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Mapping the development of virtual laboratories in higher education in China: a bibliometric study

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Abstract:
The growing incorporation of virtual laboratories in higher education marks a historical turning point in the practice of experimental teaching. The research examines the Chinese literature of virtual laboratories collected from the CNKI database through a comprehensive bibliometric analysis. Key research areas, research hotspots and research trends are determined by the use of co-word and clustering analysis through COOC software. The results show that the core technology of virtual simulation technology plays an irreplaceable role in improving the experimental teaching method, while revealing the shortcomings of the integration of the emerging technologies of Artificial Intelligence and Virtual reality in the research of this subject area. The information obtained is going to prove to be very useful for improving the functioning of the virtual laboratories in relation to the promotion of greater interactivity, personalisation and scalability of learning environments. The study proceeds to make some strategic suggestions important for future work in the field as well as for practical applications of the technology in both precarious and in firm areas of development found in relation to virtual laboratories in education.

Keywords:
Virtual laboratory, Higher education, CNKI database, Word frequency analysis, Cluster analysis

1.Introduction

The accelerated development of digital technologies has changed the entire education sector, with virtual laboratories representing the key innovation of higher education. Virtual laboratories take the forms of virtual reality (VR), augmented reality (AR) and cloud computing to create an immersive and participatory environment for students, overcoming the previously existing barriers to experimentation (cost, operational safety, availability of platforms) and enhancing the effectiveness of the experiments used in teaching.In the context of digital transformation, all institutions in the world are trying to put into practice the virtual laboratories as a new way of teaching that can ensure both the enrichment of the learning experiences created for the students, as well as the better results of the teaching activity.[1]

In China, the implementation of virtual laboratories is in line with national policies such as "Modernization

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of education 2035", according to which it is intended to use digitalisation tools for the purposes of educational reform and innovative teaching.However, research in this area is underdeveloped and with the gaps that exist in the current literature regarding the methods of capitalising on these technologies with a view to personalizing learning and interdisciplinary collaboration .[2]

The present paper comes to fill these gaps by making an extensive bibliometric analysis of the scientific production in the field of Chinese virtual laboratory, using the CNKI database. For the co-word and cluster analysis it was made use of the COOC software, these revealing the new research trends, respectively the new and emerging research themes in the field. These analyses can be used as a guide to taking strategic decisions for the entire categories of stakeholders involved in the creation of virtual laboratories in higher education.[3]

2.Research Methods

A comprehensive bibliometric analysis is conducted in this study considering the research status of virtual laboratories in higher education. [4] The data was collected from the China National Knowledge Infrastructure (CNKI) database, which is regarded as one of the authentic Chinese academic database in the field. The search was executed by applying the following search terms “virtual laboratory”, “virtual simulation”, “teaching application” and “experimental teaching”. With regard to these, another similar concept like “virtual reality”, “network virtual laboratory” etc. were applied to ensure the completeness of the survey. [5] The time period indicated for the survey was from January 1, 1997, to September 16, 2023. The total number of articles found that being relevant to our study are 7411 .

2.1. Data Collection and Preprocessing

The collected data contained article titles, abstracts, keywords, authors, and publication information. The data was first cleaned by deleting duplicates and irrelevant records.[6] Like terms were merged for consistency in the analysis. Non-relevant terms without substantive meaning to the study were deleted so as to avoid adding noise to the data .[7]

2.2. Analytical Tools

The bibliometrics and co-occurrence analysis mainly apply the COOC software tool to extract keywords and conduct co-word analysis. This tool is also applicable for clustering and for obtaining visualizations of the research trends. [8] From the keyword co-occurrence matrix, the strategic coordinate diagram, and the core-edge structure, we can perceive the relationship between the topic focus and research fields.

2.3. Keyword Frequency and Co-word Analysis

A word frequency analysis was performed to discover the most frequently occurring keywords through the dataset. High frequency keywords were selected for word co-occurrence analysis which strives to discover the relationship of key terms with each other through their association. A 16x16 keyword co-occurrence matrix was formed, and keywords occurring a frequency of 84 or above were included for analysis. This matrix was converted to a similarity matrix, which was converted into a dissimilarity matrix for purposes of enabling cluster analysis.

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2.4. Clustering and Strategic Mapping

Utilizing the COOC software, we performed a cluster analysis to classify keywords into topic clusters. The clusters were determined by the similarity of keywords, and the distance of the clusters were corrected to increase the intelligibility of the resulting dendrograms. The COOC software was then used to map the strategic coordinates creating a map that emphasized core and peripheral topics in the field. [9] Not only did this analysis graphically illustrate the relationships between various research topics, but it also exposed the emerging trends and voids.

2.5. Limitations

While the bibliometric analysis provides a robust overview of research trends, it is limited by the scope of the CNKI database, which focuses primarily on Chinese-language literature. Future studies should incorporate international databases to provide a more global perspective on the research landscape of virtual laboratories.[10]

3 Analysis of research results

3.1. Analysis of publication volume

The change in the number of publications can reflect the development status and different development stages of a field. The number of papers on data research virtual laboratories in the field of higher education in China is statistically analyzed by time distribution, and a line chart is drawn, as shown in Figure 1 below. As mentioned in the previous article, the "virtual laboratory" was formally proposed in the academic community in 1997, so the papers published after 1997 are comprehensively counted. As shown in Figure 1, the number of data research papers on virtual laboratories in the field of higher education in China in 1997 was 1. Further analysis of these documents shows that The paper mentioned more words such as "circuit", "computer-aided analysis", "virtual laboratory" and "software". The research object of this paper mainly introduces a "circuit analysis platform" software that can simulate and analyze analog and digital circuits. The software has a very good visual human-computer interface and ease of use. It can build a virtual circuit on the computer like doing experiments in the laboratory, and then close the virtual switch to turn on the power, observe the real-time display data and analysis results on the virtual instrument. It can be called an electronic circuit virtual laboratory on a personal computer and a powerful computer-aided analysis tool for electronic engineers. From 2000 to 2012, the number of papers published in the field of big data research in domestic higher education still grew slowly, but "simulation technology", "virtual reality", "virtual technology" and other research contents in the field of higher education have become important research contents in the field of higher education, laying the foundation for the start of data research. After 2012, the number of papers published on virtual laboratories in the field of domestic higher education began to grow rapidly and the increase was large. Virtual technology has received more and more attention in the field of higher education and has rapidly increased. It has become a research hotspot, with 836 papers published in 2019.

In the field of domestic higher education, the earliest academic annual conference that mentioned the concept of "virtual laboratory" can be traced back to 2002. In this year, the concept of "virtual laboratory" was

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clearly proposed for the first time at the "Sixth National Academic Annual Conference on Educational Technology" hosted by the China Educational Technology Association. The theme of the conference revolved around the innovation of information technology and teaching models, and discussed the application of information technology in education and teaching, including the development prospects of virtual laboratories in colleges and universities.

At the annual meeting, the following issues were discussed in detail:

1. Definition and practical application of virtual laboratories: Participants discussed the technical implementation forms of virtual laboratories, especially their possible applications in higher education, and emphasized their potential to provide experimental teaching in resource-constrained environments.[11]

2. The teaching value of virtual simulation technology: As an innovative teaching tool, virtual simulation technology can help students perform practical operations in a virtual environment, especially in disciplines such as engineering, physics and medicine that require a lot of experimental operations. Simulation technology is believed to improve students' hands-on ability and practical understanding.[12]

3. Sustainable development of virtual laboratories: The conference also discussed the construction cost, technical support and sustainability of virtual laboratories in future teaching, and emphasized its strategic significance as an important direction in education reform.[13]

In 2004, Chen Zhenqiu and Hu Dezhao published a paper entitled "Research Status and Development Trends of Virtual Laboratories" in "Audio-visual Education Research". As one of the earliest research papers in China to systematically explore virtual laboratories, this paper deeply analyzes the current status of virtual laboratories at home and abroad and looks forward to their future development trends. It lays a theoretical foundation for the research of virtual laboratories and promotes the development of subsequent technologies and innovations in educational applications. This document has been widely cited in China and has become a classic in the field of virtual laboratory research, especially in the fields of educational technology, information-based teaching and virtual simulation applications.

It has important reference value. This article concerns itself with the usage of virtual laboratories in higher education in China, and discusses how the use of virtual experimental technology can provide teaching supports when limited resources are available. The article has a strong local perspective and has a practical guiding significance to domestic researchers and practitioners. In addition to this the author, not only reviews the researches made up to that time concerning the virtual laboratories, but also forecasts their future development, discussing the in-depth application of the virtual experimental technology and the direction of the educational models in reform, thereby exhibiting an important reference and stimulus for future research.

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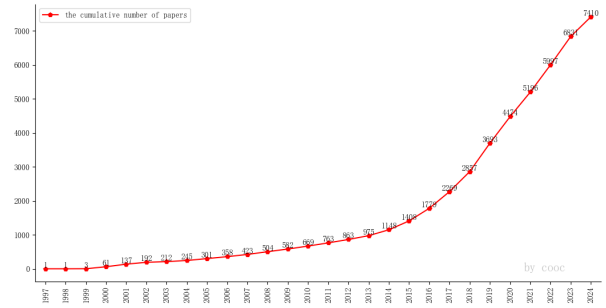


Figure 1 Changes in the number of domestic virtual laboratory research paper (1997–2023)

Figure 1 demonstrates the annual publication trends of the research work concerning virtual laboratories in the higher education system in China from 1997- 2023. The graph indicates important periods of growth, which should stand out prominently particularly after 2012, at which time the virtual laboratories were coming into regard as the scientific developments of the virtual simulation technologies began being epoch making assistances in connection with the educational reforms instituted by the Government of China. The marked peak of 836 publications in 2019 indicates an increase of research activity due to assistance both from the "Virtual Simulation Experiment Teaching 2.0" program and by virtue of its inherent worth via the increase of interest in the digital education. The slip in 2021 followed by the increase the following year indicates fluctuations.[14]

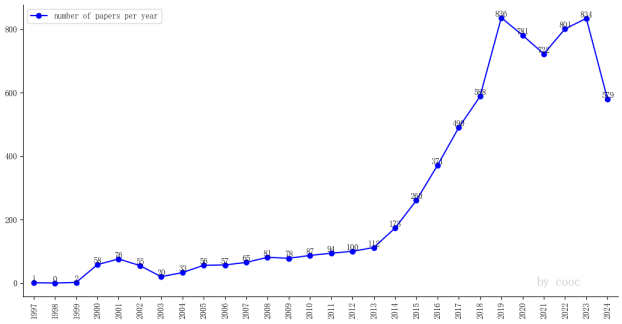


Figure 2 Cumulative number of papers on domestic virtual laboratory research

Figure 2 illustrates the cumulative number of publications produced in the field of virtual laboratories over time, which underscores the gradual growth in this important field of research. The cumulative curve exhibits a stepwise increase after 2012, which reflects the ever-increasing importance of virtual laboratories in the educational arena. By the year 2023, the cumulative total exceeded 7400 publications, which reflects the fact that virtual laboratory research has grown up to be an established and major field of study in higher education. This sustained increase highlights the expanding scope and depth of research, as well as the adoption of virtual laboratories as a key component in modernizing experimental teaching.

Figures 1 and 2 are statistical tables of articles published in the field of domestic virtual teaching from 1997 to 2024. As can be seen from Figures 1 and 2, the number of articles related to virtual laboratories in the field

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of domestic virtual teaching reached a peak in 2019, fluctuated in the following years, was the least in 2021, and began to increase again in 2022, indicating that relevant theoretical research has gradually matured, and the technology may be updated in the future and attract the attention of scholars again.

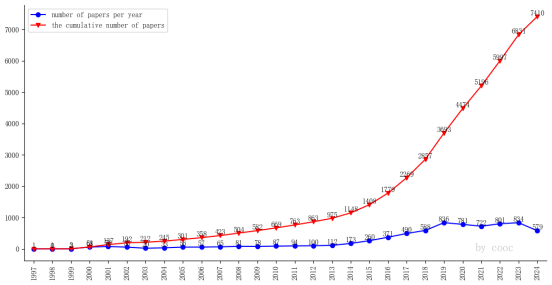


Figure 3 Comprehensive comparison chart

Figure 3 presents the most frequent keywords in virtual laboratory research within Chinese higher education. The keywords appear in decreasing order of frequency, and the more important keywords include "virtual simulation," "experimental teaching," and "virtual laboratory." These high-frequency words involve the central themes of the research and clearly indicate the overall theme of the study concentrating on the combination of virtual simulation technology in educational work.The presence of terms such as "teaching reform" and "practical teaching" underscores the broader educational context in which virtual laboratories are applied. This keyword analysis highlights the centrality of virtual laboratories to discussions of educational innovation and reform.[15]

3.2. Word frequency statistical analysis

Keywords are a direct reflection of the research content of the paper. The frequency statistics and co-word analysis of keywords can reflect the research topics of virtual laboratory research in the field of domestic higher education. Using COOC software to extract keywords and perform frequency statistics, 7411 papers on virtual laboratory research in the field of domestic higher education contain a total of 22080 keywords. Keywords with similar meanings or no practical meaning are merged and removed, and arranged in descending order of frequency. 16 high-frequency keywords are listed with a frequency of ≥84, as shown in Table 1. As can be seen from Table 1, practical teaching research in the field of domestic higher education has generated a series of keywords around "virtual laboratory", including "virtual simulation", "experimental teaching", "teaching mode", "virtual reality", "teaching", "virtual simulation technology", "virtual simulation experiment", "teaching reform", "practical teaching", etc. As an innovative platform for teaching and scientific research, virtual laboratories have brought many advantages, but they also face a series of challenges. These challenges mainly include: difficulties in technical implementation and maintenance, resource sharing and standardization, acceptance of students and teachers, cost and funding issues, teaching effect evaluation, authenticity and accuracy of virtual experiments, network security and data privacy, long-term sustainability, etc. The development of technology is promoting changes in the service mode and teaching method of virtual laboratories.[16]

The 16 high-frequency keywords in the study of virtual laboratories in the field of higher education in Chi-

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na were counted in pairs, and a 16*16 keyword co-occurrence matrix was constructed and converted into a similarity matrix. Due to the length and layout issues, the top 7 are listed as shown in Table 2. The values in the similarity matrix are between 0 and 1. The closer the value is to 1, the greater the similarity between the two keywords, and vice versa. In order to further reduce the error and better perform cluster analysis, strategic coordinate map analysis and keyword co-occurrence structure analysis, the similarity matrix is converted into a dissimilarity matrix, as shown in Table 3.

Table 1 High-frequency keywords in domestic higher education research papers on virtual laboratories

Keywords		Keywords		Keywords	
virtual simulation	3608	teaching reform	558	application	135
experimental teaching	1614	practical teaching	502	new engineering	124
virtual laboratory	919	teaching mode	171	simulation	117
virtual simulation technology	690	virtual reality	166	talent training	93
virtual simulation experiment	654	teaching	148	combination of virtual and real	84

Table 2 Similarity matrix of high-frequency keywords in domestic higher education field virtual laboratory research papers

	virtual simulation	experimental teaching	virtual laboratory	virtual simulation technology	virtual simulation experiment	teaching reform	practical teaching
virtual simulation	1	0.6838	0.0811	0.0984	0.0784	0.3752	0.4585
experimental teaching	0.6838	1	0.0281	0.0205	0.1094	0.2552	0.1244
virtual laboratory	0.0811	0.0281	1	0.1070	0.0952	0.0894	0.1076
virtual simulation technology	0.0984	0.0205	0.1070	1	0.0968	0.0287	0.0040
virtual simulation experiment	0.0784	0.1094	0.0952	0.0968	1	0.0173	0.1077
teaching reform	0.3752	0.2552	0.0895	0.0287	0.0173	1	0.1382
practical teaching	0.4585	0.1244	0.1076	0.0040	0.1077	0.1382	1

Table 3 Dissimilarity matrix of high-frequency keywords in domestic higher education virtual laboratory research papers

	virtual simulation	experimental teaching	virtual laboratory	virtual simulation technology	virtual simulation experiment	teaching reform	practical teaching
virtual simulation	1.1102	0.5839	0.9940	1	1	0.8301	0.7882
experimental teaching	0.5839	-2.2205	0.9138	0.9100	0.8715	0.8988	0.9944
virtual laboratory	0.9940	0.9138	-2.2205	0.9987	0.9987	0.9777	0.9809

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virtual simulation technology	1	0.9100	0.9987	1.1102	0.9970	0.9114	0.9133
virtual simulation experiment	1	0.8715	0.9987	0.9970	-2.2205	0.9239	0.9721
teaching reform	0.8301	0.8988	0.97766	0.9114	0.92385	-2.2205	0.9395
practical teaching	0.7882	0.9944	0.9809	0.91335	0.97208	0.9395	0

3.3. Cluster analysis

Clustering is the process of classifying data into different classes or clusters. Objects with great similarity will be clustered into the same cluster, and objects in different clusters have great dissimilarity. The high-frequency keyword dissimilarity matrix of domestic library and information field big data research papers was imported into COOC software, and cluster analysis was performed using similarity clustering. After re-adjusting the cluster distance, a clustering tree diagram was obtained, as shown in Figure 4. As can be seen from Figure 4, except for bibliometrics, theory and practice, and information literacy, which did not form obvious clusters.[17]

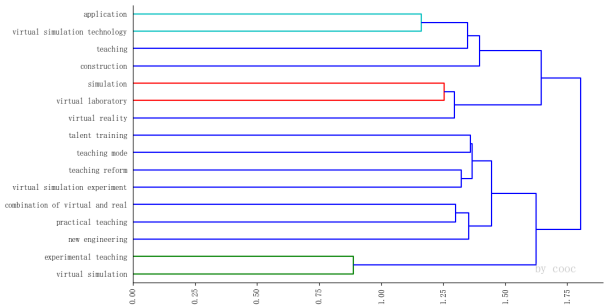


Figure 4 Similarity matrix cluster analysis of high-frequency keywords in domestic higher education research papers on virtual laboratories

As shown in the Figure 4, the co-occurrence network high-frequency keywords related to virtual laboratory. Nodes correspond to keywords, while the lines go back and forth according to the strength of the relationship (thick lines mean stronger co-occurrence). Keywords such as “virtual simulation,” “experimental teaching,” and “virtual reality” are at the core of the network, reflecting the main focus of the research area. The other keyword, such as "teaching mode" and "simulation technology," is peripheral and not co-occurring frequently, but they can still expand the application scope of virtual laboratory. The analysis of research Networks reveals the key research topics as well as the link between them, which may point the way to future research. [18]

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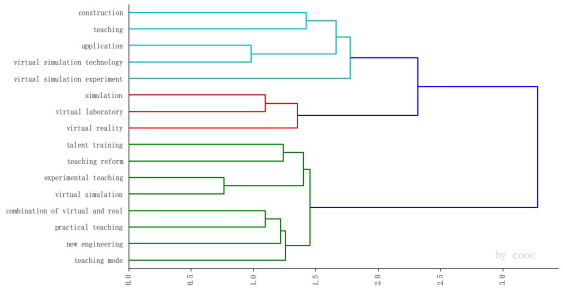


Figure 5 Cluster analysis of high-frequency keywords in domestic higher education virtual laboratory research papers

The clustering analysis results of high-frequency keywords in research of virtual Laboratories in domestic universities are shown in Figure 5. The clustering of relevant keywords is apparent in the tree structure and the closely clustered words indicate that the topics are closely related to each other. The clustering relationship in which "virtual simulation" and "experimental teaching" reflects that the two have close proximity in research, which shows the researchers' focus on the use of virtual simulation technology to enhance practical teaching. This cluster analysis provides a more identifiable structure of the research field by which we can investigate the distribution of virtual laboratory research, related topics with virtual labs, and their role in the overall research of virtual laboratories.

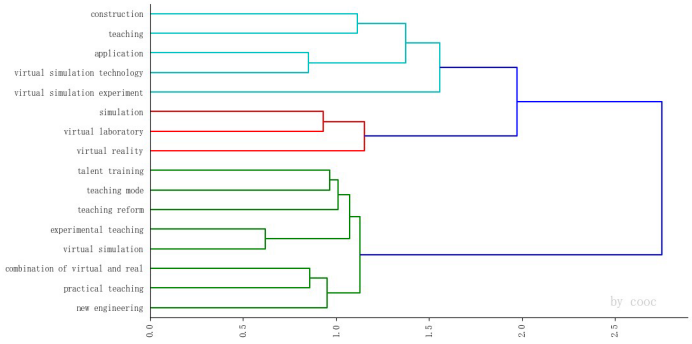


Figure 6 Cosine matrix cluster analysis of high-frequency keywords in domestic Higher education virtual laboratory research papers

Figure 6 shows the cosine matrix cluster analysis results of high-frequency keywords in the research of virtual laboratories in higher education, and the keywords are positioned in the two dimensions of centrality and density through the strategic coordinate diagram. Keywords in the upper right quadrant, such as "virtual simulation" and "teaching reform", usually represent mature and widely studied topics; while keywords in the lower left quadrant, such as "virtual reality" and "practical teaching", are mostly emerging or non-core research fields. This map helps to visually identify core and peripheral topics within the field, providing strategic insights into which areas are well-developed and which offer opportunities for future research and innovation.[19]

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3.4. High-frequency keyword co-occurrence network structure

The keyword co-occurrence network can reveal the degree of association between different keywords. The relationship is reflected by the number and thickness of lines. The more lines there are, the more co-occurrences there are between keywords, which reflects the concentration of the core and hot research content in this research field. The keyword co-occurrence network of virtual laboratory research in the field of domestic higher education constructed by COOC software (see Figure 7) shows that the core keywords include virtual simulation, experimental teaching, virtual laboratory, virtual simulation technology, virtual simulation experiment, teaching reform, practical teaching, teaching mode, virtual reality and teaching. [20] These high-frequency keywords have high word frequency and high density and centrality in their respective groups, indicating that the research in this field has become mature and stable. Despite this, there are still a large number of structural marginal keywords. Over time, these marginal keywords may gradually connect with the core keywords and become new research hotspots. By positioning the high-frequency keywords along the two axes of centrality and density (as shown in Figure 7), it can be observed that the keywords with high centrality and high density are located in the upper right quadrant, representing relatively mature and widely studied topics, such as "virtual simulation" and "teaching reform"; while the keywords in the lower left quadrant, such as "virtual reality" and "practical teaching", represent emerging or not yet core research fields. The map provides researchers with intuitive strategic insights, helping them identify which research areas are mature and which areas still have potential for further exploration and innovation.[21]

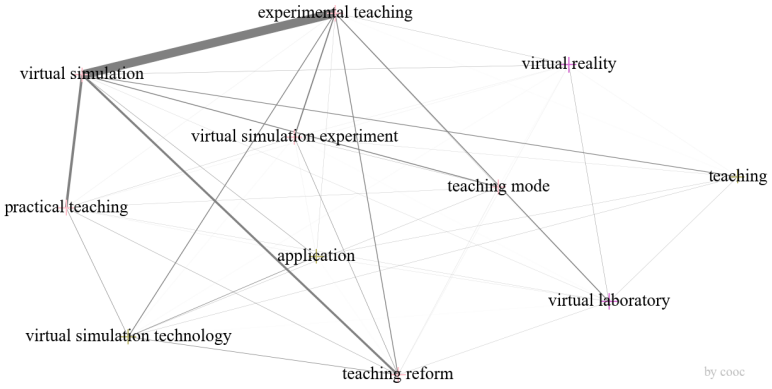


Figure 7 COOC high-frequency keyword co-occurrence knowledge graph

4.Analysis of research topics on virtual laboratories in the field of domestic higher education

In the field of domestic higher education, the research topic of virtual laboratories has become a hot topic in the fields of educational technology, digital teaching, and innovative experimental teaching[13] . Virtual laboratories use virtual simulation technology to simulate real-life experimental scenes and equipment, providing more flexible and economical teaching solutions, especially in situations where resources are limited or high-risk experiments cannot be carried out. The following is an analysis of the research topics of virtual laboratories in the field of domestic higher education.

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4.1. Definition and Function of Virtual Laboratory

4.1.1 Definition of Virtual Laboratory

A virtual laboratory is an experimental platform based on digital technology and network environment, which uses computer simulation, virtual reality (VR), augmented reality (AR) and cloud computing to simulate the real experimental environment. Users can perform experimental operations and scientific research in a virtual environment, replacing traditional physical laboratories. Virtual laboratories are highly interactive, flexible and remotely accessible, and can effectively solve the limitations of experimental equipment, space and safety, providing efficient, convenient and low-cost experimental experience.[22]

4.1.2 The role of virtual laboratories

Virtual laboratories promote teaching model reform in higher education, improve learning effects, and expand resource coverage [23] .

1. Improving students' practical ability.

Virtual laboratories provide students with opportunities for repeated operation and practical exercises, breaking away from the restrictions of time and apparatus in traditional experiments, and increasing the students' power to consolidate their acquisitions and solve problems .[24]

2. Reduction in cost and restrictions on resources

The simulation technology of virtual laboratories makes less dependence on the expensive apparatus and consumable articles encountered in practical work necessary, makes it easy to overcome restrictions in experimental quarters, and is particularly applicable to those colleges and schools where resources are limited .[25]

3. Personalised learning

Virtual laboratories trainer some, personalised experimental experiences according to their progress and interests in their studies, teachers being able to adapt the experimental work to the requirements of different students.[26]

4. Promotion of interdisciplinary co-operation.

Virtual laboratories with their multidisciplinary knowledge necessitate cooperation among the branches of learning and contribute to interdisciplinary novelty and provide the technical basis for experimental work in the fields of medicine, engineering, art and others .[25]

5. Teaching quality and efficiency

Virtual laboratories are in a position to offer possibilities for instant feedback, while they are in a position to enforce necessary changes in teaching in its data-based method, enabling teachers to record students' progress in experimental work, facilitate learning, and improve teaching methods).[27]

6. Improve educational equity and accessibility

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Through remote experiments, virtual laboratories provide fair learning opportunities for students in remote areas and those with scarce resources, reducing the impact of uneven educational resources.[23]

7. Ensure safety and environmental protection

Virtual laboratories eliminate safety hazards in high-risk experiments, while reducing the consumption of materials and energy, which has positive significance for environmental protection.[28]

4.2. Application of virtual simulation technology in teaching

This project uses virtual simulation technology to transform the traditional teaching method based on theoretical abstraction and textual explanation into a teaching model based on specific objects, autonomous operation and sensory experience. [29] Through diversified teaching methods such as questioning, task-driven, and discussion, it breaks through the limitations of "teaching knowledge", "observation construction", and "case analysis" in traditional teaching, greatly stimulates students' learning interest, reduces learning difficulty, and effectively improves learning efficiency.

1. Interactive teaching method: combining classroom teaching, physical observation and online learning to promote autonomous learning.

(1) Purpose: This project aims to combine offline course materials with online virtual experimental teaching to provide a teaching environment that is both real and virtual. By giving full play to the advantages of both, it breaks the limitations of "knowledge-dependent teaching" in traditional teaching and stimulates students' ability to think actively and explore independently . [30]

(2) Implementation process: Relying on this project platform, students can independently learn relevant course content online. [31]After entering the classroom, the teacher designed a series of knowledge questions around the course to form a "question-driven" teaching model, transforming the traditional "teacher explains, students listen" into an interactive model of "teacher asks, students answer". During the offline physical display stage, the teacher designed a "quick find physical object" game to guide students to match the material characteristics in the virtual project with the physical objects in the real world, thereby deepening their perception and memory of the materials.

(3) Implementation effect: This teaching method breaks through the limitations of time and space, provides complete, intuitive and vivid learning content, and makes the learning process more interesting and active through interactive teaching. Students can understand and remember knowledge more deeply, effectively reducing the difficulty of learning, and significantly improving class participation and learning effects.[32]

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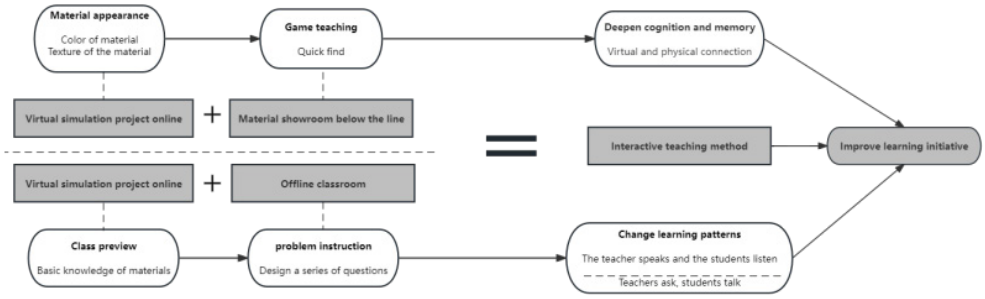


Figure 8 illustration of interactive teaching method

2. Adopt the teaching method of "observation promotes practice, competition promotes learning"

Through the interactive disassembly of material components in virtual projects, "operational learning" is achieved.

(1) Purpose: Give full play to the advantages of virtual display of material construction technology, break the limitation of "observation of construction" in traditional teaching, and improve students' hands-on practical ability.[33]

(2) Implementation process: With the help of virtual simulation projects, students can independently perform material construction operations after class. In addition, the "operation assessment" module in the project can be used for learning and testing. By constantly correcting errors in operation, students can gradually deepen their understanding of knowledge and master the material construction process. In class, teachers further strengthen students' practical skills and stimulate their interest in learning through the "operation proficiency" competition in material and process design.[34]

(3) Implementation effect: This teaching method enables students to repeatedly perform actual operations of the process flow, carry out practical operations while learning theoretical knowledge, reduce the abstractness of construction technology learning, and help students understand the teaching content faster and more accurately.

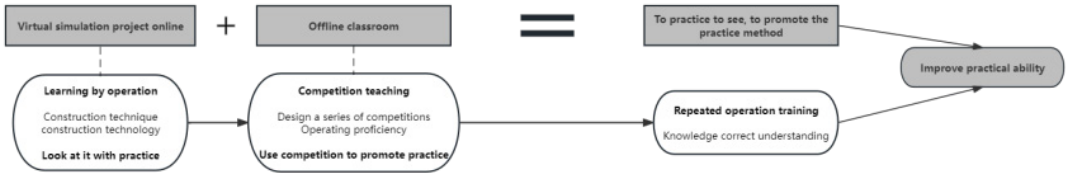


Figure 9 Schematic diagram of operational learning teaching method

3. Use case and task-driven teaching methods to achieve "experiential learning" through virtual space

(1) Purpose: Give full play to the advantages of virtual simulation in spatial perception and experience, break through the limitations of "case teaching" in traditional teaching, and improve students' ability to apply materials.[35]

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(2) Implementation process: The project constructed some classic or difficult-to-access spatial scenes, and quickly presented materials through virtual space to help students form emotional resonance in understanding design intentions, effect analysis and cultural connotations. The teacher issued a "design task" and students used their knowledge to complete the design of the virtual space. In the "scheme review" stage, through online student review, students can observe and learn from each other, learn from each other, and improve together. The "scheme review meeting" led by teachers and participated by students is conducted offline to provide targeted modifications and guidance.[36]

(3) Implementation effect: Task-driven learning helps students combine knowledge with specific situations and stimulate practical enthusiasm and creativity. Online review makes the design plan more intuitive and visible, and interactive assessment gives full play to the main role of students, enhancing the sense of participation and experience in learning.

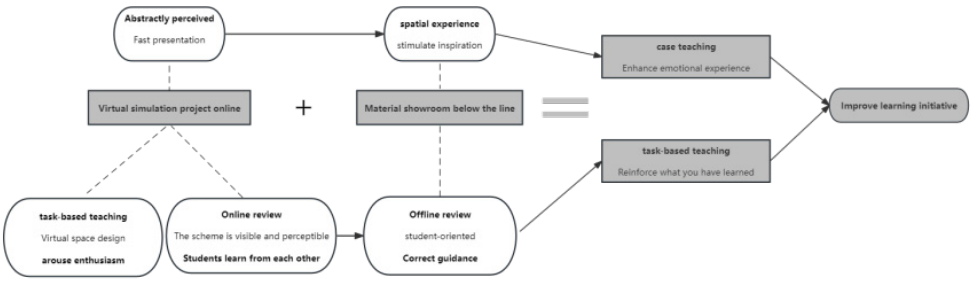


Figure 10 Schematic diagram of experiential learning teaching method

4.3. Technical innovation and trends of future development

1.The domain of virtual laboratories, is witnessing a fast paced technological revolution that is changing the face of education systems worldwide. Virtual laboratories are evolving as the new channels by which humans are able to complete their studies or skill training, and in this area of technology, there is still a lot of room for growth.[25]

2.Advancements in Tech: When it comes to enhancing the student experience through depth and engagement in the learning experience, AR and VR technologies can be game changers. These technologies make learning fun and engaging by developing immersive realities where students can practice experiments in realistic simulations or interact with sophisticated ideas in a safe virtual environment where no real tools are damaged or harmed. For instance, students can use AR to overlay virtual elements onto real surroundings to illustrate experiments, while VR can guide students through reconstructed virtual experimental areas.[37]

3.Using AI for Personalization: AI is used to personalize the virtual laboratory learning experience. AI can analyze students' learning data to give them tailored recommendations and adaptive learning paths to optimize their strengths and target their weaknesses. This makes learning more efficient since it is also more personalized, not only is it more beneficial to engage your students, it is also a better way to bridge learning gaps(if there are any).[38]

4.Cloud computing scalability: The growth of cloud computing paved the path for virtual laboratories to accommodate more users even from remote locations in parallel across different geographies. Cloud computing

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helps students afford laboratory resources after class at any time and any place which can compose a flexible learning environment and promote communication and learning in collaborative projects among students.[39]

5.More Attention to Interdisciplinary Integration: Future development of virtual laboratories will pay more attention to interdisciplinary integration, which will enable students to explore the connections among different research fields. In addition to advocating that students are taught to use their multidisciplinary knowledge to solve complex problems, this also promotes their holistic understanding and fosters the growth of critical thinking skills.[40]

6.It also requires constant updating of content and functions due to technology development. This requires the integration of modern advancements in science and pedagogy in order to reinforce and update educational material. Additionally, the advancement of intelligent systems designed for autonomous learning will further the efficiencies and capabilities of remote virtual labs.

7.Relevant To Industry Needs: Projected advancements of virtual labs will prioritize integration with the evolving social landscape and the demands of current industries . Educational partnerships with enterprises and research institutes can provide students with practical and problem-centered educational projects. This will enhance students' innovative problem-solving skills for the workplace and strengthen their employability. In conclusion, the flow of new technologies into virtual labs will reshape education. Incorporating sophisticated technologies, AI for personalization, and collaborative architectures in the cloud will vastly enhance virtual labs to keep pace with learning expectations of students and the demands of industries. In the coming years, virtual labs will be of greater importance in education as these technologies enable enhanced learning experiences.[25]

4.4. Use of virtual laboratories in different disciplines

In 2013, the Ministry of Education started to build national virtual simulation experimental teaching centers, and gradually promoted the application of virtual laboratories in various disciplines. By December 2023, 1,194 national virtual simulation experimental teaching centers had been established in 31 provinces, autonomous regions, and municipalities directly under the central government across the country. [41]The database integrates 12 disciplines education, namely philosophy, law, education, literature, history, science, engineering, economics, agriculture, medicine, management and art, a total of 2,649 virtual simulation experimental teaching projects.[14]

Among them, the number of virtual simulation courses in science and engineering disciplines is the most, which is 2076 courses; in agriculture, forestry and medicine, there are 661 virtual simulation courses; there are 812 humanities and social science courses. [43]Of course, the demand and requirements for virtual simulation experimental technology in science and engineering fields are higher than those in humanities and social sciences, which is closely related to the precision and complexity of experimental operations in science and engineering fields(Potkonjak et al., 2016).[41]

Moreover, the Ministry of Education pays great attention to the independent innovation and development of virtual simulation experiments in colleges and universities and has launched nearly 1,000 demonstration virtual simulation experiment teaching projects from 2017 to 2020(Gao & Zhu, 2023). [42]As of February

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2020, there were 255 and 41 virtual experiment simulation projects covering majors and professional categories respectively, and 1,561 associated courses, across the country.[23]

The virtual experiment has the advantage of providing students with more opportunities for experiments, also improving the quality of experimental teaching. And in Table 1, the test times of the iLab experimental platform were shown, while the data statistics of popular experimental projects was indicated in Figure 4. These data demonstrate that the input-output ratio of virtual laboratories is high and disciplines are covered with wide coverage, which fully reflects the important role of virtual experiments in promoting the teaching mode innovation.[44]

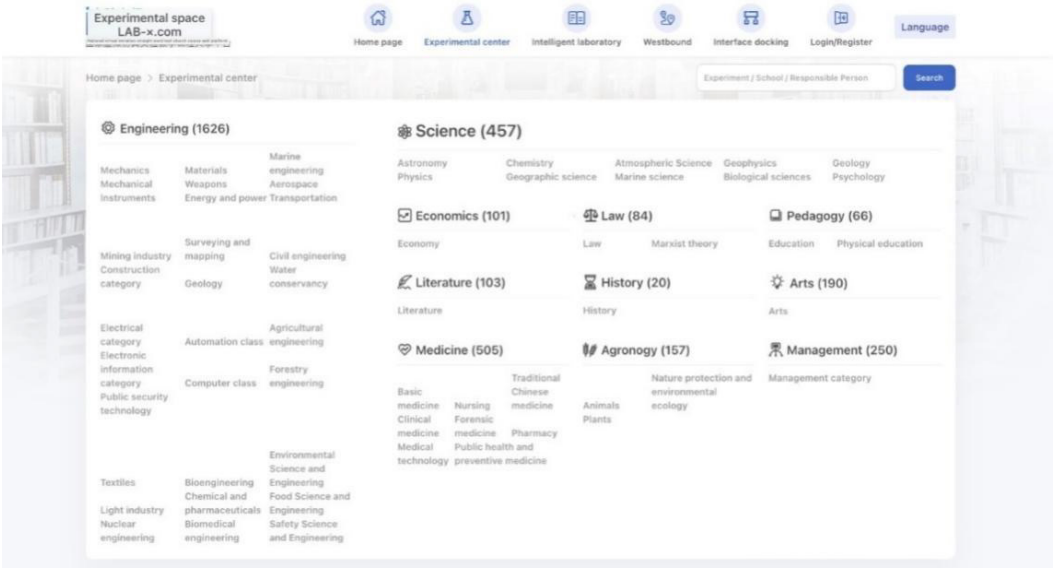


Figure 11 Test quantity of each specialty of iLab experimental platform

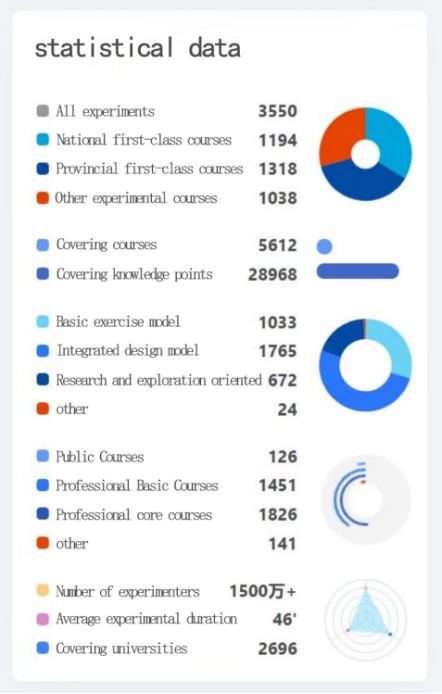


Figure 12 Statistical table of popular experimental data of iLab

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5.Future directions and practical significance

Cluster and network evidence converge on four priorities:

From simulation to immersion. Move beyond screen-based simulation toward VR-supported, high-presence tasks where procedural accuracy and decision-making can be assessed.

Personalization and analytics. Couple virtual labs with adaptive pathways and learning analytics to individualize difficulty, feedback timing, and remediation.[45]

Standards and evaluation. Develop shared rubrics for authenticity, safety surrogates, and transfer of training; institutionalize cost–benefit tracking.[46]

Interdisciplinary scaling. Extend proven patterns from engineering/science to design, healthcare, and the arts with discipline-specific scenarios and outcomes.The field has matured in adoption and vocabulary but remains poised for advances in immersive fidelity, assessment rigor, and equitable scaling across disciplines.[47]

6.Conclusion

By comprehensively grasping the research situation and future development trends, the field was able to gain insight into the condition of virtual laboratories in China. Results: Emerging research into the virtual laboratory technology highlights increasing contributions to the enhancement of experimental pedagogy within higher education. While diminishing persisting cost and accessibility issues within traditional laboratory settings, expanding technologies in virtual reality (VR) and cloud computing continue to transform the laboratory experience in education.[48]

Identifying gaps in knowledge and research, in particular, the seamless integration of new technologies, such as artificial intelligence (AI) in spawned personalized adaptive learning in virtual laboratories. [49]underscores the need to pursue research that focuses on optimizing virtual laboratories in digital education. Furthermore, the potential of virtual laboratories as a new educational tool can only be realized when designed within a framework of interdisciplinary teamwork.[24]

This reference shapes the way educators, virtual laboratories and educational technology developers, and policy makers can better leverage integrated virtual laboratories, improve educational quality, and promote new online educational practice structures. [25] In the interim, we anticipate the collaboration of academia and industry will uplift and strengthen the role of virtual laboratories, positioned to provide flexible, open, and attractive learning experiences and to cover the outlined gaps in this research. As educational innovations to digital transformation in higher education begin with virtual laboratories, this innovation will be pivotal to the change underlying the research in higher education.[50]

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