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TRACING TECHNOLOGICAL TRANSFORMATION IN EDUCATION: A BIBLIOMETRIC ANALYSIS OF SPECIAL EDUCATION AND VIRTUAL LABORATORIES

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Abstract

This study examines the literature at the intersection of special education and virtual laboratories through bibliometric methods, identifying research trends in the emerging field. Growing interest has been observed between STEM/STEAM education and special education, with virtual laboratories serving as a bridge connecting these domains. A total of 1000 publications indexed in the Web of Science Core Collection between 2000 and 2025 were analyzed, using the keywords "Special Education" and "Virtual Laboratory," with data visualized through VOSviewer software. The analyses covered four main categories: international collaboration, institutional collaboration, author collaboration, and keyword distribution. Findings show that China and the United States lead in publication output. While international collaboration networks exist among many countries, they remain concentrated in specific geographic regions and limited at the global scale. At the institutional level, Chinese universities such as Nanjing University and Beijing University stand out, showing high publication volumes. The author collaboration network reveals intensive scientific production among China-based researchers, though interdisciplinary collaboration remains limited. Keyword analysis highlights the predominance of virtual reality and experience-based learning environments, alongside growing interest in virtual laboratory applications for specific groups such as autism spectrum disorder and Williams syndrome/intellectual disability. The study concludes that the field continues to expand, but greater interdisciplinary collaboration and global knowledge exchange are needed, noting that integrating virtual laboratories with special education within STEM/STEAM remains a still-emerging area.

Keywords: bibliometric analysis, special education, virtual laboratory, stem/steam education, VOSviewer

INTRODUCTION

Education systems have undergone a process of transformation over the past two decades under the influence of rapidly advancing digital technologies. In particular, the digitalization of learning environments has fundamentally altered the ways in which students access information, as well as instructional strategies and assessment approaches (Selwyn, 2016). One of the most notable examples of this transformation is the integration of virtual laboratories into educational processes. Virtual laboratories enable students to carry out the experimental processes of traditional laboratories in a digital environment, removing physical constraints and rendering learning experiences more flexible and accessible (Potkonjak et al., 2016).

The field of special education, in turn, stands out as a discipline in which individual differences are taken into account and in which the individualization of learning processes is a fundamental requirement. In this context, virtual laboratories carry the potential to offer an inclusive and accessible learning environment for individuals with special needs (Smith & Johnson, 2020). Moreover, the education of gifted and talented individuals, as a sub-dimension of special education, is one of the

areas in which individualized learning opportunities are most intensely needed. Virtual laboratories can offer these students dynamic learning environments that foster the development of problem-solving, creativity, and higher-order thinking skills (Brown, 2021). A meaningful increase has also been observed in recent years in the use of virtual laboratories for special needs groups such as autism spectrum disorder and intellectual disability (Garcia et al., 2022).

Although the literature contains strong evidence that virtual laboratories are effective in science, engineering, and medical education (Heradio et al., 2016; de Jong et al., 2013), their use within the special education context appears to be more limited and to be predominantly studied in conjunction with STEM/STEAM approaches. While the majority of existing studies focus on science and engineering education, research on how virtual laboratories can be applied in special education remains relatively scattered and limited (Garcia et al., 2022). In particular, growing interest is observed in applications targeting special needs groups such as autism spectrum disorder or Williams syndrome/intellectual disability, yet studies in this area remain relatively limited (Kim & Lee, 2023). At this point, bibliometric analyses come into play, making it possible to comprehensively examine the academic output in the field. Furthermore, STEM (Science, Technology, Engineering, Mathematics) and STEAM (Science, Technology, Engineering, Arts, Mathematics) educational approaches have, particularly over the past decade, begun to gain traction in special education as well. Research shows that STEAM-based virtual laboratory applications support the problem-solving, critical thinking, and creativity skills of individuals with special needs (Blackley & Howell, 2015; Han et al., 2015). Bibliometric methods provide guidance for future research by mapping the developmental trajectory, collaborations, and thematic concentrations of a research field (Donthu et al., 2021). In this context, a holistic examination of the output produced at the intersection of special education and virtual laboratories is of critical importance for identifying research gaps and rendering international collaborations visible. Accordingly, the main purpose of this study is to examine, through bibliometric methods, the scientific publications on special education and virtual laboratories, and to reveal the current state of the field in terms of countries, institutions, authors, and keyword trends. The study aims to determine how the field is shaped on a global scale, which researchers and institutions stand out, and which themes are most prominent. In this way, the traces of technological transformation in special education will be mapped, and strategic implications will be drawn to guide future research, thereby offering a framework to inform researchers and practitioners.

METHOD

Research Design

This study was designed using bibliometric analysis, one of the quantitative research designs. Bibliometric analysis is not merely a scanning technique; it is a distinctive methodology that reveals the intellectual structure, network connections, and developmental trajectory of a given scientific field through mathematical and statistical data.

Bibliometric analyses aim to reveal the overall structure of a scientific field by examining scientific output, collaborations, and thematic trends through quantitative data (Donthu et al., 2021). This method is regarded as a particularly effective approach for mapping the development of specific concepts and research networks (Zupic & Čater, 2015).

Data Source

In the data collection process, the Web of Science (WoS) Core Collection, a comprehensive scientific database with high international reliability, was preferred. WoS is a data source frequently used in bibliometric analyses owing to its indexing of high-impact journals across different disciplines and its provision of robust bibliometric indicators (Falagas et al., 2008). The Web of Science (WoS) Core Collection was selected as the primary data source because it indexes high-impact international publications and provides a standardized, reliable structure for bibliometric analyses. Thanks to its multidisciplinary structure, WoS enables a holistic search of qualified literature at the intersection of

different fields such as educational technology and special education, thereby enhancing the methodological rigor of the analysis and the representativeness of the data.

Data Collection Process

The dataset of the study was constructed using the keywords "Special Education" and "Virtual Laboratory." English search terms were utilized because the vast majority of indexed publications in WoS are written in English, thereby ensuring broader coverage and internationally comparable results. This contributes to obtaining an internationally comparable and reliable dataset. Within the framework of the specified criteria, the search covers publications between January 2000 and March 2025. According to the specified criteria, a total of 1000 articles were included in the review. During the search process, only publications indexed by WoS and classified as scientific articles were included; book chapters, conference proceedings, and non-review documents were excluded from the analysis. In this way, a reliable dataset was constructed and analyses were conducted using only peer-reviewed publications of high academic value.

Analysis Process and Tools Used

The data obtained were visualized and analyzed using VOSviewer (van Eck & Waltman, 2010), one of the bibliometric analysis software programs.

VOSviewer is one of the most widely used open-access software programs in bibliometric analyses (van Eck & Waltman, 2010). VOSviewer was adopted owing to its seamless compatibility with WoS export data, intuitive network map visualization via color clusters and node sizes, and robust density analysis features. In VOSviewer, each color represents a cluster (a research group), node size represents the number of publications or citations, and link thickness represents the intensity of collaboration. Density maps reveal the level of visibility of particular concepts or actors within the field. The software allows for the visualization of author collaborations, country and institutional connections, and keyword co-occurrences.

The analysis process was carried out across four main categories:

1. International collaboration
2. Institutional collaboration
3. Author collaboration
4. Keyword distribution

This multidimensional analytical approach made it possible to comprehensively examine trends in the literature and to shed light on future research. However, the fact that this study is limited to the Web of Science database alone, and thus does not encompass the entirety of the literature in the field, may be regarded as a limitation.

The VOSviewer Software and Interpretation of the Data

The VOSviewer software used in the analysis process visualizes data using the VOS (Visualization of Similarities) clustering algorithm (van Eck & Waltman, 2010). This algorithmic structure automatically groups units that are strongly related to one another, forming clusters. In the maps, each unit (author, country, or word) is represented as a node; the size of these nodes reflects publication/citation density, while the distance between them reflects the degree of thematic similarity.

The choice of VOSviewer is further supported by its proven efficacy in mapping bibliometric networks within large datasets and its widespread recognition as a reliable open-access analytical tool (Donthu et al., 2021).

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Reading the VOSviewer Network Maps and Analysis Parameters

The VOSviewer software used to visualize the bibliometric data obtained in this study maps the data using a "distance-based" approach. The fundamental structural elements and their algorithmic correspondences, essential for the correct interpretation of the maps, are detailed below:

1. Nodes and Size Analysis

- Each circle (node) shown on the maps represents an author, institution, country, or keyword, depending on the type of analysis.
- Node Size: The size of a node indicates the weight of that unit in the relevant analysis. For instance, in a keyword analysis, node size indicates the frequency of occurrence of that word, while in a country analysis it indicates the total number of publications for that country. A large node symbolizes the centrality and influence of that element within the field.

2. Links and Total Link Strength

- The lines between nodes represent the relationship between two units (co-authorship, co-citation, or co-occurrence).
- Distance: The closeness of the distance between two nodes indicates a high degree of similarity and relational strength between those units. Nodes positioned close to one another are thematically similar or represent actors who collaborate frequently.
- Line Thickness: The thickness of the lines refers to the "Total Link Strength." A thick line demonstrates that the two units in question (for example, two keywords) are used together very frequently in the literature.

3. Colors and Clustering

- The colors in the VOSviewer maps represent the clusters assigned by the software's own internal algorithm, VOS Clustering (Similarity Visualization).
- Meaning: Nodes sharing the same color bring together units that interact more intensively with one another than with other nodes and that share similar research trends.
- Interpretation: A given color (red, green, blue, etc.) does not carry a fixed meaning; colors are used solely to distinguish different disciplines or thematic groups from one another. A high number of clusters in a map indicates that the field is fragmented and composed of diverse sub-disciplines, whereas a low number indicates that the field is gathered around certain mainstream themes.

4. Density Visualization

- Density maps present a color scale based on the number of nodes in a given region and their weights.
- Yellow/Bright Regions: These represent the "hot spots" where academic interest and publication volume are highest, constituting the core topics of the field.
- Blue/Dark Regions: These indicate areas where publication density is low—areas that are less frequently studied in the literature or that are still emerging. These regions are interpreted as potential "research gaps" for researchers.

5. Temporal Effect (Overlay Visualization)

- If the map is time-focused (Overlay), colors vary according to year.
- Dark Colors (Purple/Blue): These indicate older, foundational (classic) studies and concepts in the field.

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- Light Colors (Yellow/Green): These represent concepts that have recently entered the literature, newly emerging trends, and technological transformations (for example, recent artificial intelligence or advanced virtual laboratory studies).

Reliability of the Data Analysis

In bibliometric analyses, the reliability of the data source and the scientific acceptance of the software used are important criteria. Because WoS is accepted as a standard database among international citation indexes, its data reliability is considered high (Mongeon & Paul-Hus, 2016). The appearance of the country name as "Peoples R China" in the WoS database stems from WoS's own recording conventions, this expression being the official abbreviation for the People's Republic of China within the database. In addition, VOSviewer and Bibliometrix, being widely used and validated tools in bibliometric analyses, further enhance the methodological rigor of the analyses.

RESULTS

In this study, 1000 publications obtained as a result of a search conducted in the Web of Science database using the keywords "Special Education" and "Virtual Laboratory" were analyzed. The bibliometric analyses conducted were evaluated across four main categories: author collaboration, international collaboration, institutional collaboration, and keyword distribution.

Findings on Author Collaboration

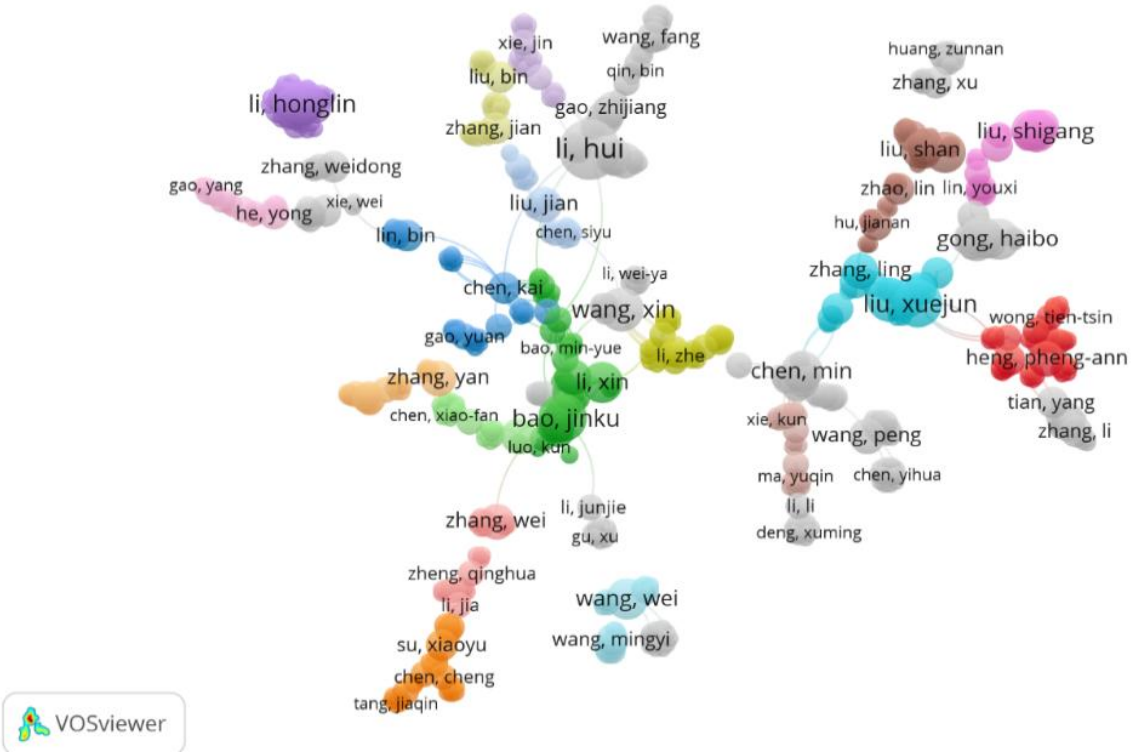


Figure 1. Findings on author collaboration

As illustrated in Figure 1, researchers such as Li Hui, Liu Shigang, and Chen Min occupy central positions within the collaboration network. These scholars exhibit extensive collaborative ties and contribute substantially to interdisciplinary research at the intersection of special education and virtual laboratories. In addition, researchers based in China were found to be intensively engaged in scientific production in this field. The density of connections among authors indicates that certain researchers occupy a more central position than others and play a significant role in knowledge production and sharing within the research field. Furthermore, an examination of the clustering structure reveals that

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different working groups focus on particular themes, with these focal points concentrated on how virtual laboratory technologies can be applied within the context of special education.

Findings on International Collaboration

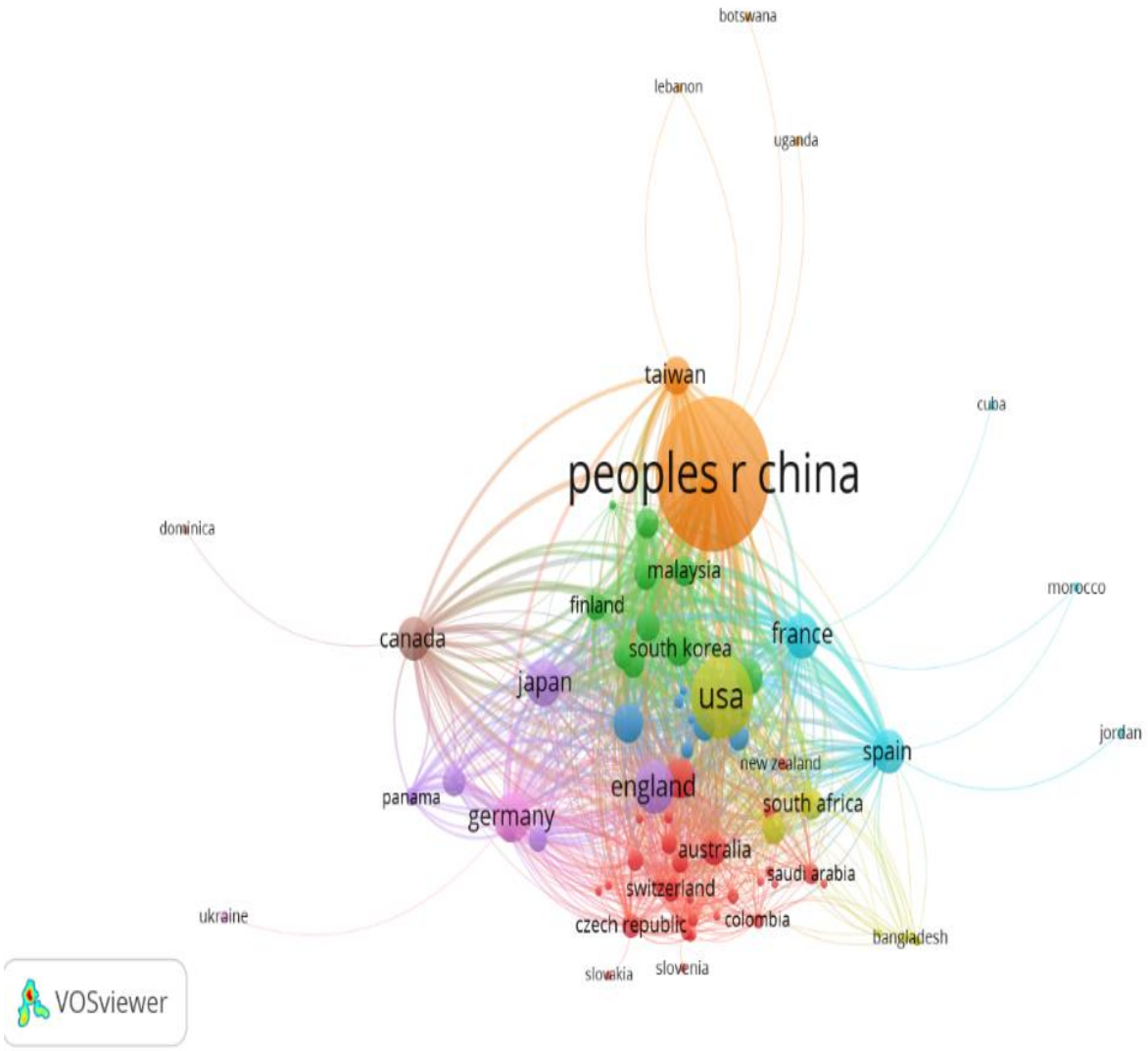


Figure 2. Findings on international collaboration

Figure 2 illustrates the international collaboration network, where the People's Republic of China ("Peoples R China") and the USA display the highest centrality and link strength. These two nations lead international efforts in integrating virtual laboratories into special education through extensive cross-border partnerships. In addition, countries such as Canada, Japan, Germany, and the United Kingdom are also observed to play active roles in academic collaborations in this field. The collaborations carried out among countries are considered important for the global adoption of virtual laboratory technologies and their integration into special education practices. Furthermore, among the other countries in the collaboration network, France, South Korea, Spain, and Malaysia were also observed to contribute to studies in this field. This indicates that virtual laboratories are attracting increasing international attention and that global research networks are expanding.

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Findings on Institutional Collaboration

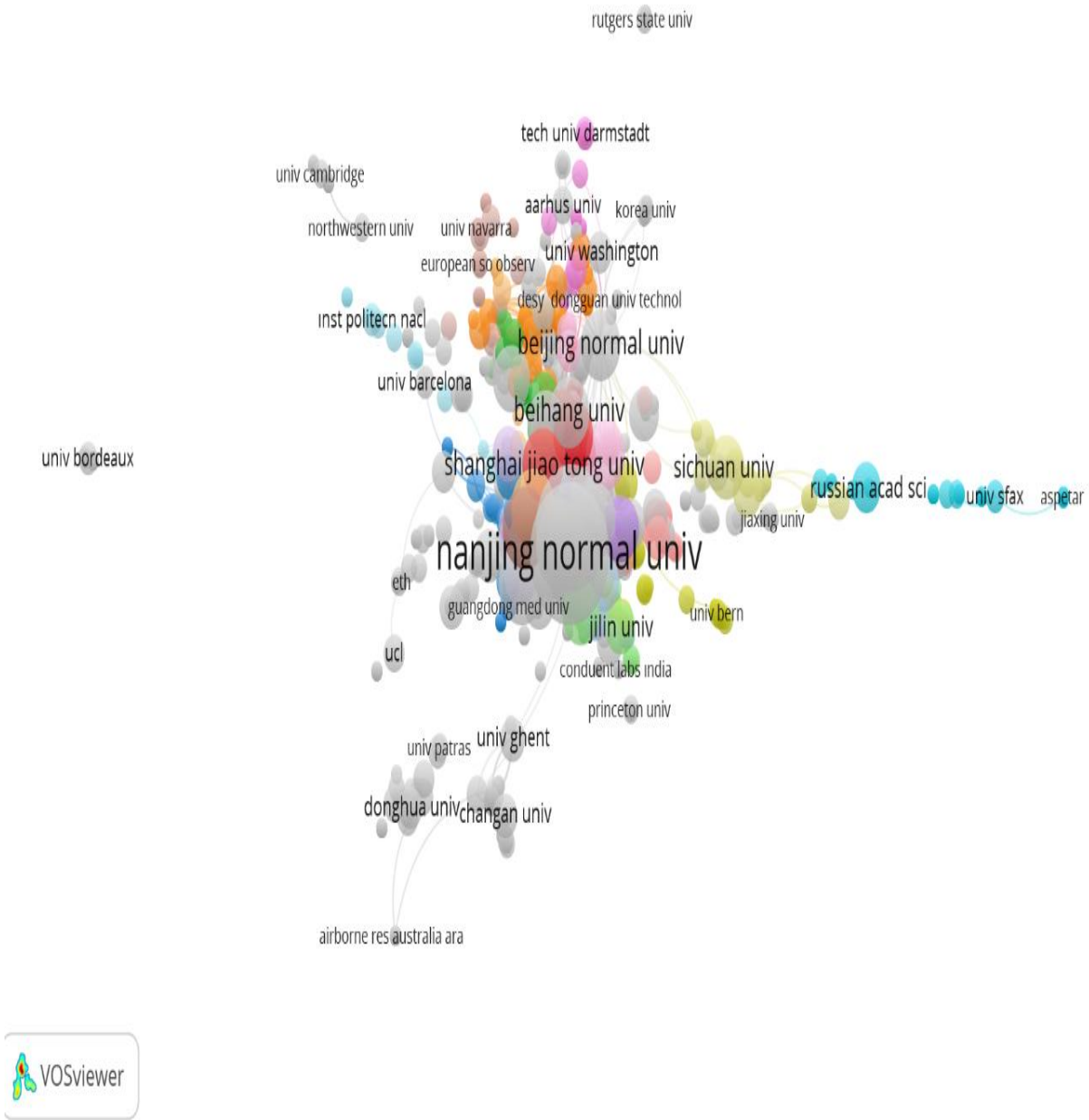


Figure 3. Findings on institutional collaboration

The institutional-level analyses presented in Figure 3 show that institutions such as "Nanjing Normal University," "Beijing Normal University," and "Shanghai Jiao Tong University" play a leading role in the field of virtual laboratories and special education. In addition, universities in China were determined to conduct intensive research at the intersection of these two fields and to contribute to knowledge production through international collaborations. Furthermore, institutions such as the "University of Washington" from the United States and "Aarhus University" from Europe were also found to have developed significant collaborations. The analysis of the institutional collaboration network reveals the particular importance that research centers and universities place on interdisciplinary and international collaboration in this field. It is also observed that Asia- and Europe-based research institutions play an active role in global knowledge sharing and technology transfer.

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Findings on Keyword Distribution

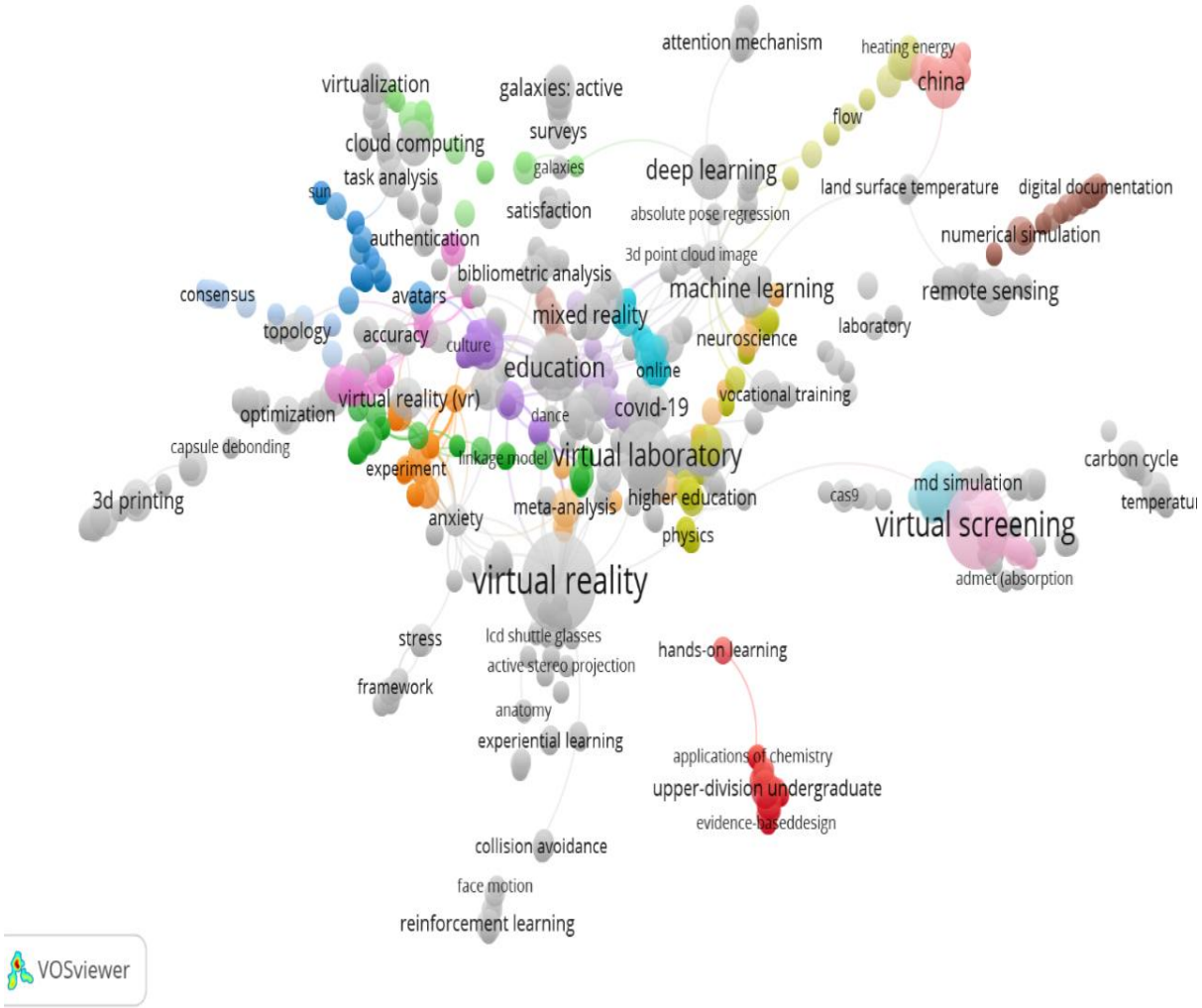


Figure 4. Findings on keyword distribution

An examination of Figure 4 shows that the keyword analysis results reveal the main themes that stand out in the field of virtual laboratories and special education. The terms "Virtual Reality," "Education," "Machine Learning," and "Virtual Laboratory" are the most frequently used keywords across the studies. These keywords highlight how virtual laboratories are used in educational settings and the role of artificial-intelligence-supported applications in this process. In addition, terms such as "Deep Learning," "Hands-On Learning," and "Remote Sensing" are also observed to be integrated into research in this field. Virtual laboratories appear to have the potential to support individualized learning experiences in special education and to offer advantages in adapting to different learning styles. The connections among keywords show that research is concentrated on particular technologies (for example, augmented reality and machine learning) and pedagogical approaches (for example, experiential learning). It was further determined that concepts such as "Cloud Computing" and "Bibliometric Analysis" shape the methodological framework of studies in this field. The absence of a central position for the term "gifted" (gifted/talented) in the keyword network may stem from the fact that virtual laboratory studies in the literature primarily concentrate on "intervention-oriented" special needs groups such as autism and learning difficulties. This suggests that digital learning environments for gifted and talented individuals remain a still-developing field, and that there is an important gap in the literature regarding the extent to which the enriched educational needs of this group of students are being met through virtual laboratory technologies.

These findings reveal that research on the use of virtual laboratories in special education is steadily increasing and that collaborations in this field are diversifying at both the national and international levels. Furthermore, it appears that interdisciplinary and globally conducted collaborations contribute to virtual laboratories finding a broader field of application within the context of special education.

DISCUSSION, CONCLUSION, and SUGGESTIONS

This study aimed to analyze in detail the relationship between special education and virtual laboratory applications and the collaboration within this field. As a result of the bibliometric analyses conducted, "Peoples R China" and the "USA" were found to be the countries with the highest level of collaboration in this field. This may be regarded as an indicator of growing interest in research on the use of virtual laboratories in special education in China and the United States (Zhao et al., 2020; Wang et al., 2021). In addition, the institutional-level analyses reveal that Chinese universities such as "Nanjing Normal University" and "Beijing Normal University" carry out intensive research activity in the field of special education and virtual laboratories. This finding is consistent with studies in the literature indicating that China also plays a leading role in technology-supported education (Li & Chen, 2022; Huang et al., 2023). The dominance of these countries (China and the USA) in the literature is closely related not only to their technological infrastructure strength but also to their digital-transformation initiatives in special education policy. In particular, the central role played by Chinese institutions such as Nanjing Normal and Beijing Normal is supported by the "National Laboratories of Educational Technology" housed within these institutions and by large-scale, state-supported funding (for example, projects of the National Social Science Fund of China). These institutional structures enable virtual laboratories to be developed not merely as tools, but as sustainable pedagogical models directly integrated into the special education curriculum. In the case of the United States, legal requirements regarding the technological support of individualized education programs (IEPs) in special education, along with high-budget university-industry collaborations, can be regarded as key factors increasing the publication volume and international influence in this field.

The keyword-based analyses show that terms such as "Virtual Reality," "Education," and "Machine Learning" are frequently used within the context of special education. These findings support research arguing that virtual laboratories play a critical role, particularly in experiential learning and the acquisition of complex skills (Smith & Johnson, 2020; Brown, 2021).

The findings of this study indicate that specific countries such as China and the USA have a dominant influence on the field. However, this also points to a global research imbalance. The fact that studies at the intersection of special education and virtual laboratories remain largely confined to a small number of countries indicates that this topic has not yet been sufficiently addressed in developing countries. Accordingly, research with broader geographic diversity is needed so that all students worldwide can benefit equally from the potential of virtual laboratories in inclusive education.

The findings reveal that virtual laboratory research is largely clustered in countries with strong technological infrastructure, such as China and the USA. Since this situation poses a risk of a "digital divide" for special education students in developing countries, increasing global collaboration around low-cost or open-access models of virtual laboratories is of critical importance.

The findings further reveal that author collaborations are concentrated in particular clusters. This indicates that interdisciplinary interaction remains limited, and that strong bridges have not yet been established, particularly within the triangle of special education, computer science, and educational technology. Innovative solutions that will enable the effective use of virtual laboratories in special education can only be developed through collaborations among these countries.

The keyword analyses show that technologies such as virtual reality and machine learning are prominent. However, what is striking in light of the current data is that virtual laboratory applications for gifted and talented individuals remain relatively limited at the international level. This gap can be

considered a significant deficiency in both theoretical and applied research. In this context, future studies should focus not only on areas such as autism, intellectual disability, or Williams syndrome, but also on the diverse learning needs of these individuals.

Finally, this study itself has certain limitations. The analysis was confined solely to the Web of Science database; the inclusion of different databases such as Scopus or ERIC could provide a broader perspective. Furthermore, the use of a bibliometric method alone leaves the findings at a descriptive level and does not allow for a more in-depth evaluation of the pedagogical and applied dimensions of the field.

This study analyzed collaboration on the use of virtual laboratories in special education at the country and institutional level, thereby revealing the current state of the field. The findings obtained indicate that greater international collaboration is needed in research on the use of virtual laboratories in special education. In addition, it is recommended that studies in this field be expanded in the future, particularly in terms of technology integration and artificial intelligence applications (Garcia et al., 2022; Kim et al., 2023). Finally, in terms of the future of the field, it is of great importance that STEM and STEAM educational approaches be more strongly linked to special education. Increasing access to STEAM-based virtual laboratory experiences for individuals with autism spectrum disorder, intellectual disability, or learning difficulties will both improve individual learning outcomes and contribute to the realization of the principle of inclusiveness in education. In-service training programs aimed at developing special education teachers' STEM/STEAM literacy can play a critical role in this process.

The findings obtained largely overlap with current studies in the literature. China's leading role in technology-supported education has also been emphasized in previous research (Li & Chen, 2022; Huang et al., 2023). The finding that virtual laboratories are particularly effective in special education in the processes of experiential learning and the acquisition of complex skills is consistent with the studies of Smith & Johnson (2020) and Brown (2021). Nevertheless, virtual laboratory applications appear to be relatively limited for gifted and talented individuals. This points to an important gap in the field. Furthermore, the insufficiency of interdisciplinary research indicates that the interaction among special education, computer science, and educational technology needs to be strengthened. Indeed, research conducted within the Turkish context (Balım & Altay, 2024; Altay & Balım, 2024) draws attention to the fact that virtual laboratory applications remain insufficient in the contexts of both special education and science education.

Conclusion and Recommendations

This study revealed global trends by analyzing, through bibliometric methods, the academic research conducted in the field of special education and virtual laboratories. The results show that China and the USA hold leading positions in this field, and that technologies such as virtual reality and machine learning are being increasingly integrated.

Recommendations

Recommendations regarding the research findings are presented below.

- Greater international and interdisciplinary collaboration should be supported.
- Virtual laboratory applications for gifted and talented individuals should be expanded. In this context, strengthening the integration of virtual laboratories into BİLSEM (Science and Art Center) programs should be treated as a priority goal.
- The number of qualitative and quantitative studies on the place of artificial intelligence and adaptive learning systems in special education, and their effects on students, should be increased, whether through survey designs or experimental study models.
- Policymakers should develop strategies and issue announcements that encourage the use of virtual laboratories in inclusive education.

- The fragmented structure of author collaboration networks points to a disconnect between special education specialists and software developers. It is recommended that future studies focus not solely on the measurement of technical performance, but also on design-based research models that enhance special education teachers' self-efficacy in using these technologies.

The insufficiency of virtual laboratory applications for gifted and talented individuals, identified as one of the most important research gaps in this study, necessitates that this field be moved from a theoretical to an applied level. In this context, institutions serving gifted students in Türkiye, such as Science and Art Centers (BİLSEM), offer an ideal setting for integrating virtual laboratories into enriched educational programs. Within the project-based learning processes carried out at BİLSEM, students should be provided, through virtual laboratories, with research environments that are costly or physically difficult to access (for example, advanced genetics or astrophysics experiments). Such concrete applications will both support students' higher-order thinking skills and expand the current "intervention-oriented" approach in the literature toward a "potential-development"-oriented perspective, thereby enhancing the applied value of the study.

This study offers a framework to guide future research and applications by mapping the traces of technological transformation in special education.

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Ethics and Conflict of Interest
This study was presented as an oral paper at the Xth National Congress on the Education of the Gifted and Talented. All ethical rules were observed at each stage of the research. The authors declare that he acted in accordance with ethical rules in all processes of the research. The authors declare that they do not have any conflict of interest with other persons, institutions or organizations.

Author Contribution
All authors contributed equally to this study. All authors read and approved of the final manuscript.

Data Availability
The data that support the findings of this study are available on request from the author.

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