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VIRTUAL LABORATORIES IN SCIENCE EDUCATION: UNVEILING TRAJECTORIES, THEMES, AND EMERGING PARADIGMS (2013-2023)

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Abstract. *Virtual laboratories are transformative tools in science education, yet comprehensive reviews of their prospects are limited. This study addresses this gap through a bibliometric analysis of 218 articles published between 2013 and 2023. Key findings included: (1) research has evolved from initial exploration to rapid expansion; (2) virtual labs have demonstrated adaptability across various scientific disciplines, including chemistry, physics, biology, engineering, and medicine; (3) five research trajectories focus on virtual labs, science education, and computer-based learning; and (4) eight research topics, such as comparisons with physical labs and student performance, have gained prominence. These findings had implications for educational practices, research methodologies, and policy considerations. For educational practices, virtual laboratories offer benefits by removing the need for physical resources, providing flexible delivery, enabling safe exploration, fostering engagement through hands-on experimentation, and enhancing understanding with immersive experiences. For research, virtual labs improve learning and analytical skills, generate detailed data on student behaviors and learning patterns, and lead to innovations in teaching methods and curriculum design. For policymakers, strategic planning is needed to create supportive policies for the effective adoption of virtual labs, including teacher training, infrastructure development, and curriculum integration, making science education more accessible and equitable for all students.*

Keywords: *bibliometrics analysis, science education, research trends, virtual laboratory*

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Introduction

Science education, crucial for cultivating scientifically literate citizens and fostering essential 21st-century skills, has experienced a significant transformation with the advent of virtual laboratory technology. The rapid development of virtual laboratory technology offers innovative solutions to traditional challenges, signaling a paradigm shift in laboratory science education (McAteer et al., 1996; Scanlon et al., 2002). Studies have demonstrated the positive impacts of virtual laboratories, equating them to the physical science laboratories in enhancing their scientific process skills and student motivation (Gunawan et al., 2019a; Sari et al., 2019). However, concerns have been raised about the limitations of virtual laboratories, particularly in offering biological variation and the potential for complicating learning experiences (Lewis, 2014; Reeves et al., 2021). Despite these debates, there is a growing consensus on the integration of virtual laboratories with physical science laboratories as a strategy to optimize science education for the twenty-first century (Lewis, 2014; Macaulay et al., 2009). The concurrent use of both laboratory types is increasingly recommended, aiming for a symbiotic approach to enrich students' development of 21st-century skills and learning experiences (Kapici et al., 2019; Lewis, 2014; Macaulay et al., 2009).

While researchers and practitioners are increasingly exploiting the potential of virtual laboratories to improve science education, there is a notable scarcity of comprehensive review studies exploring the use of virtual laboratories for improving science education (Ge et al., 2015). This leaves key aspects such as prominent themes, developmental trajectories, and research trends in the field of virtual laboratories for science education inadequately explored. Addressing this gap necessitates a thorough examination of the existing literature to pinpoint emerging trends, define dominant themes, and highlight critical research priorities in virtual laboratories for science education. This study conducted a bibliometric analysis covering the period

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from 2013 to 2023 to delve into these aspects. This review aimed to illuminate the most discussed topics, to map out the field's evolutionary course and provide insights into future research directions. Such an analysis is instrumental in deepening the understanding of the advancements and dynamics within the field of virtual laboratories for science education.

Literature Review

Virtual Laboratories for Enhancing Science Education

The development of virtual laboratories, originating from the concept of remote access, marks a pivotal advancement in science education, especially within laboratory-based courses (Raman et al., 2022; Chan et al., 2021). Virtual laboratories are defined as dynamic, computer-based, multimedia environments that immerse learners in a simulated world (Shambare et al., 2022). Harnessing a range of computer technologies such as LabVIEW, Matlab/Simulink, Java Applet, and Flash, virtual laboratories are used to create virtual learning environments where students can design and perform experiments within a three-dimensional space. Virtual laboratories can provide students the opportunity to conduct experiments, observe outcomes, and gain learning experiences comparable to those in physical science laboratories (Chen et al., 2010). The origins of virtual laboratories can be traced back over fifty years, initially emerging as an extension of theoretical, paper-and-pencil computations, which laid the foundation for their subsequent evolution (Hut, 2006). Over time, the trajectory of virtual laboratories has seen significant evolution, advancing from elementary 2D visualizations to sophisticated 3D simulations. More recently, they have incorporated virtual reality technologies, offering users a comprehensive immersion into realistic laboratory processes (Jones, 2018; Han et al., 2017). This progression not only demonstrates the technological advancements in educational tools but also underscores the growing sophistication and potential of virtual laboratories in enriching science education.

In the 21st century, virtual laboratories have emerged as indispensable supplementary resources for teachers and students, gaining heightened relevance during the COVID-19 pandemic across engineering, computer science, and science education domains (Vasiliadou, 2020). Physics education stands out as a primary domain for the use of virtual laboratories, with capabilities extending to simulating electrical, mechanical, optical, and thermodynamic experiments (Daineko et al., 2017; Husnaini & Chen, 2019; Gamo, 2018; Gunawan et al., 2019b). Platforms like Physics Education Technology and Physics Virtual Lab are commonly employed for simulation experiments and result observation (Daineko et al., 2017; Serevina & Kirana, 2021). The application of virtual laboratories in physics learning not only aids in understanding physics concepts but also enhances problem-solving skills (Daineko et al., 2017). In chemistry teaching, virtual laboratories simulate chemical reactions, chemical analysis, and materials science experiments, serving as effective supplementary tools or alternatives to hands-on laboratories (Reeves & Crippen, 2021). Virtual chemistry laboratories offer flexibility in exploring parameter changes' effects on objects or properties, fostering illustrative connections between theory and experiment (Altarawneh et al., 2023). Virtual laboratories extend their utility beyond physics and chemistry education, playing a significant role in biology education. These digital platforms empower students to virtually interact with experimental equipment, facilitating activities like inoculating bacterial culture media and practicing aseptic techniques, which are crucial in biological studies (Makransky et al., 2019a). The incorporation of virtual reality and augmented reality technologies into these laboratories further elevates the educational experience. This advanced integration enables students to engage with three-dimensional models of microscopes and other biological apparatus, thereby helping them to acquire and refine essential operational skills (Zhou et al., 2020). This technological enhancement not only makes complex biological concepts more accessible but also provides a more interactive and immersive learning environment, crucial for understanding and mastering intricate biological procedures.

The adoption of virtual laboratories in science education brings forth distinct advantages. Firstly, the paramount consideration is safety, with virtual laboratories offering a secure environment for managing hazardous equipment and reagents (Hernández-de-Menéndez et al., 2019). Additionally, the virtual realm permits the occurrence of "damage," affording opportunities for learning from mistakes. Secondly, virtual laboratories contribute to efficiency gains by providing a cost-effective means for schools and universities to organize high-quality laboratory work, obviating the need for expensive experimental equipment (Potkonjak et al., 2016). The third advantage is flexibility, allowing students to conduct experiments at their convenience and modify parameters that may be challenging or impossible in real experiments (Husnaini & Chen, 2019). Furthermore, students can repeat experiments multiple times, deepening their understanding of changing parameters and their impact on results (Chen et al., 2010).

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The fourth advantage lies in visualization, as virtual laboratories enable the modeling of objects, processes, and phenomena that may be unobservable or impractical in reality, providing dynamic visualization and an interactive learning platform (Herga et al., 2015).

Review Studies of Virtual Laboratories for Enhancing Science Education

The exploration of virtual laboratories for enhancing science education is grounded in a rich historical context, marked by numerous insightful literature reviews. Zacharia et al. (2015) explored computer-supported inquiry learning environments, pinpointing instructional strategies that bolster student inquiry in virtual and remote science laboratories. Similarly, Fadda et al. (2022) found that integrating online laboratories into traditional teaching, coupled with adequate instructor feedback, can yield results on par with physical laboratories. In their review, Ali et al. (2022) identified the significant contributions of interactive science laboratories such as ICL, IBL, and IPL across various scientific disciplines. Shambare and Simuja (2022) examined the use of mobile virtual laboratory applications in rural educational settings, advocating for the adoption of virtual reality technology to enhance experimental learning. Chan et al. (2021) and Mercado and Picardal (2023) focused on educational strategies specific to virtual chemistry laboratories, underscoring the importance of inquiry-based learning and scaffolding to enhance the virtual laboratory experience. This trend towards immersive virtual reality technology, augmenting traditional 2D and 3D desktop applications, signifies a shift in educational methodologies (Chan et al., 2021; Mercado & Picardal, 2023).

The effects of virtual laboratories in science education are rigorously examined in the literature reviews. Potkonjak et al. (2016) and Veza et al. (2022) examined fully software-based virtual laboratories in engineering education, noting their advantages in resource sharing among geographically dispersed students and in reducing operational costs. Chan et al. (2021) found that virtual laboratories were more effective than passive teaching methods, often achieving equal or greater efficacy compared to hands-on laboratories. Reeves and Crippen (2021) conducted a systematic review in undergraduate science and engineering courses, revealing that the positive outcomes associated with virtual laboratories were often linked to their novelty rather than their design, thus boosting student motivation. Byukusenge et al. (2022) identified the significant impact of virtual laboratories on students' conceptual understanding, practical skills, and motivation in biology, indicating the broad-ranging benefits of these technologies in science education.

Previous review studies predominantly comprise empirical articles that showcase the practical applications of virtual laboratory technologies in science education. However, given the evolving theoretical and practical landscape, there is an increasing need for a comprehensive review to provide deep insights into current research trends and prominent themes within this field, as well as to identify potential avenues for future research. This study used a bibliometric analysis method to examine overall trends, development trajectories, and the evolution of main research themes in the field of virtual laboratories for enhancing science education. The following four research questions were addressed:

(1) What trends have characterized the virtual laboratory landscape for enhancing science education over the past decade? (RQ1)
(2) How are virtual laboratory applications distributed across various disciplines within the broader field of science education in the last ten years? (RQ2)
(3) What are the research hotspots and the key developmental paths that shape research in the field of virtual laboratories for enhancing science education in the past decade? (RQ3)
(4) What are the prevailing research themes in virtual laboratories for enhancing science education, and how have they evolved throughout the past decade? (RQ4)

Research Methodology

Overview

This study used bibliometric analysis to uncover the dynamic trends in research on virtual laboratories for science education between 2013 to 2023. Bibliometric approaches provide a powerful means to comprehensively analyze extensive volumes of publications, ranging from detailed studies of individual institutions to broad assessments of the global research landscape. This analysis allows for the visualization of diverse research characteristics

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and trends, including subject domains, keywords, thematic focuses, and contributors across geographical dimensions such as countries or regions, institutions, and authors (Aktoprak & Hursen, 2022; Zou et al., 2022). Bibliometric analysis has been widely applied in various fields, including business research (Donthu et al., 2021; Kumar et al., 2021) and education (Rashid et al., 2021; Zou et al., 2021).

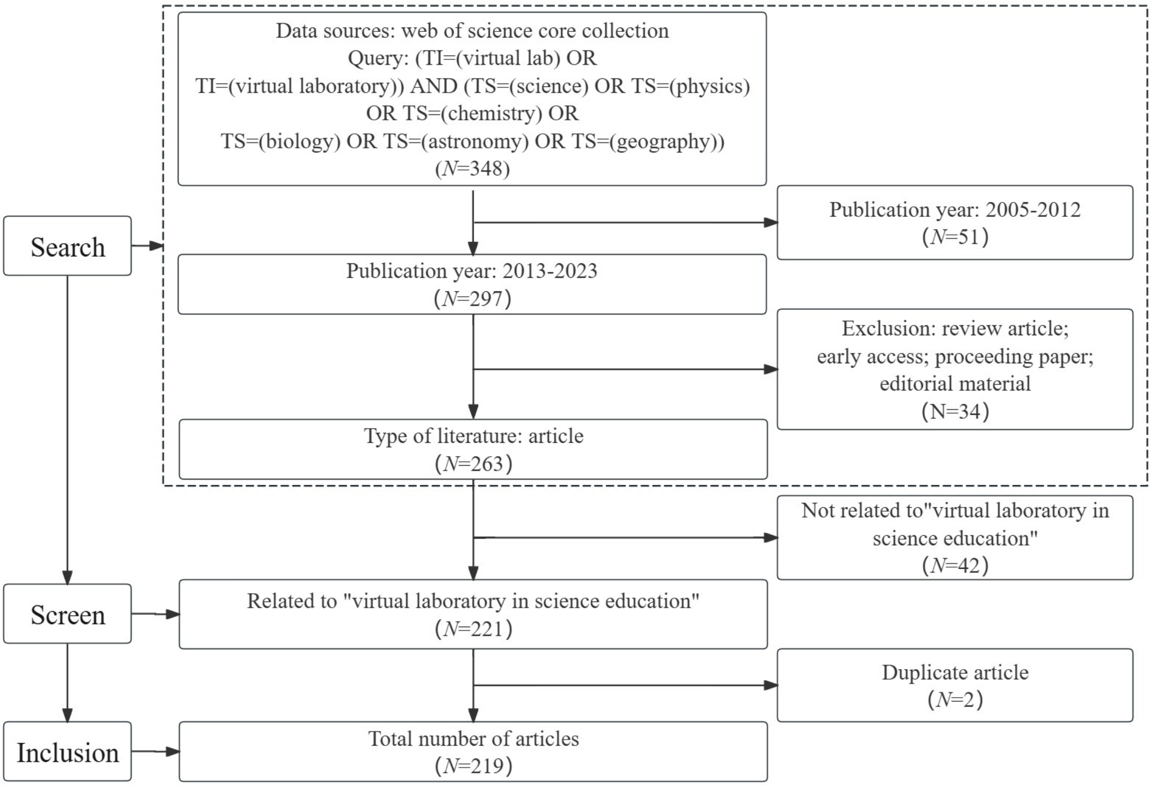
Data Collection

This study conducted an exhaustive literature search within the Web of Science Core Collection to explore the domain of virtual laboratories for enhancing science education, setting the search date to October 2023. The selection process is visually represented in Figure 1. Employing an advanced search strategy, the study used the formula "(TI = (virtual lab) OR TI = (virtual laboratory)) AND (TS=(science) OR TS=(physics) OR TS=(chemistry) OR TS=(biology) OR TS=(Astronomy) OR TS=(geography))" as the initial search condition.

The initial document pool, spanning from 2005 to 2023, yielded 348 articles. Narrowing the timeframe to 2013-2023, we refined the pool to 297 documents. Focusing specifically on the document type "article" and excluding review papers, online publications, editorial materials, and conference proceedings papers, we retained 263 articles. Ensuring the literature's quality, a manual screening process eliminated irrelevant documents, resulting in 221 pertinent articles. Subsequent checks for duplications within the 221 documents led to the removal of 2 duplicate entries. Consequently, the final effective document record comprises 219 articles.

In the concluding phase, each result was individually downloaded and exported in plain text format, encompassing full records and cited references. This stringent search and screening protocol aimed to curate a comprehensive and high-quality compilation of literature on virtual laboratories in science education. The systematic process ensured the reliability and relevance of the identified literature for our study.

Figure 1
The Procedure of Selecting Articles for Further Analysis



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Data Analysis

This study used CiteSpace v.6.2.R2 (advanced) to conduct a bibliometric analysis of relevant research on virtual laboratories for enhancing science education. CiteSpace combines information visualization methods, bibliometrics, and data mining algorithms in an interactive visualization tool for visualizing knowledge areas and analyzing trends and patterns in scientific literature (Synnestvedt et al., 2005). CiteSpace can analyze the number and growth trends of papers published each year, explore collaboration networks between authors/institutions/countries, identify co-cited references, capture keywords with strong citation bursts over time, and identify research frontiers and emerging trends of a certain field (Guo et al., 2022; Shi & Liu, 2019).

Analyzing the overarching trend (RQ1). To explore the decade-long trends in virtual laboratory research within science education, the study began with a citation analysis. Annual publication and citation data were systematically gathered from the Web of Science database and recorded in Excel spreadsheets. Subsequently, the study used Excel software to craft visually informative charts illustrating the distribution trends of annual publications and citations. The inclusion of carefully designed data labels enhanced the clarity of the overall developmental pattern from 2013 to 2023, elucidating the evolving trends in related fields and the shifting focus of research. Moreover, the study used the *Add Trend Line* function in Excel to facilitate the fitting of exponential functions to both the annual publication volume trend line and citation trend line. This critical step enabled the precise description of growth and change trends in the number of publications and citations. The derived exponential function formula and the associated R^2 value, serving as a goodness-of-fit indicator for both polyline and exponential functions, offered profound insights into the trajectory of research and development in virtual laboratory research within science education.

Analyzing virtual laboratory applications (RQ2). Using subject distribution statistics from 219 articles, the study classified these academic works into distinct subject areas. To ensure precision, articles covering multiple fields, such as physical chemistry or biochemistry, were categorized as comprehensive science. This study then counted the documents in each subject area and presented the data as a percentage of the total number of documents. The data were organized in Excel sheets to facilitate easy visualization and analysis. To clearly show the distribution of virtual laboratories across different subject areas, we used a pie chart. This approach simplified data representation and provided a clear view of the diverse applications of virtual laboratories in various scientific disciplines.

Exploring the research developmental paths and research hotspots (RQ3). To explore the research evolution trajectory of virtual laboratories in science education, a keyword-based co-occurrence knowledge graph analysis method was adopted. Initially, the co-occurrence knowledge graph of keywords was used to outline the development trend of virtual laboratories in science education. We configured the software to define keywords as node types and set Top N to 50. The pruning strategy combined a pruning slice network with the minimum spanning tree method to construct the co-occurrence knowledge graph of keywords. After generating the co-occurrence map, we carefully inspected each keyword, eliminated meaningless words, and merged words with overlapping meanings to form a final keyword co-occurrence map. This approach allowed us to gain a deep understanding of the evolution and key themes of virtual laboratory research, revealing the knowledge structure and development trends in this field.

Analyzing prevailing research themes and their progression (RQ4). A two-step procedure was employed to examine the main themes of virtual laboratories for enhancing science education and their progression over time. First, CiteSpace's clustering function was used to identify salient themes in the field of virtual laboratories in science education research. This method effectively classifies frequently occurring keywords and organizes them into different topic clusters. Next, visual cluster plots were generated to enhance understanding and interpretation of the study domain. To capture the thematic gist of each cluster, the following steps were performed: the titles and abstracts of all articles related to the keywords within each cluster were imported into an Excel database. The information extracted from each article was then refined, combined, and detailed to create comprehensive summaries that contained the core ideas of each source. Subsequently, the timeline view function of CiteSpace was used to track the evolution of virtual laboratory-related research in the field of science education within a specific topic cluster. This approach enhances understanding of how research evolves over time. By examining the trajectory of this research field, a deeper understanding of its historical context is achieved, along with significant progress in predicting future research trends. This comprehensive analysis contributes to a deeper grasp of the dynamic research landscape in the field of virtual laboratories in science education.

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Research Results

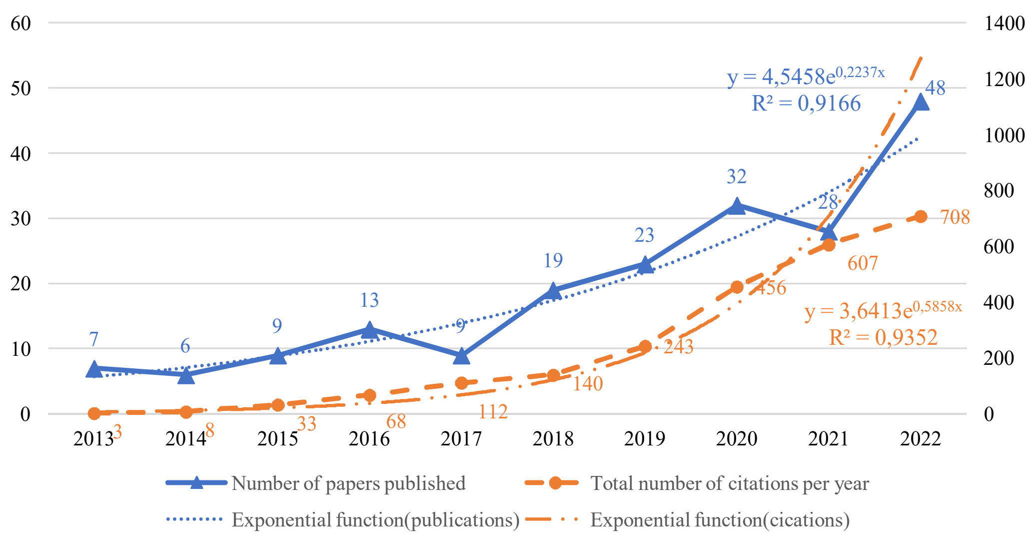
The Overarching Trend in Research on Virtual Laboratories for Enhancing Science Education from 2013 to 2023

Figure 2 shows the distribution of virtual laboratories for enhancing science education publications and citations from 2013 to 2022 (excluding 2023 due to incomplete data). As can be seen from Figure 1, the research on virtual laboratories for enhancing science education in the past ten years can be divided into two stages: the initial exploration stage and the rapid development stage.

From 2013 to 2017, the initial exploration stage, a total of 44 articles were published, averaging about 9 articles per year. The research entered a rapid development stage from 2018 to 2023, during which 175 articles were published, averaging approximately 29 articles per year and accounting for about 80% of the total sample documents. Notably, during this rapid development stage, there was a temporary dip in 2021, interrupting the growth trend observed from 2018 to 2020. However, the upward trajectory resumed in 2022.

Figure 2 fits the exponential function $y=e^x$ to the number of articles published from 2013 to 2022. We found that the R-square of the polyline fitting of the annual publication volume was 0.9294, and the polyline fitting of the number of citations was 0.8932. Obviously, the research scale of virtual laboratories for enhancing science education was approximately an exponential function, both in terms of the number of publications and the number of citations. These results suggested that the influence of virtual laboratories for enhancing science education was constantly escalating, demonstrating its lasting and growing influence.

Figure 2
The temporal distribution of research publications and citations of the research on Virtual Laboratories for Science Education from 2013 to 2023



The Distribution of Virtual Laboratory Applications in Various Disciplines in Science Education from 2013 to 2023

Figure 3 illustrates the distribution of virtual laboratory applications across various scientific domains. Chemistry emerged as the predominant subject with 67 applications, highlighting the versatility of virtual laboratories in simulating chemical reactions and material analyses. Physics closely followed with 54 applications, predominantly utilized for simulating physical phenomena and testing theoretical models.

In general science and STEM courses at K-12 education, we identified 25 articles utilizing virtual laboratories. Biology prominently featured with 22 applications, showcasing the effectiveness of virtual experiments in biological research, including genetic and cellular studies. Engineering, encompassing domains such as design, material testing, and structural simulation, exhibited 20 applications. Synthetic science, spanning multiple disciplines,

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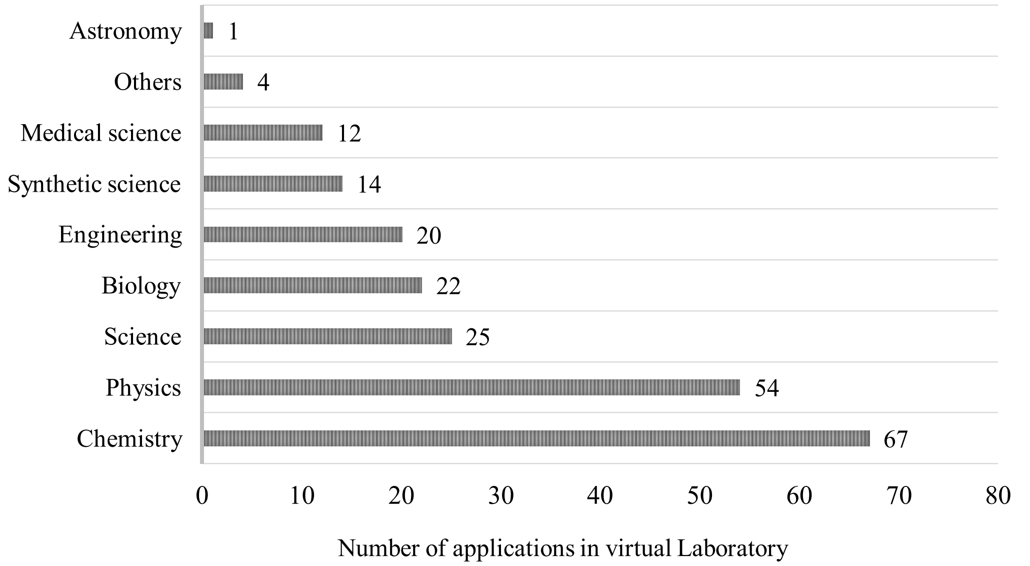
including engineering and science, biochemistry, physical chemistry, molecular chemistry and molecular biology, etc., contributed 14 application documents.

The medical field incorporated virtual laboratories in 12 papers, encompassing medical experiments, disease simulations, and drug research. In contrast, the field of Astronomy demonstrates limited use of virtual laboratories, represented by a singular document. Additionally, there are four documents that, while not explicitly tied to a specific discipline, delve into studying the influencing factors and effectiveness of virtual laboratory applications.

In summary, these results suggest that virtual laboratories were most prevalent in Chemistry and Physics, emphasizing their role in simulating chemical reactions, material analyses, and physical phenomena. Meanwhile, their application extends across various scientific domains, including Biology, Engineering, and the medical field, indicating their broad utility in research and education. However, Astronomy shows minimal engagement, highlighting a disparity in adoption across disciplines, suggesting a potential area for growth or differing needs within this discipline.

Figure 3

The Distribution of Virtual Laboratory Applications in different Disciplines in Science Education



Research Hotspots and Key Research Developmental Paths in the Field of Virtual Laboratories for Enhancing Science Education from 2013 to 2023

Research Hotspots. Figure 4 shows the keyword-based co-occurrence graph in the field of virtual laboratories for science education from 2013 to 2023. In Figure 4, each circular node intuitively represented a different keyword, and its node size corresponds to the frequency of occurrence. The larger the radius, the higher the frequency of occurrence, which represented a common research hotspot in the field. Out of 303 keywords identified, virtual laboratories emerged as the most prominent, signifying its central role in current studies. The thickness of the lines connecting these nodes denotes the strength of the relationships between keywords.

This visualization underscored the vibrant research activities centered around the adoption and impact of virtual laboratories in both K-12 and higher education across various disciplines including science, engineering, physics, chemistry, and biology. Notably, science, education, students, computer-based learning, and design emerged as major focus areas, reflecting a keen interest in examining how virtual laboratories influence students' learning approaches, outcomes, and skills enhancement in the context of science education.

Moreover, Table 1 provides a breakdown of the most frequent keywords, those with nine or more occurrences, drawing from Figure 4's data. This table revealed notable shifts in keyword prominence, particularly highlighting a surge in research activity between 2013 and 2017. This trend underscored the rapid evolution and sustained interest in these research themes over the past decade.

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Figure 4
Keyword-based Co-occurrence Knowledge Map of Virtual Laboratories for Enhancing Science Education from 2013 to 2023

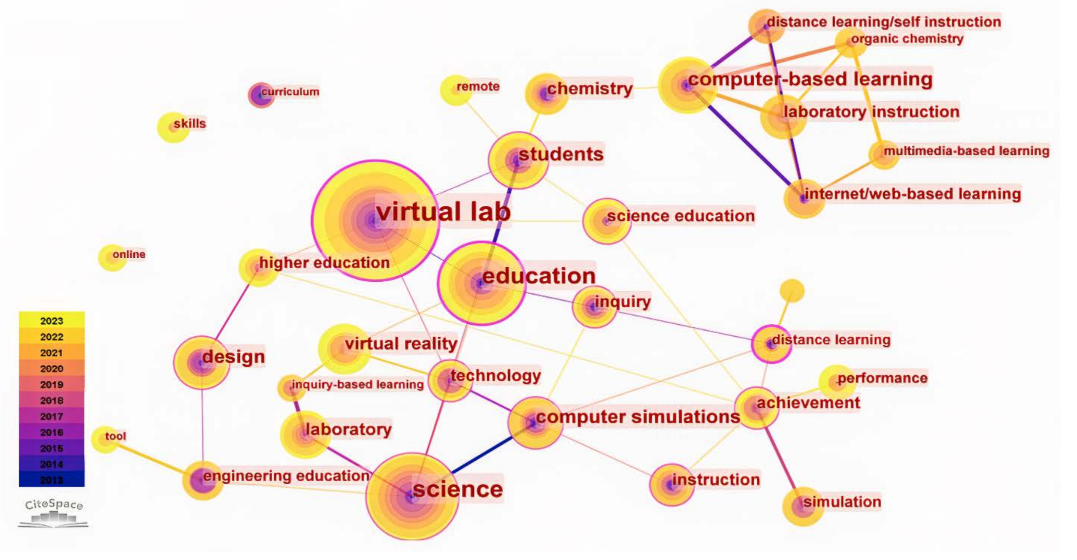

Table 1
List of High-frequency Key Words

No	Keyword	Frequency	Year	No	Keyword	Frequency	Year
1	Virtual laboratories	85	2013	11	Science education	12	2014
2	Science	43	2013	12	Laboratory instruction	12	2017
3	Education	39	2013	13	Inquiry	11	2013
4	Students	20	2014	14	Instruction	11	2013
5	Computer-based learning	19	2015	15	Technology	11	2016
6	Design	18	2013	16	Achievement	11	2017
7	Computer simulations	17	2013	17	Internet/web-based learning	10	2015
8	Virtual reality	15	2020	18	Higher education	10	2017
9	Chemistry	14	2013	19	Engineering education	9	2016
10	Laboratory	13	2017	20	Simulation	9	2018

Key research developmental paths. In Figure 4, keywords were categorized based on the closeness of their connections, resulting in five distinct developmental trajectories, as depicted in Figure 5. These paths outlined the evolution and focal points of research within the field of virtual laboratories for science education. The first path, computer-based learning-distance learning/self instruction-laboratory instruction-internet/web-based learning-multimedia-based learning-organic chemistry, outlined the progression from computer-based learning through various stages, culminating in organic chemistry. It highlighted the role of virtual laboratories and virtual reality in enhancing chemistry education, encompassing a wide spectrum of research and innovation aimed at leveraging technology to boost learning outcomes and immerse students in comprehensive laboratory experiences, as studied by Tauber et al. (2022) and Williams et al. (2021). Studies regarding this trajectory done by researchers such as Dunnagan et al. (2019), Dunnagan et al. (2020), Galang et al. (2022), and Ullah et al. (2016), address the design, implementation, and evaluation of virtual laboratories, along with their adaptation to virtual and remote learning environments, particularly in response to the COVID-19 pandemic's challenges.

The second development path was virtual lab (laboratories)-education-inquiry-science education-students-

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remote-chemistry. This path explored the integration of virtual laboratories and simulations into science education, assessing their impact and potential benefits. It included comparative studies between virtual and physical science laboratories across different disciplines, as evidenced by Darrah et al. (2014) and Puntambekar et al. (2021), and examined the effects of virtual laboratories on student learning, engagement, self-efficacy, and conceptual understanding as evidenced by Arista and Kuswanto (2018), Kolil et al. (2020), and Nolen and Koretsky (2018).

The third development path was science-computer simulations-technology-virtual reality-inquiry-based learning-laboratory. This path emphasized the enhancement of student learning through the use of virtual laboratories, comparison with physical science laboratories, and the integration of inquiry-based learning. It suggested that virtual laboratories combined with inquiry-based approaches can advance students' conceptual understanding and problem-solving skills, as studied by Husnaini and Chen (2019), and Kapici et al. (2022).

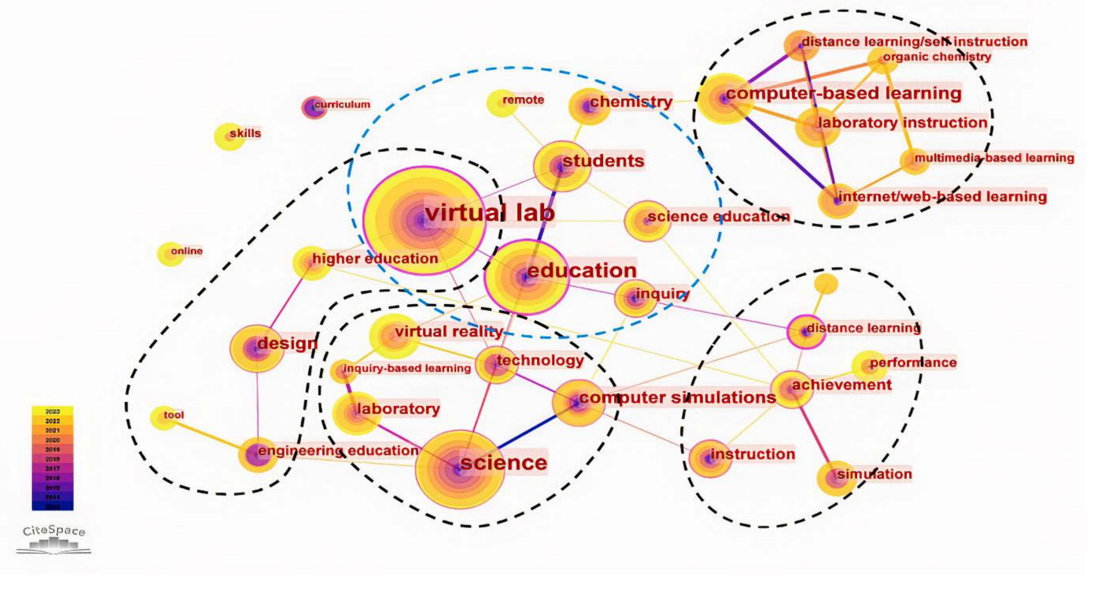
The fourth development path was virtual laboratory-higher education-design-engineering education-tool. Focusing on higher education, this path examined how instructional design and teaching strategies influenced the effectiveness of virtual laboratories, as studied by Liu et al. (2022) and Nolen et al. (2018), particularly within engineering and STEM education, as done by scholars such as Tejado et al. (2021) and Trúchly et al. (2019). It reflected on the role of virtual laboratories in supporting innovative teaching and learning approaches.

The fifth development path was achievement-instruction-simulation-performance-distance learning. This path examined the achievement of educational objectives and learning outcomes through virtual experiments in science education, done by Paxinou et al. (2022) and Tatli et al. (2013). It highlighted the importance of student participation and experience with virtual laboratories, aiming to understand how virtual experiments can facilitate science learning processes, as illustrated by researchers such as Reeves et al. (2021) and Su and Cheng (2019).

Overall, these development paths collectively provided a comprehensive overview of the current research landscape in virtual laboratory utilization for science education, indicating a rich field of inquiry that spanned technological innovation, pedagogical strategies, and educational outcomes.

Figure 5

Developmental Paths of Virtual Laboratories for Enhancing Science Education from 2013 to 2023



Dominant Research Themes and Their Progression in Virtual Laboratories for Enhancing Science Education from 2013 to 2023 (RQ4)

Research themes. Figure 6 presents an overview of the dominant research themes in the field of virtual laboratory for enhancing science education, including nodes (N = 302), node connections (E = 1299) and network density (D = 0.0286). Table 2 presents the indicators of each cluster. In Figure 6, the clustering modularity index Modularity Q = 0.5064 (> 0.3) and the intra-class similarity index Silhouette = 0.8021 (> 0.7) indicated a relatively stable and

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internally homogeneous clustering structure. Figure 6 and Table 2 illustrate the existence of eight different research themes with detailed indicators.

Cluster #0, identified as virtual laboratory, stood out as the most substantial cluster, encompassing 51 keywords with a notable Silhouette value of 0.722. This metric signified a strong cohesion within the cluster, indicating its clear focus and relevance. The primary exploration within this cluster revolved around the efficacy of virtual experiments and their consequential impact on enhancing students' interdisciplinary learning experiences. Key investigations include comparisons between virtual and physical science laboratory settings, the incorporation of virtual laboratories into science education curricula, and the examination of how virtual laboratories contribute to elevating student engagement and deepening understanding. Noteworthy topics covered by researchers in this cluster, as done by scholars such as Wong et al. (2020), Su et al. (2019), Nolen and Koretsky (2018), and Tatli and Ayas (2013), emphasized the transformative potential of virtual laboratories in educational settings. Prominent keywords such as virtual laboratories, students, higher education, and impact underscored the cluster's dedication to understanding the multifaceted effects of virtual laboratories on the educational landscape.

Cluster #1, titled laboratory instruction, featured 39 keywords and boasts a Silhouette value of 0.8, indicating strong internal consistency and distinctiveness within the cluster. This cluster focused on the use of virtual laboratories, utilizing technologies like virtual reality (VR) and augmented reality (AR), to enrich chemistry education. Studies within this cluster, such as those by Chiu et al. (2015) and Winkelmann et al. (2017), explored the enhancement of chemistry teaching through these immersive tools. Additionally, research examined the effects of procedural guidance and auxiliary tools in virtual laboratories on fostering students' skills development, as evidenced by Ali et al. (2023) and Ullah et al. (2016). Predominant keywords included computer-based learning, chemistry, laboratory instruction, internet/web-based learning, distance learning/self-instruction, and multimedia-based learning.

Cluster #2, labeled virtual reality, comprised 38 keywords, with a Silhouette value of 0.863. This cluster emphasized the use of virtual laboratories within science and engineering educational frameworks, highlighted in studies by Cheong and Koh (2018), and Singh et al. (2021). A focal point of this cluster was the evaluation and integration of virtual laboratories alongside physical science laboratories, examining their comparative benefits and synergies, as explored by Kollöffel and De Jong (2013), and Hawkins and Phelps (2013). Key themes were marked by keywords such as science, education, virtual reality, technology, model, and skills.

Cluster #3, named engineering education, contained 32 keywords and a Silhouette value of 0.847, reflecting its coherence and specificity. This cluster explored the application and implications of virtual laboratories across a spectrum of disciplines, including chemistry, physics, engineering, and biology. It focused on their influence on student motivation, self-efficacy, and the overall learning experience, with contributions from Su and Cheng (2019), Husnaini and Chen (2019), and Zhang and Li (2019). Notable keywords such as laboratory, engineering education, simulation, remote and inquiry-based learning underscored the cluster's commitment to enhancing educational outcomes through virtual laboratory integrations.

Cluster #4, virtual learning, encompassed 26 keywords and had a Silhouette value of 0.742, signifying a coherent focus within the cluster. Unlike other clusters that compared virtual to physical science laboratories, this cluster delved deeper into the behavioral and attitudinal differences of students within these distinct environments, as studied by Hu-Au and Okita (2021), and Špernjak and Šorgo (2018). Additionally, it explored frontline teachers' perceptions and utilization of virtual laboratories, highlighting the educational community's evolving relationship with virtual laboratory technologies. Key themes were captured by keywords such as science education, performance, environment and cognitive load theory.

Cluster #5, improving classroom teaching, also with 26 keywords and a Silhouette value of 0.771, extended beyond the mere application of virtual laboratories across various educational fields to examine their effects on students, including academic performance, motivation, learning experience, and cognitive development. Influential studies in this cluster, like those by Dyrberg et al. (2017), Hirshfield and Koretsky (2021), Reeves et al. (2021), and Tatli and Ayas (2013), contributed to understanding how virtual laboratories can enrich classroom teaching. Common keywords included design, instruction, conceptions, academic achievement and improving classroom teaching.

Cluster #6, titled inquiry learning, contained 24 keywords, boasting the highest Silhouette value among the clusters at 0.878. This cluster focuses on using computer simulations within online virtual laboratories to achieve educational goals, and enhance students' experimental skills, as evidenced by research from Makransky et al. (2016) and Uribe et al. (2016). Keywords such as computer simulations, inquiry, knowledge and curriculum underscored the cluster's focus on promoting active learning and inquiry within virtual environments.

Cluster #7, distance learning, comprised 22 keywords and a Silhouette value of 0.845, focusing on the application of virtual laboratories in distance education. This cluster highlighted the significant advancements and

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improvements in learning outcomes within scientific disciplines such as physics, chemistry, and biology through distance learning modalities, as shown in studies by Husnaini and Chen (2019), Broyer et al. (2020), and Kobayashi et al. (2021). Keywords such as achievement, distance learning and school reflected the cluster's emphasis on enhancing educational accessibility and effectiveness through virtual laboratories.

The analysis of clusters revealed a diverse landscape of research on virtual laboratories, highlighting their significant role in enhancing science education through various technological means such as virtual and augmented reality. Insights from these clusters emphasized the importance of understanding students' behavioral and attitudinal shifts in virtual versus physical science laboratories, the impact of virtual laboratories on academic performance and engagement, and the potential of virtual environments for fostering inquiry-based learning and improving classroom teaching. This comprehensive overview underscored the transformative potential of virtual laboratories in enriching educational experiences across disciplines and educational levels.

The progression of the research themes. Figure 7 shows a topic-based analysis of research progress in virtual laboratories for enhancing science education from 2013 to 2023. It illustrates the distribution of research themes through a plot with axes corresponding to different document clustering categories, where each cluster was defined by a set of closely related keywords. The numeric labels on each cluster topic represent the count of keywords, with smaller numbers indicating clusters of narrower focus and larger numbers denoting more extensive topics.

The analysis revealed a substantial duration of research activity across the eight identified clusters, underscoring a deep-seated research foundation in the use of virtual laboratories to bolster science education. Notably, clusters #0, #2, #5, and #6 had the most extended span of research, stretching from 2013 to 2023, indicating sustained interest and investigation in these areas. Cluster #0, in particular, stood out for its early and recurring emphasis on virtual laboratories, highlighting the foundational role of virtual laboratories in science education from the outset. Meanwhile, Cluster #3 emerges as the most recent focus area, with engineering education and related terms like inquiry-based learning and simulation signaling a shift towards integrating virtual laboratories in engineering education to foster innovative and creative student outcomes. Furthermore, the presence of high-frequency keywords in Clusters #1, #2, and #3 in recent years pointed to the growing prominence of laboratory instruction, virtual reality, and engineering education as current and future research hotspots in the field. This pattern suggested an ongoing and possibly increasing interest in these areas, anticipating their continued relevance in shaping the trajectory of virtual laboratory research in science education.

Figure 6

Theme-based Co-occurrence Knowledge Map of Virtual Laboratories for Enhancing Science Education Research from 2013 to 2023

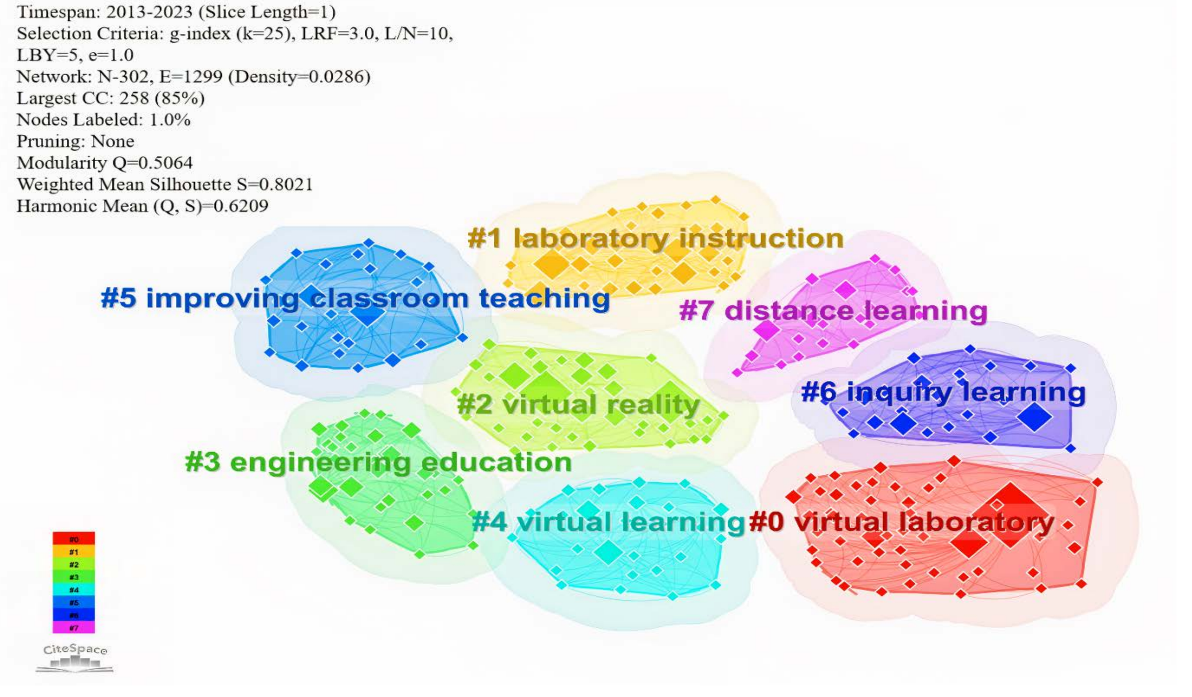

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Table 2
Details of the Major Themes of Virtual Laboratories for Enhancing Science Education Research from 2013 to 2023

ID	Cluster name	Size	Silhouette	Year	Keyword
0	Virtual laboratory	51	0.722	2017	#1, #4, #18
1	Laboratory instruction	39	0.8	2017	#5, #9, #12, #17
2	Virtual reality	38	0.863	2019	#2, #3, #8, #15
3	Engineering education	32	0.847	2019	#10, #19, #20
4	Virtual learning	26	0.742	2016	#11
5	Improving classroom teaching	26	0.771	2016	#6, #14
6	Inquiry learning	24	0.878	2015	#7, #13
7	Distance learning	22	0.845	2018	#16

Discussion

Despite the growing importance of using virtual laboratories for science education, there remains a notable lack of comprehensive reviews that map out the existing landscape of virtual laboratories within science education comprehensively. This review aimed to shed light on the present state, trace the evolutionary paths, and identify recurring themes and priorities by conducting a bibliometric analysis of research on virtual laboratories in science education from 2013 to 2023. It synthesized key findings, discussed their implications, and outlined the study's limitations, offering a thorough examination of the field's progression.

The overarching trend in virtual laboratories for science education. The trend in virtual laboratories for enhancing science education from 2013 to 2023 delineated a clear trajectory of research development, as highlighted by our analysis of annual publication and citation statistics. The period between 2013 and 2017 marked the nascent stage of exploration in this domain, setting the groundwork for subsequent advancements. From 2018 onwards, the field witnessed a transition into a phase of accelerated growth, signaling a burgeoning interest and expansion of research activities. Notably, 2021 presented an anomaly with a temporary reduction in research output, introducing a brief period of deceleration within an otherwise rapidly advancing field. This temporary setback, however, did not deter academic enthusiasm. Instead, a resilient resurgence in research activity had been observed post-2021, illustrating the academic community's sustained commitment to this area of study. Despite the transient dip in 2021, the enduring trend of exponential growth in both publications and citations reaffirmed the increasing importance of virtual laboratories within the science education research landscape. This analysis not only maps out the chronological development of virtual laboratory research but also underscores the need for further exploration into the drivers behind these trends (Ray & Srivastava, 2020). This comprehensive perspective contributes to a nuanced understanding of the trajectory of research in virtual laboratories for science education.

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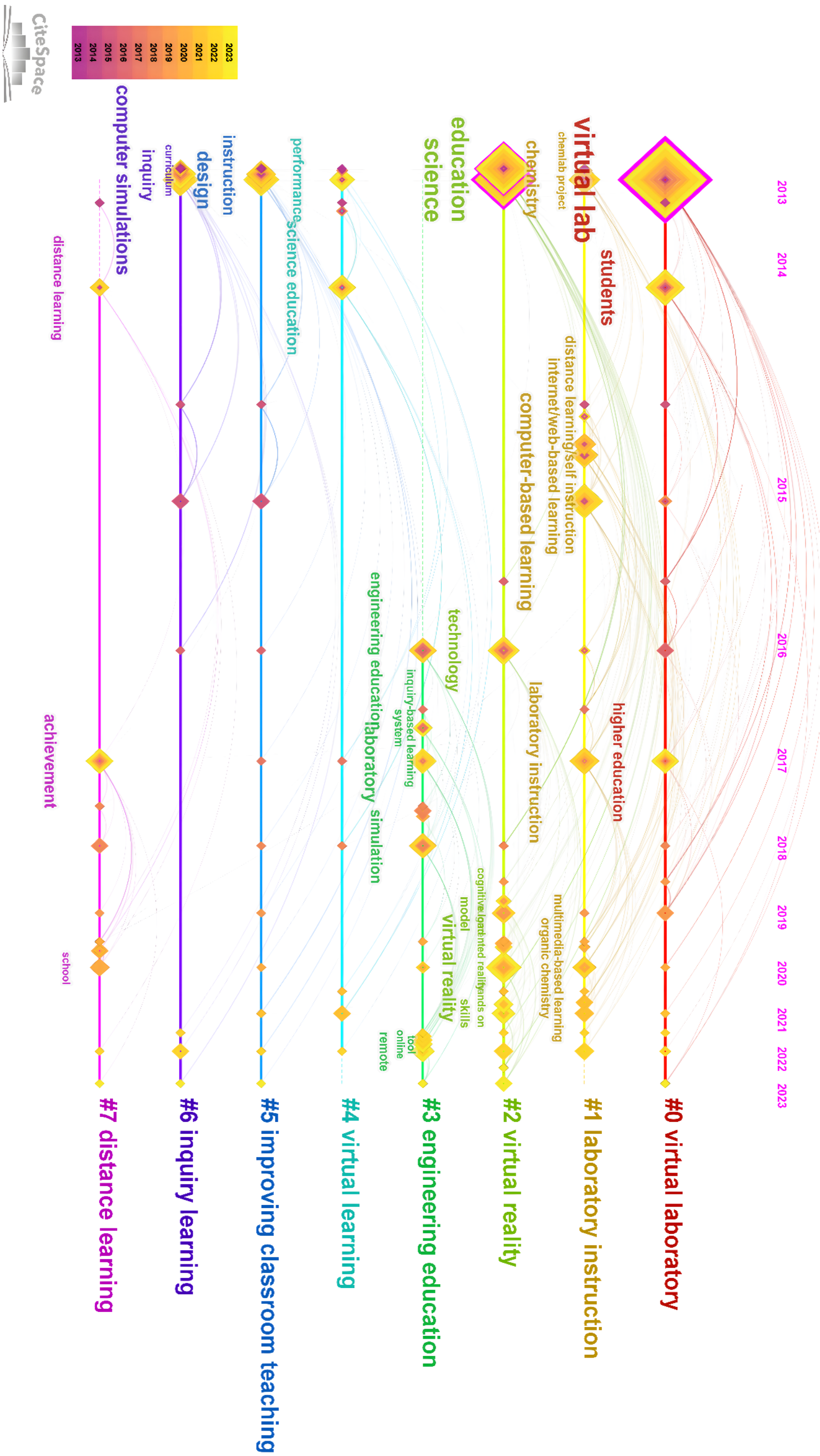
Figure 7
Theme-based Progression Analysis and Visualization of Virtual Laboratories for Enhancing Science Education Research from 2013 to 2023



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The distribution of virtual laboratory applications in various disciplines in science education. The adoption of virtual laboratories across a diverse range of disciplines from 2013 to 2023 demonstrates their significant versatility and utility in science education. This study found that virtual laboratories were extensively used not only in traditional subjects like chemistry and physics but also in engineering, medicine, astronomy, and interdisciplinary science studies. Chemistry and physics were highlighted as the most prominent areas of focus, collectively accounting for over half of the research literature, reflecting their foundational role in educational programs and research, as noted by Bao and Koenig (2019) and Silva et al. (2023). Beyond these core sciences, the application of virtual laboratories extended to engineering, medicine, and comprehensive sciences, indicating an evolution towards more diverse scientific domains. This expansion aligns with previous literature, emphasizing the importance of integrating technology in education and the growing relevance of virtual laboratories in various fields (Dal Mas et al., 2023; Fida & Tuncel, 2019; Mansurjonovich, 2023; Mansurjonovich & Davronovich, 2023; Vilia & Candeias, 2020). Such trends underscore the broadening impact of virtual laboratories, suggesting their key role in advancing science education across disciplines (Reeves & Crippen, 2021; Santos & Prudente, 2022). This concise overview captures the essential contributions of virtual laboratories to science education, highlighting their expanding scope and importance.

The key research developmental paths and research hotspots in the field of virtual laboratories for science education. The analysis of keyword-based co-occurrence knowledge graphs from 2013 to 2023 emphasized the virtual laboratories as a central theme in the expanding field of virtual laboratories for science education. Key terms like science, education, students, computer-based learning, and design emerged as fundamental aspects of this academic exploration, resonating with earlier studies that highlight the positive impact of virtual laboratories on student learning (Arista & Kuswanto, 2018).

This study identified five key developmental paths in the evolution of virtual laboratories, underscoring their critical role in enhancing student learning and offering insights into the comparison with physical science laboratories (Darrah et al., 2014; Puntambekar et al., 2021; Tauber et al., 2022; Williams et al., 2021). This focus aligns with prior research, showcasing the comprehensive benefits of virtual laboratories in improving educational experiences and outcomes (Husnaini & Chen, 2019). Notably, the emphasis on engineering education and the shift towards distance learning during the global pandemic indicate significant changes in educational methodologies, further accelerated by the advent of virtual reality technology (Serafin & Chabra, 2020).

The importance of guidance from teaching assistants and user-friendly guides in virtual laboratories has consistently been highlighted, aligning with studies that emphasize the need for supportive instructional frameworks to enhance the effectiveness of virtual laboratories (Dunnagan et al., 2019; Levonis et al., 2020). Our findings echo previous research while shedding light on the adaptive evolution of virtual laboratories in response to new educational trends and technological developments. The multifaceted impact of virtual laboratories on student learning underscores their ongoing importance and innovative role in modern science education.

The dominant research themes and their progression in virtual laboratories for science education. Keyword-based cluster analysis from 2013 to 2023 identified 13 distinct research themes in the use of virtual laboratories to enhance science education, each signifying a unique area of focus. This analysis underscored the multifaceted nature of virtual laboratories, ranging from their comparison with physical science laboratories to their impact on student performance. The consistency in cluster modularity and silhouette values suggested a robust and cohesive structure across these research topics, aligning with studies that highlight the significant role of virtual laboratories in boosting student engagement and comprehension (Nolen & Koretsky, 2018; Tatli & Ayas, 2013). The advantages of virtual laboratories over physical science laboratory settings included enhanced learning outcomes, encouragement of innovative thinking, and improved practical skills (Husnaini & Chen, 2019; Su & Cheng, 2019; Wong et al., 2020; Zhang & Li, 2019), although challenges such as potential distractions and increased cognitive load are noted (Makransky et al., 2019b).

Progression analysis reveals sustained interest in areas like virtual reality, classroom teaching enhancement, and inquiry learning, indicating their ongoing relevance and contribution to the discipline. The emergence of engineering education as a recent focus suggests evolving research directions, with virtual laboratories poised to influence future educational methodologies significantly. These insights provide a comprehensive view of the field's dynamic nature and the potential of virtual laboratories to transform science education by enhancing academic performance, motivation, and learning experiences (Dyrberg et al., 2017; Hirshfield & Koretsky, 2021; Reeves et al., 2021), guiding future research and pedagogical strategies.

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Implications for Educational Practices, Research and Policy Makers for Using Virtual Laboratory for Enhancing Science Education

The adoption of virtual laboratories in science education brings implications for educational practices, research, and policy-making, reflecting insights from recent academic studies.

Implications for educational practices. Virtual laboratories introduce a suite of compelling benefits to science education that cannot be overlooked. Firstly, they eliminate the dependency on physical laboratory resources, thus offering unparalleled flexibility in how and where education can be delivered. This aspect is particularly beneficial in remote or resource-limited settings, enabling continuous learning without geographical or infrastructural constraints. Secondly, the inherent safety of virtual laboratories allows for the exploration of experiments that would otherwise be deemed too risky or impractical in a physical science laboratory setting, thus broadening the scope of scientific inquiry accessible to students. Thirdly, the digital nature of these laboratories facilitates an environment where students can experiment freely, making mistakes and learning from them without the fear of wasting materials or causing accidents, thereby fostering a deeper engagement with the scientific process. Finally, the interactive and immersive experiences provided by virtual laboratories make abstract scientific concepts more tangible, thereby enhancing comprehension and retention.

Implications for educational research. The integration of virtual laboratories into science education offers a rich vein of inquiry for educational researchers. While there is a general consensus on their positive impact on enhancing learning and analytical skills, the dialogue around their potential drawbacks, such as the risk of cognitive overload and distraction, especially with the use of immersive technologies like virtual realities, calls for a balanced approach in their implementation. This dichotomy highlights the need for ongoing research to navigate these challenges effectively. Moreover, the data-intensive nature of virtual laboratories presents a fertile ground for educational researchers to dissect and understand student behaviors, learning patterns, and outcomes in unprecedented detail, paving the way for innovations in pedagogical strategies and curriculum design.

Implications for policy makers. For policymakers, the rise of virtual laboratories in science education prompts a series of strategic considerations. Recognizing the current trends and research in virtual laboratory applications can guide the development of supportive policies that facilitate the adoption and effective use of these technologies in educational settings. Such policies could focus on providing resources for teacher training, infrastructure development, and curriculum integration, ensuring that educators and students alike are equipped to leverage virtual laboratories effectively. Additionally, virtual laboratories offer a unique solution to democratize science education by removing barriers related to physical resources, geographical isolation, and economic disparities. Policymakers have the opportunity to harness this potential to foster inclusivity and equity in science education, making quality scientific learning accessible to all students, regardless of their background.

Limitations and Future Directions

While this study offers valuable insights into the use of virtual laboratories in science education, it acknowledges several limitations that should be considered. Primarily, the research is based on English-language articles from the Web of Science Core Collection spanning from 2013 to 2023, focusing exclusively on basic science disciplines such as physics, chemistry, biology, astronomy, and geography. Although this selection criteria are meticulous, it may overlook pertinent studies outside this dataset, potentially limiting the breadth of our analysis. Consequently, our findings provide a snapshot rather than a comprehensive view of the field. Future studies could expand the scope by exploring a broader array of databases, including both English and Chinese sources like SCOPUS and CNKI, and extending the research to encompass virtual laboratories in applied sciences such as agricultural engineering and biomedical engineering. Such an expanded approach would offer a more holistic understanding of virtual laboratories in science education.

Additionally, the use of data analysis tools like CiteSpace introduces a layer of variability dependent on specific parameter settings, including the number of slices, Top N keywords, and clustering functions. These settings can influence the conclusions drawn from the data, suggesting that the insights provided, while valuable, come with inherent limitations. Future research should aim for a nuanced analysis by adjusting these parameters and employing multiple data analysis tools to produce a varied range of visualizations, thereby offering a richer depiction of research trends within the domain.

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Lastly, the study highlights major research themes and forecasting future directions for the research field of virtual laboratories for enhancing science education, paves the way for more nuanced studies. Further research could delve into the synergies between virtual laboratories and other educational methodologies, such as multimedia and inquiry-based learning. Investigating these intersections will enrich our understanding of the dynamic evolution of science education, guiding educators and policymakers in optimizing the integration of virtual laboratories for enhanced learning outcomes.

Conclusions

This bibliometric review of virtual laboratories in science education from 2013 to 2023 underscores their pivotal role in transforming science education through innovative technological integration. The findings reveal a significant expansion in the application of virtual laboratories across diverse scientific disciplines, demonstrating their versatility in enhancing learning experiences and outcomes. This decade-long trajectory showcases a shift towards more interactive, accessible, and flexible education models, responding to the evolving educational needs and technological advancements. The emergence of distinct themes, such as the emphasis on interdisciplinary approaches, the integration of virtual reality, and the focus on developing critical thinking and problem-solving skills, highlights the dynamic nature of virtual laboratory research. These themes underscore the potential of virtual labs to not only complement traditional laboratory experiences but also to pioneer new pedagogical strategies that are in tune with the digital age. Furthermore, the discussion points towards an increasing recognition of the importance of aligning virtual lab designs with educational theories and practices to maximize their effectiveness. The integration of virtual laboratories into science education marks a paradigm shift towards more learner-centered approaches, facilitating personalized, engaging, and impactful learning experiences. Moving forward, it is imperative to address challenges such as accessibility and the need for robust assessment methodologies to fully leverage the potential of virtual laboratories. Insights from this review advocate for ongoing research and development in this field, emphasizing the importance of collaboration among educators, researchers, and policymakers. Together, they can innovate and implement virtual laboratories that meet the future demands of science education.

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Declaration of Interest

The authors declare no competing interest.

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