Indonesia ranks among the top ten countries with 62 articles and a relatively high proportion of international collaboration (29%), which is the highest among the countries listed in this dataset. This indicates that a comparatively large share of Indonesia's publications involved international co-authorship. In contrast, Turkey (131 articles) shows a predominance of domestic publications, with a lower international collaboration rate (7.6%), suggesting that its output in this dataset is more strongly concentrated in domestically authored work. Overall, this comparison highlights variation in cross-national collaboration patterns within simulation-based education research, with some countries showing a stronger international co-authorship profile than others (Deichmann et al., 2020; Jacob & Meek, 2013).

More broadly, the country-level results indicate that SBSE develops through uneven but meaningful forms of internationalization. The dominance of the United States and China in publication volume reflects their large research capacity and strong position in global scientific production, whereas countries such as Indonesia, Germany, Brazil, the United Kingdom, and Canada appear more prominently through international co-authorship profiles. This distinction is important because it suggests that countries participate in the field in different ways: some act primarily as high-output hubs, whereas others appear more strongly connected through collaborative networks. From a knowledge-development perspective, these patterns imply that SBSE advances not only through institutional productivity but also through cross-border scholarly exchange. Even so, the current distribution also suggests the need for broader and more balanced participation so that the field is not shaped mainly by a limited number of dominant national systems.

Challenges and Future Directions

The thematic development results indicate that SBSE is moving from foundational concerns toward more complex and technology-rich learning environments. Themes such as virtual reality, augmented reality, machine learning, gamification, and computational thinking suggest that the field is increasingly responsive to ongoing technological change (Linn & Eylon, 2011; Zhao et al., 2024). However, the educational significance of this transition depends on whether these tools are integrated in ways that genuinely improve conceptual understanding, inquiry, engagement, and inclusiveness rather than functioning merely as markers of novelty. For this reason, future work should pay greater attention to the pedagogical conditions under which simulation is most effective, including instructional design, scaffolding, student support, and the role of teachers in mediating technology use.

Another challenge concerns ethics, access, and sustainability. As simulation-based learning becomes more immersive and data-rich, issues such as student privacy, equitable access to digital infrastructure, and the pedagogical value of data-driven systems become increasingly important

(Hlosta et al., 2022; Tzimas & Demetriadis, 2021). The relatively peripheral position of themes such as professional development also suggests that teacher readiness may still be underexplored, even though sustainable implementation depends heavily on educator capacity and institutional support. In addition, the broader corpus captured in this study indicates that SBSE shares conceptual space with simulation-based education more generally. This creates an opportunity for cross-disciplinary learning, but also underscores the need for future studies to define the scope more precisely when distinguishing science education from wider simulation literatures.

Overall, the future of SBSE lies not simply in adopting newer technologies but in integrating them into theoretically grounded and pedagogically meaningful science learning environments. Future research may therefore benefit from examining how simulation can support equitable participation, meaningful inquiry, teacher capacity-building, and sustainable instructional improvement across diverse settings. It may also be useful to explore partnership models that connect major research universities in developed countries with institutions in developing countries, not as a simple solution narrative, but as one possible pathway for broadening participation, strengthening scholarly exchange, and supporting more balanced growth in the field.

LIMITATIONS

While this study offers valuable insights into the research trends of simulation-based science education (SBSE), several limitations should be acknowledged. First, the data analyzed were obtained exclusively from the Scopus database, which may not capture all relevant literature indexed in other major databases such as Web of Science or ERIC. As a result, some relevant publications may have been omitted, potentially limiting the comprehensiveness of the findings. Second, the search-query design used relatively broad terms related to simulation, education, and science. Although this approach increased retrieval sensitivity, it may also have captured publications from adjacent domains, particularly medical, clinical, and nursing education, thereby reducing the specificity of the dataset to science education in a narrow sense. Consequently, the findings should be interpreted with caution, as the corpus may reflect a broader simulation-based education landscape rather than science education alone.

Second, this research focuses solely on articles published in the English language, which may restrict the scope, considering the significant contributions that could come from non-English language publications, especially from countries where research is often published in local languages. This linguistic limitation may lead to underrepresentation of research from certain regions, particularly developing countries.

Third, although bibliometric analysis provides an overview of trends and patterns, it does not offer in-depth insights into the methodological quality or validity of the findings in the studies analyzed. Consequently, this study does not explore in detail the methodological approaches that may influence the outcomes of the research in the SBSE field, which could have implications for the robustness and generalizability of the conclusions drawn.

Lastly, while the analysis includes data up to 2025, the data used was not fully complete at the time of analysis, meaning that emerging trends may evolve or shift as further data becomes available and is indexed. Therefore, this analysis may not capture the most recent developments in the field.

CONCLUSION

This study mapped 4,489 international publications on SBSE and identified a significant growth trend over the past three decades, with publication output peaking during the 2020–2024 period. This increase may be associated with the growing use of AR/VR technologies and the expanded relevance of online learning in the post-pandemic period. Keyword analysis suggests a shift in research focus from traditional concepts such as “computer simulation,” “students,” and “learning systems” toward the integration of more advanced technologies, including virtual reality, augmented reality, machine learning, gamification, and learning analytics. Overall, these findings indicate an increasingly immersive, adaptive, and data-informed direction in the literature. The findings further suggest that SBSE is no longer centered solely on conventional simulation as an instructional aid, but is increasingly positioned within digitally mediated and interdisciplinary

learning environments. At the same time, the source distribution, keyword profile, and thematic structure indicate that the retrieved corpus overlaps with broader simulation-based education research, including health and technology-oriented domains. Therefore, the contribution of this study lies not only in documenting growth trends but also in showing that contemporary SBSE develops at the intersection of science education, educational technology, and wider simulation-based learning ecosystems. Another important conclusion is that the field remains unevenly structured in terms of institutional and geographical participation. Highly productive institutions and countries continue to dominate publication output, while countries such as Indonesia stand out more through international co-authorship than through publication volume alone. This suggests that the future development of SBSE will depend not only on technological innovation but also on the extent to which international collaboration, institutional support, and knowledge-sharing networks can be broadened beyond a relatively small number of dominant research hubs.

Future research should move in more specific directions. First, empirical studies are needed to test how AR/VR-, virtual laboratory-, and machine learning-supported simulations affect conceptual understanding, inquiry skills, and scientific literacy in science learning contexts, particularly in online and blended environments. Second, more research is needed on teacher professional development and instructional design, since the effective use of simulation depends not only on access to technology but also on pedagogical readiness and scaffolding strategies. Third, future work should examine issues of equity, accessibility, and infrastructure, especially in low-resource or developing-country contexts, so that simulation-based science education does not deepen digital disparities. Finally, comparative and cross-country studies would be valuable for identifying collaboration models that strengthen participation from underrepresented institutions and regions while supporting more balanced growth in the field.

AUTHOR CONTRIBUTIONS

SS Conceptualization, Methodology, Data Curation, Formal Analysis, Writing Original Draft, Writing Review & Editing, Visualization. MMi Conceptualization, Supervision, Writing Review & Editing. MMa Conceptualization, Supervision, Writing Review & Editing. LK Resources, Investigation, Supervision. QQ Data Curation, Formal Analysis, Writing Original Draft, Writing Review & Editing. MZBA Methodology, Software, Data Curation, Visualization. NFAR Validation, Project Administration, Funding Acquisition. All authors have read and approved the final manuscript.

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