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EDITED BY
Fabrizio Consorti,
Sapienza University of Rome, Italy

REVIEWED BY
Wahyu Widada,
University of Bengkulu, Indonesia
Giuseppe Familiari,
Sapienza University of Rome, Italy

*CORRESPONDENCE
Nan Zhang
✉ nanzhang@nankai.edu.cn

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Design and implementation of virtual laboratories for higher education sustainability: a case study of Nankai University

Nan Zhang* and Yin Liu

School of Medicine, Nankai University, Tianjin, China

Laboratory learning has a vital role in science education. With the application of information technologies in educational domain, virtual experiment has become an effective supplement to traditional experimental teaching. Moreover, virtual experimentation can expand experimental field, enrich teaching content and reduce experimental risk, which provides strong support for the sustainable development of higher education. Using cutting-edge technologies such as virtual reality (VR), augmented reality (AR), computer simulation and interaction, we developed two public virtual laboratories and 41 virtual-simulation-experiment projects. They are integrated into an interactive learning environment, that is, virtual experiment learning management platform. The method is based on ADDIE (Analysis, Design, Development, Implementation, and Evaluation). In this paper, one virtual-simulation-experiment project is taken as a case study. The project includes 4 virtual practical activities mapped to the medical courses; and they were implemented in the third year of the bachelor's degree. The proposed virtual learning environment has been evaluated by learners for 2 years. The results achieved and similar findings from other studies, show that the use of virtual learning environment has a positive impact on the learning process and outcomes.

KEYWORDS

education technology, higher education, hands-on experiment, virtual experiment, virtual laboratory, learning platform, sustainable development

1 Introduction

W.A. Lay believed that only when the purpose of an experiment is to solve the problems of education, it is an experiment of pedagogy. Experimental resources should have educational objectives, characteristics, and its own norms. Therefore, laboratory experiments cannot be simply replaced by natural science experiments (Li et al., 2014).

Experiment is an effective educational model combining theory with practice. Learners can transform their knowledge and skills into problem-solving ability, and at the same time, they can further deepen their understanding of scientific concept. The reforms of experimental teaching are the important contents of carrying out "quality-oriented education," and improving the quality of higher education (Outline of National Medium-and Long-Term Education Reform and Development Plan, 2011-2020).

The serious imbalance of resource in different countries, regions or universities is directly related to the level of social and economic development. Good experimental conditions and high-quality resources are meaningful when they are used. Therefore, only by opening and sharing experimental learning resources can we continuously inject vitality and power into sustainable development (Gao, 2016).

In recent years, Internet of Things, virtual reality, cloud computing, big data, artificial intelligence and other information technologies are constantly emerging, which are profoundly changing the way we live, work and study. The 10-Year Development Plan of Educational Informatization (2011–2020) points out that in order to meet the requirements of rapid economic and social development for talent cultivation, universities are encouraged to explore new personalized, intelligent experimental teaching mode combining online and offline (Ji, 2012; The General Offices of the General Office of the Central Committee of the CPC and the State Council issued the Implementation Plan for Accelerating Education Modernization, 2018-2022).

Virtual experiment is an important measure to promote the integration of modern information technology into experimental teaching, expand the experimental content, extend the time and space of experimental teaching. Virtual experiment can reproduce the whole process of real experiment, overcome the constraints of traditional experiment, and become an important development direction of higher education in China (Gao et al., 2020; Yang et al., 2020; Dong et al., 2021) and the world (El Kharki et al., 2021; Li et al., 2022).

In particular, when the educational activities related to the epidemic situation in COVID-19 were affected, the potential of virtual experiment was paid attention to. In order to complete the syllabus, Chinese Ministry of Education requires to make full use of high-quality online course resource (Ting, 2020). While the theory classes were held online, the laboratory experiments were much more difficult due to the closure of universities. Virtual laboratories have appeared as an alternative to traditional laboratories.

Nankai University is national "Double First-class" "985 Project" university, and is the alma mater of Premier Zhou Enlai (Nankai University, n.d.). Since 2014, Nankai University has fully tapped all kinds of online experimental training and virtual platform resources. There are 2 national virtual experimental centers, 7 national excellent online open courses, 5 national virtual experimental projects and 6 provincial virtual experimental projects. During the pandemic, all resources opened to universities nationwide for free, covering 18 undergraduate disciplines, and provided online experimental support and teaching assessment (Gao and Han, 2018).

The purpose of this paper is to introduce the virtual laboratories and virtual-simulation-experiment projects, deployed by the virtual experiment learning management platform. It also introduces the techniques and tools for creating and developing virtual practical learning environment. Further, the virtual experiment platform was implemented for 2 years in medical course of bachelor's degree, and then evaluates whether the effect on students' learning process and outcomes has been improved in laboratory educational procedures.

The rest of this paper is organized as follows: Part 2 introduces the role of virtual experiments and laboratories in science education. Part 3 describes the adoption of the ADDIE methodology. Part 4 introduces a case study. Part 5 provides an overview of the learner's feedback. Finally, Part 6 is the conclusion.

2 Literature research

Traditional experimental techniques and means exist some problems that hard to overcome, such as high-risk, high-cost, high-consumption, serious pollution. There are also some unattainable or irreversible, large-scale comprehensive experiments that cannot be carried out, and some experimental projects are limited by time, place, material resources, financial resources, etc. Therefore, it is imperative to reform and innovate experimental teaching techniques and means (Tian et al., 2021; Yun et al., 2021; Wei et al., 2022).

With the development of information technology, virtual experiment has become an important means to enhance practical experience and improve learning quality, solved many problems existing in real laboratory activities. Virtual experiment is a large concept that covers many approaches and tools such as remote laboratories (Ouatik et al., 2017; Samuelsen and Graven, n.d.), virtual laboratories (Potkonjak et al., 2016), virtual and augmented reality (Cabero-Almenara et al., 2019; Calabuig-Moreno et al., 2020), gamification, and other technological tools.

At present, there are many examples of the application of virtual experiments and laboratories in different scientific disciplines, including physics, chemistry, biology, medicine, geology, and mathematics. El Kharki et al.'s study (El Kharki et al., 2020) in the development of virtual practical learning environment in Physics discussed many advantages compared with traditional practice. In Achuthan et al.'s study (Achuthan et al., 2018), using virtual laboratories as an interactive tool in chemistry classrooms enhances laboratory skills and concept learning. Whitworth et al.'s study (Whitworth et al., 2018) revealed in Biology labs with interactive computer simulations could be used to engage students in analytical, creative learning. Studies (Jia et al., 2020; Wei et al., 2022) revealed that the use of virtual simulation platform in Medical colleges could improve the effect of online experimental course, and promote the sharing of experimental teaching resources.

Virtual experiment has many advantages for learners, such as increasing flexibility, and effectively augmenting their participation and motivation, because learners can repeat the experiment at anytime and anywhere with unrestricted use of their computer and Internet connection (Heradio et al., 2016).

Further, they are likely to improve learning skills, attitudes and understanding of theoretical concepts. In different fields of science education, many studies show that the learning results of using a virtual laboratory are at least as good as those of traditional laboratories (Achuthan et al., 2018; Whitworth et al., 2018).

In addition, virtual laboratories have other benefits: they are cheaper because they do not need any materials or equipment, and they have less impact on the environment (Coenders et al., 2020). As well, virtual laboratories promote the opening and sharing of high-quality educational resources, expanding educational opportunities for more learners, and therefore the virtual laboratories is undoubtedly a means to support the sustainable development of universities (Salmerón-Manzano and Manzano-Agugliaro, 2018). Also, virtual laboratory is a very useful tool, which can ensure educational continuity of laboratory practices when learners can no longer enter the real laboratory (Gamage et al., 2020).

Virtual experiments focuses on solving the problems that the real experimental conditions are not available or the actual operation is difficult. During the COVID-19 pandemic, most college students adopted home online learning, while on-campus students suspended the arrangement of off-campus internship and training. The use of virtual experiment increased significantly, which has become an important development direction of higher education in China and the world (Badilla-Quintana and Sandoval-Henríquez, 2021; Leon et al., 2021).

Leon et al. (2021) presented the application of BIM virtual models for sustainable teaching environment in the context of COVID-19; students learned to collaborate and acquire skills to effectively deal with complicated real situation. Badilla-Quintana and Sandoval-Henríquez's (2021) study suggests that the virtual worlds developed during the epidemic should be used to innovate online and sustainable education.

3 Materials and methods

The application of virtual simulation technology in education is a new opportunity and challenge we are facing now. Building a virtual laboratory for teaching and learning is a highly complicated process, because experiments performed in traditional hands-on laboratories are not easy to transfer to the online environment. The design of the laboratory highlights the scientificness of virtual simulation, and the authenticity of time/space, involving the design of texts, images, experimental instruments and other specialized equipment. Instead of animation or film teaching mode in the past, several technologies are needed to express the behavior in the form of a computer, such as mathematical model/multiple algorithms, real-time rendering and three-dimensional intersection.

ADDIE (Cabedo et al., 1823) includes 5 steps has been used as an instructional design model for projects for many years.

3.1 Analysis

In the analysis phase of the work, experimental content is closely related to scientific problems, so that experimental teaching and scientific research can be integrated to produce innovative results. In addition, we explore the reform of virtual simulation technology on experimental teaching. Instead of animation or film teaching methods, new educational model can be realized based on multiple algorithms, real-time rendering and 3D interaction. What's more, combinations of virtual and hands-on laboratory activities, provide resource sharing and learning management, gradually set up a new teaching mode.

3.2 Design

For the development of virtual experiment platform, the architecture shown in Figure 1 was composed of five layers, and each layer provides services for its upper layer. Based on B/S, users can conduct remote experiments directly through the browser without using a specific operating system or installing a special client. The following will explain the specific functions of each layer.

(1) Data layer.

Here, experimental course library, standard answer library, rule library, and user information are set up, respectively, to realize the storage and management of corresponding data.

(2) Support layer.

It is responsible for the operation and maintenance of the whole system. It includes subsystems such as security, service container, resource monitoring, domain management, etc.

(3) Service layer.

That is, the open virtual experiment learning management platform provides general support components, include intelligent guidance, interactive communication, automatic correction of results, experimental report management, teaching effect evaluation, etc.

(4) Simulation layer.

It mainly carries out the equipment modeling, scene construction, virtual instrument. Tools include the Unity3D, 3D Studio Max, Maya, ZBrush, SketchUp, Adobe Flash, Unreal Development Kit, etc.

(5) Application layer.

Users with multiple terminals can access the server by browsers supporting WebGL (such as Chrome, Edge, Firefox, etc.) and complete remote virtual experiments independently.

3.3 Development

3.3.1 Public virtual laboratory

Two campuses of Nankai University have built virtual laboratory respectively, with area of 182 square meters. The lab can accommodate 36 people to attend classes at the same time (Figure 2). It provides functions such as teaching, scientific research, and display of virtual resources of different college. Furthermore, it supports VR-based laboratory safety, large-scale instrument training and other core curriculum for all students. At present, the laboratory has the functional modules of 3D arc large-screen interactive system, virtual simulation exploitation, VR interactive operating system, AR interactive display system, multi-person cooperative operating system, etc (Figure 3, Table 1). They cultivate students to use the virtual system by means of augmented reality, virtual reality, multi-person collaboration and immersion interaction.

3.3.2 Virtual-simulation-experiment projects

Aiming at different majors of Nankai University, the virtual experiment project is refined from solving the experimental problems and transforming scientific achievements. Every virtual experiment project will be carefully organized, mainly including simulation model design and scene presentation, experimental process and result analysis, experimental assessment and experimental report, R&D technical specifications, etc.

There are four versions of virtual experiment software, which can meet the needs of universities with different hardware levels, finally achieve better teaching effect at the lowest cost. They are 3D large-screen version, virtual reality version, PC version and mobile version (Figure 4).

Nankai University Virtual Experimental Project Platform[1] has established, it realizes the centralized management of virtual experimental projects in different departments. The content server is CentOS_7. 3 of Linux Server, the database is Oracle 11 g, and the Web service is Apache. The server of virtual project is Windows 2012 Server, the database is MS SQL Server 2012, and the Web service is IIS. The URL address of each virtual experiment project is unique. The platform is free to be used by people inside and outside the university, forming online sustainable operation mechanism.

1 https://ilab-x.nankai.edu.cn/

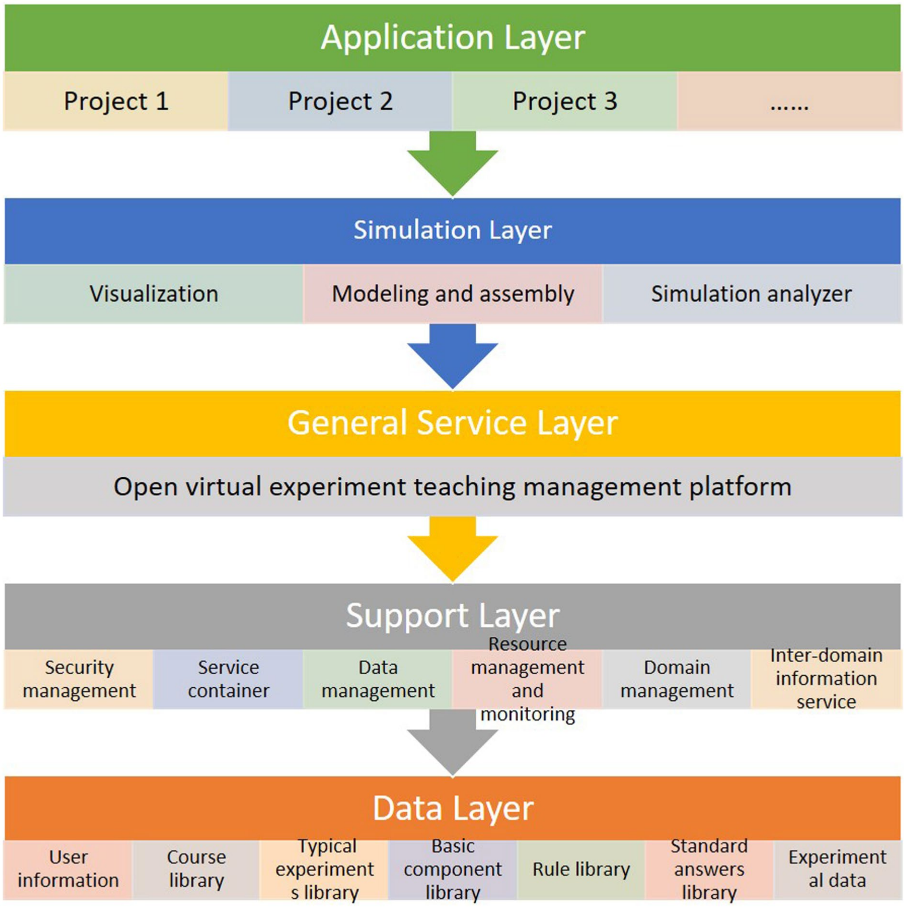


FIGURE 1
The architecture of virtual experiment platform.

Each project will present promotional video, seamless experimental jump, and detailed project description, including project team, network requirements, technical architecture, service plan, etc.

3.4 Implementation

Most colleges and universities use experimental teaching software for courses, but the working environment, programming language, developed methods, etc. are different. In view of the existing problems, it is necessary to build a virtual experiment learning management platform, which can support the recording, tracking, and reporting of laboratories, training plans, and online activities.

The platform provides a full range of virtual experiment teaching auxiliary functions as Figure 5: theoretical study before experiment, maintenance of typical experiment database, experimental teaching arrangement, intelligent guidance of experimental process, automatic correction of experimental results, statistical inquiry of experimental results, interactive communication between teachers and students.

At the same time, the platform has the function of data statistics and comparative analysis, the overall control of the experimental teaching process and effect can be realized, and the corresponding decision-making basis can be provided for managers.

The platform adopts Browser/Server(B/S) structure, connects with the school system through unified authentication, which is convenient for teachers and students to complete experimental tasks.

3.5 Evaluation

In order to verify the virtual learning environment, teachers and studens have carried out experiments and tests on the simulation functions and developed activities. Comments, feedback and suggestions were incorporated into the final version.

4 Case study: the virtual practical activity of microbiology

Medicine is a subject of scientific practice. Medical experiments consume a large number of animals, materials, drugs and reagents. Also, it is difficult to set up high-risk experiments such as biosafety, toxicity and radiation. Due to the limitations, medical students' hands-on practice is not sufficient, which often leads to the lack of clinical thinking and professional ability. The operations that are difficult to show in the real learning

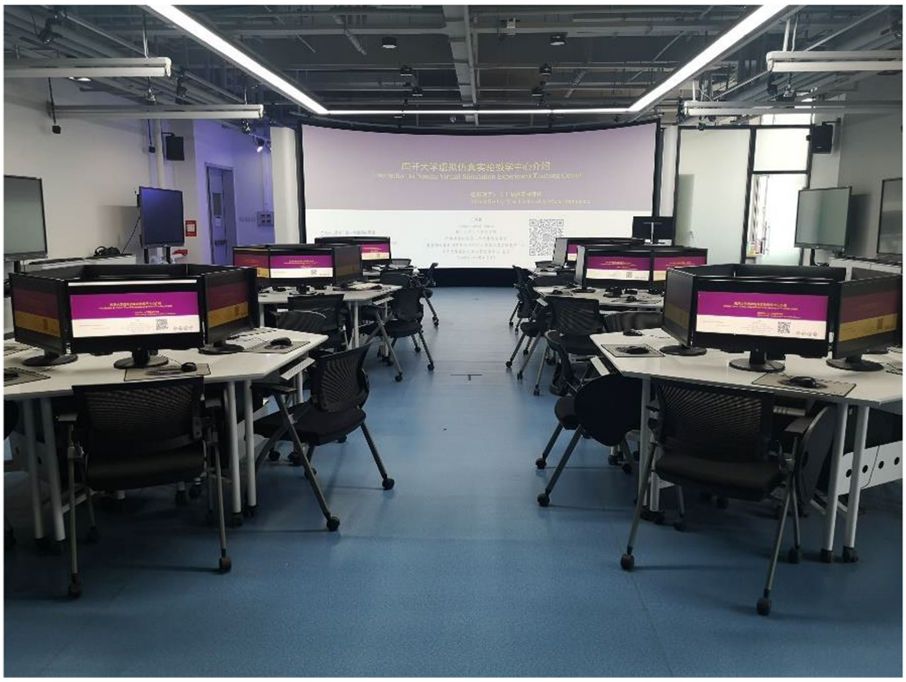


FIGURE 2
Nankai University Virtual Laboratory.

FIGURE 3
Functional diagram of virtual simulation public laboratory.

environment can be replace by the way of virtual simulation, so as to obtain the experiences and effects close to the real experiment. This case study presents the virtual experiment of pathogenic microbes detection in clinical samples developed by the medical college team.

4.1 Pathogenic microbes

At present, iatrogenic infection has become an important way to spread infectious disease. In recent years, more attention has been paid to preventing iatrogenic infections due to the emergence of superbugs, high prevalence of influenza, and highly transmissible pathogens such as SARS. Therefore, it is important to improve students' safety awareness of preventing iatrogenic infection, learning to detect pathogens in clinical samples under the condition of biological safety.

4.2 The virtual practical activity of microbiology

Based on the requirements of biosafety, experiments on infectious samples cannot be carried out in routine teaching

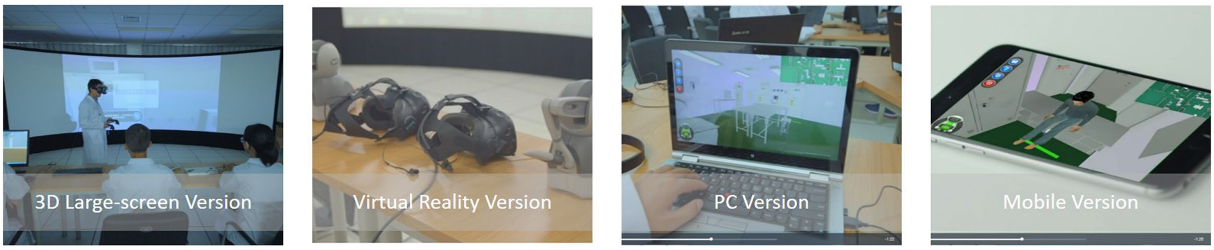


FIGURE 4
Four software versions of virtual-simulation-experiment project.

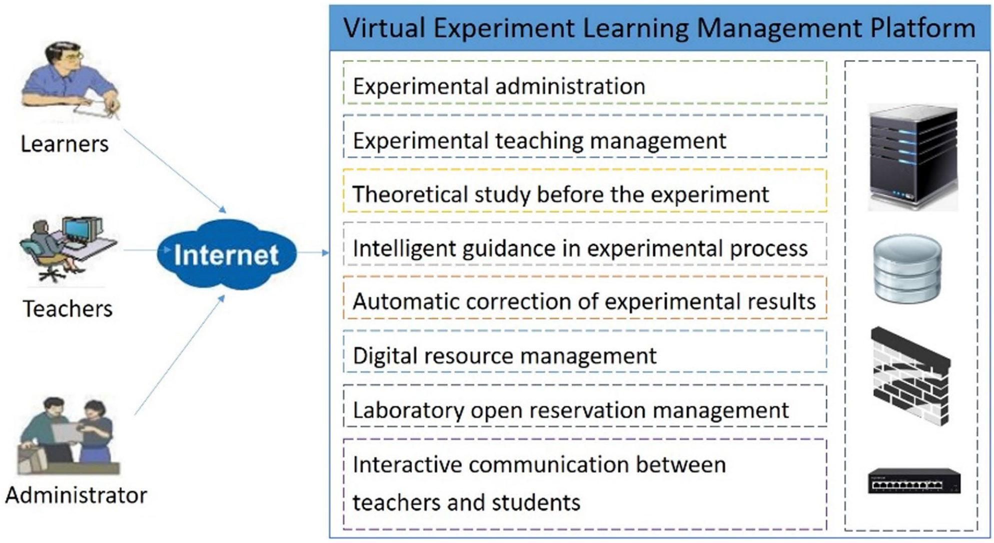


FIGURE 5
The architecture of virtual experiment learning management platform.

TABLE 1 Presentation of 5 functional modules of virtual simulation public laboratory.

Functional modules	Description
3D large-screen interactive system	It adopts 3D arc large-screen, equipped with two engineering projections with high lumen and resolution. It realizes multi-directional stereo display and interactive operation.
Virtual simulation exploitation	It supports 36 of 6 groups of students, equipped with graphic workstations, 3D automated modeling scanners and triaxial force feedback devices.
VR interactive operating system	VR headsets and other wearable devices allows the learner to fully immerse in the virtual world, greatly enhance interest and effect.
AR interactive display system	Holographic imaging technology shows the real and virtual information overlapped at the same time. Learners get closer to things that are inconvenient to touch at ordinary times.
Multi-person cooperation system	The system consists of 20 optical-motion-capture cameras, $100m^2$ free walking space, and supports wireless collaborative experiments for 8 people.

laboratories. The virtual simulation experiment project of pathogenic microbes detection in clinical samples can solve this contradiction well. They can learn about the protection of personnel and environment, the disposal of polluting samples. Through virtual experiments, learners choose samples and detection methods (morphological test, Isolation and Culture of bacteria, ELISA test and PCR test) according to patients' symptoms. After the experiment, negative or positive results are given according to the learners' choice, and then learners analyze and write experimental reports (Table 1).

The system randomly selects patients. According to the clinical symptoms of patients, the learners can infer what kind of pathogens may cause infectious diseases. The learners can also select one of the detection/test methods according to the pathogen. At present, four kinds of pathogens are preset in this project, corresponding to different clinical detection methods (Table 2).

TABLE 2 Presentation of 4 detection methods in clinical samples of pathogenic microbes.

	Clinical symptoms	Clinical samples	Detection method
1	Tuberculosis	Sputum	Morphological test
2	Cholera	Feces	Isolation Culture
3	Hepatitis B	Blood	ELISA
4	Dengue hemorrhagic fever	Blood	PCR

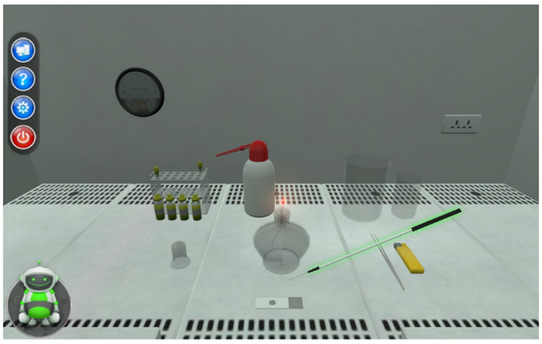


FIGURE 6
Experiment 1: Method of morphological detection of pathogenic microorganisms.

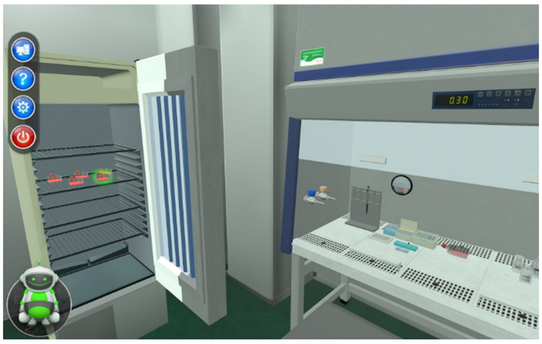


FIGURE 7
Experiment 2: Method for separating, culturing and detecting bacteria.

Morphological detection mainly uses dyeing and microscope technology to dye pathogenic microorganisms, and then observe their morphological characteristics. The commonly methods are Gram and antacid staining (Figure 6).

Bacterial isolated culture mainly selectively cultivates certain kinds of bacteria through their physiological features, so as to obtain the pure pathogen (Figure 7).

ELISA belongs to immunological detection method, and its basic principle is that the detected sample and enzyme-labeled antigen or antibody react on the surface of solid carrier, so it can be analyzed qualitatively or quantitatively according to the depth of color reaction (Figure 8).

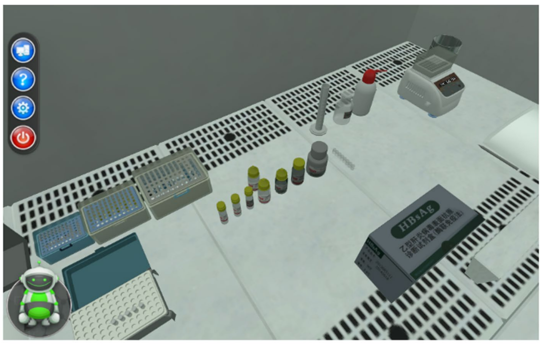


FIGURE 8
Experiment 3: Immunological detection method of pathogenic microorganisms.

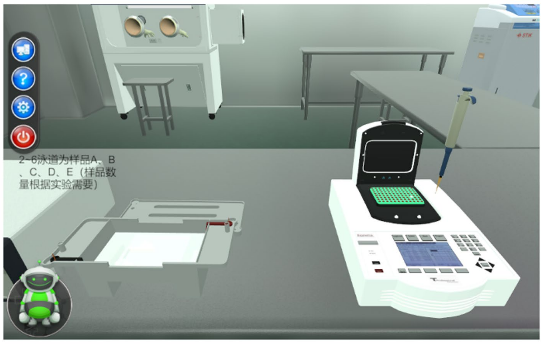


FIGURE 9
Experiment 4: Methods of molecular biology to detect pathogenic microorganisms.

PCR is to specifically amplify the pathogen nucleic acid fragments by designing primers for specific sequences on the genome, and then determine whether the samples contain pathogens by detecting the amplified products (Figure 9).

In the developed graphical interfaces, learners can use medical instruments including bio-safe cabinet, incubator, microscope, PCR, ELIASA. The learner can also display and use iodine, alcohol, distilled water, slide, cover glass, Elisa plate, and other experimental materials. The experimental principle of this experiment mainly includes 10 knowledge points and 25 corresponding steps, which require learners to complete more than 50 interactive operations.

4.3 The sequence of virtual practical activity

After passing the platform certification, the learner chooses from the 4 suggested practical activities. First, the learner refers to the theoretical course materials online through the platform, to understand the overall requirements and purposes of the experiment. The learner independently watches micro-lecture video of each activity, understand the experimental process, methods, and operation steps.

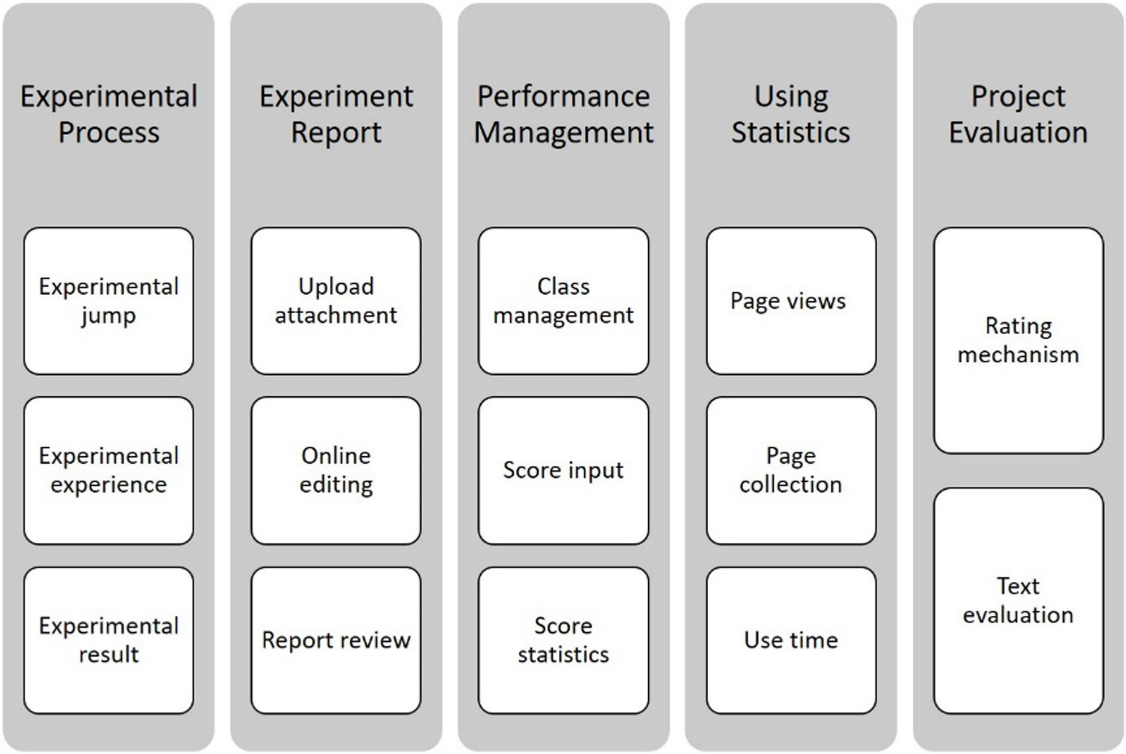


FIGURE 10
Monitoring of learner activities on the virtual experiment platform.

At class, the teacher briefly explains the principles and reminders involved, and demonstrates the virtual experiment process through 3D arc large-screen for the students. The student operates the experimental procedure through PC version software, also using VR equipment in turn to complete VR practice.

Finally, according to the results provided automatically by the system, the student judges whether the experiment is successful, and analyze the reasons. The student answers the guiding questions of the report and submit it to the teacher. After class, student can also make an appointment for VR practice at free time, repeat the experimental process, and do the operations skillfully.

4.4 The learner activities tracking

The platform provides a number of methods and reports to monitor the activities of learners (Figure 10). In the process of experiment, the effects and results of certain inputs are recorded in the simulation report, error correction tips can be given during learner's operation. With the experiment completed, the learner receives scores immediately and sends them on the platform.

If the learner cannot finish the experimental activities at one time, the platform can save the progress of the experiment so that the next time he can continue where he left off at the previous stage.

Furthermore, the statistical data of learners using the virtual laboratory on the platform, including click rate, number of experimenters, average experimental time, completion rate and passing rate, serves as a reference for project evaluation.

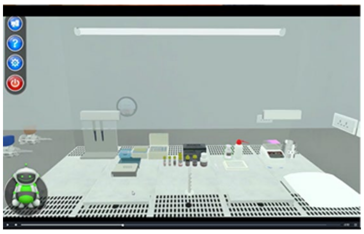
5 Results and discussion

5.1 The developed virtual experiment projects

Laboratory activities are an important pedagogical element in scientific disciplines, however, many experimental subjects cannot or are not easy to be carried out in traditional laboratories. Nankai University has implemented interactive scientific experiments and laboratories in many fields of science education, which are integrated into a suitable online learning environment. The adoption of virtual learning environment provides learners with the opportunity to carry out virtual practice activities, which can simulate the processes and behavior similar to actual experiments.

Around the practical courses of different subjects, 41 virtual-simulation-experiment projects have been carried out, and can be accessed through educational platform (see text footnote 1). They have independent intellectual property rights, covering 18 disciplines of literature, science and engineering. These are mainly provided for undergraduates in 12 colleges of Nankai University. Among them, it was selected into 5 national first-class projects and 6 provincial first-class projects, Table 3, Table 4 present a summary of these practical activities produced. Unlike other virtual laboratories that only use a mouse as an interactive means, virtual-simulation-experiment projects are equipped with interactive devices of many kinds such as headset and touch gloves, thus learners can acquire more perceptual dimensions in virtual experiments. In addition, there are self-designed and innovative experiments in virtual-

TABLE 3 Presentation of National first-class virtual-simulation-experiment projects.

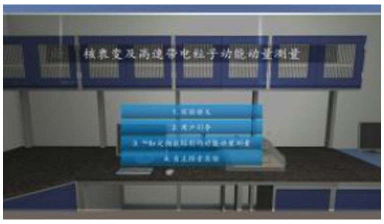
	Title of virtual experiment project	Discipline categories
	Waste incineration power generation resource utilization technology	Environmental Science and Engineering
	Secondary metabolites of scarce medicinal plants	Plant
	Poetry recitation in Chinese poetry Teaching	Literature
	Pathological diagnosis of renal biopsy specimen	Basic medicine
	Clinical pathogenic microorganism detection in samples	Clinical medicine

simulation-experiment projects, which provide several experimental modules, various tools and materials, learners may be able to explore freely, get different experimental results, and even make new discoveries. Moreover, virtual experiment is developing towards a large-scale and systematic direction. It is no longer an independent experiment content, but can be embedded in specialized experimental course system, which is related to many experiments and knowledge points in the curriculum.

Practical laboratory experience is often seen as an opportunity for learners to obtain a positive attitude toward science, helping them understand the theoretical topics taught in class, and enabling them to develop practical skills and abilities (Kukulska-Hulme et al., 2020). Traditional hand-on laboratories provide physical infrastructure, scientific equipment and material; but may always face location, scheduling, and other economic and environmental issues (Tian et al., 2021; Yun et al., 2021; Wei et al., 2022). Virtual experiments and laboratories have become an alternative to the weakness of traditional laboratories, and they are considered as an appropriate approach for training learners by offering views and working methods similar to real practical experience (Wästberg et al., 2019). Nowadays, virtual laboratories are becoming mainstream in colleges and universities all over the world (Gao et al., 2020).

At present, there are many virtual laboratories applied to many fields of science education, such as physics. Chemistry, biology, medicine and so on (Achuthan et al., 2018; Whitworth et al., 2018; El Kharki et al., 2020). The use of virtual laboratories as proved to be as an effective tool to expand the teaching methods and enhance the learning experiences. As the experiments provide online access, learners can choose when, how and where to study through a computer and Internet connection (Hoosen et al., 2016), in addition to increasing educational opportunities for more learners (Paredes-Labra et al., 2018; Zajko and Hojnik, 2018). As well, there is no need for materials or equipment, and they have little impact on the environment, so the virtual laboratory is undoubtedly a means to support the sustainable development of universities (Salmerón-Manzano and Manzano-Agugliaro, 2018).

TABLE 4 Presentation of Provincial first-class virtual-simulation-experiment projects.

	Title of virtual experiment project	Discipline categories
	Intelligent internet of things for fire fighting	Electronic information
	UAV cooperative intelligent task planning	Automation
	Porcelain making technology and identification in Song and Yuan Ming kilns	History
	Measurement of kinetic energy and momentum of nuclear decay and high-speed charged particles	Physics
	Cross-domain laser timing virtual experiment project	Electronic information
	Design experiment of emission trading auction mechanism	Economy

However, not all real laboratories can be simulated or replicated on the computer, and not all practical skills can be obtained through virtual experiments (Salmerón-Manzano and Manzano-Agugliaro, 2018). They are still regarded as important chance for learners to practice their inquiry and science skills, cannot be completely replaced by virtual experiments (Brinson, 2015). Nevertheless, many studies in different fields of education show that using virtual laboratory can achieve the same learning effect as traditional hands-on laboratories (Achuthan et al., 2018; Wästberg et al., 2019), especially when real experiments are not available or difficult to complete.

5.2 Results on the learning process

The evaluation of the online virtual learning environment can be carried out from two aspects: learning process and learning outcomes. The former mainly evaluates whether the online simulations and the platform resources help to improve students' interests, self-learning ability, and knowledge understanding. The latter mainly evaluates whether helps to improve students' academic performance.

In this study, the experiments were carried out in the first semesters of 2021 and 2022, and the subjects were junior students of grade 2019 and 2020 majoring in stomatology and clinical medicine at medical college. After the completion of the virtual laboratory of microbiology, we used a survey tool to gather information about practice process in the new learning environment. The questions included are designed to collect the learners' ideas and satisfaction with virtual laboratory activities on the platform.

The questionnaire was designed by a five-point Likert scale, ranging from "strongly disagree"" disagree" "neither agree nor disagree" to "agree" "strongly agree." Each level in the scale has a numerical value, starting from 1 (strongly disagree), increased by one for each level, to arrive at 5 (strongly agree). Students can choose one of the five levels for each question. There were 56 dental students and 277 clinical students (Table 5), Table 6 shows the opinions received from 333 learners who participated in the survey.

Generally speaking, Table 6 reveals that the newly proposed learning environment for virtual practice activities has been positively evaluated by students. From each question, the students' average scores for the platform and virtual experiments are all greater than or equal to 4 points. For all questions, the majority of students choose 4 or 5 points, more than 76% people answered "agree" "strongly agree." In addition, about 3% students answered "disagree" "strongly disagree"; This can be proved by the fact that only 4 virtual practice activities are not enough, and they do not cover all the content of the curriculum.

TABLE 5 Number of students in the survey in grades of clinical medicine and stomatology.

	2018	2019	2020
Stomatology	31	26	30
Clinical medicine	88	156	121

In addition, the internal consistency of the data is assessed using Cronbach's alpha calculations, considering a Cronbach's alpha value higher than 0.70 as significant as far as the good internal consistency of the questionnaire was concerned. The Cronbach's alpha value of this scale is 0.977 > 0.9, which shows that the reliability of this scale is excellent.

Figure 11 shows learners' overall satisfaction with the platform; a good percentage 94% of students said that the platform was very satisfactory. As well, about 4.8% said "Less satisfactory," and 1.2% said "Not at all satisfactory."

Most of the students gave positive comments on the effectiveness and practicability of the virtual practical activities provided by the platform. They liked the proposed learning environment and feel involved in their active learning process, which improves their

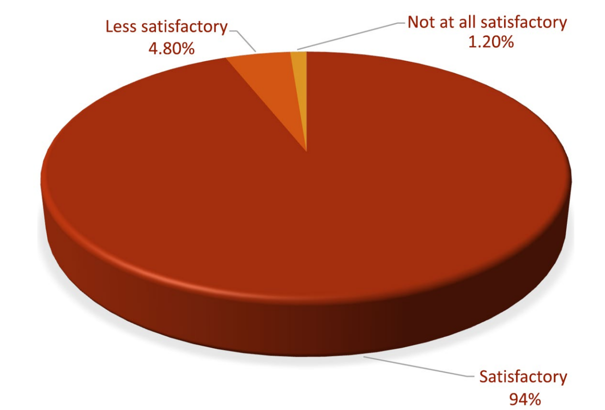


FIGURE 11
Learners' overall satisfaction with the virtual practice working platform.

TABLE 6 Students' opinions about the platform and the activities of virtual laboratory developed.

	Mean	95% Confidence interval for mean		Std. Deviation	Mode
		Lower bound	Upper bound		
Can it be helpful to master the experimental principles and skills through the platform?	4.19	4.02	4.35	0.759	4
Can we cultivate biosafety awareness and strengthen biosafety protection skills through the platform?	4.17	4.01	4.34	0.770	5
Can the platform improve the experimental operation ability and solve the problems in the physical experiment?	3.98	3.79	4.17	0.881	5
Can the virtual simulation experiment improve the ability of analyzing and solving problems in the experiment?	3.90	3.67	4.12	1.029	5
Can the experiment be completed independently through virtual simulation experiment?	3.70	3.47	3.93	1.064	3
Compared with traditional experimental teaching, can virtual simulation experiment improve the efficiency?	4.37	4.22	4.52	0.704	4
Can you be more interested in the experimental class and improve your learning enthusiasm through the platform?	4.27	4.10	4.43	0.773	4
It is necessary to extend the virtual simulation experiment to other experimental teaching.	4.27	4.07	4.46	0.913	4

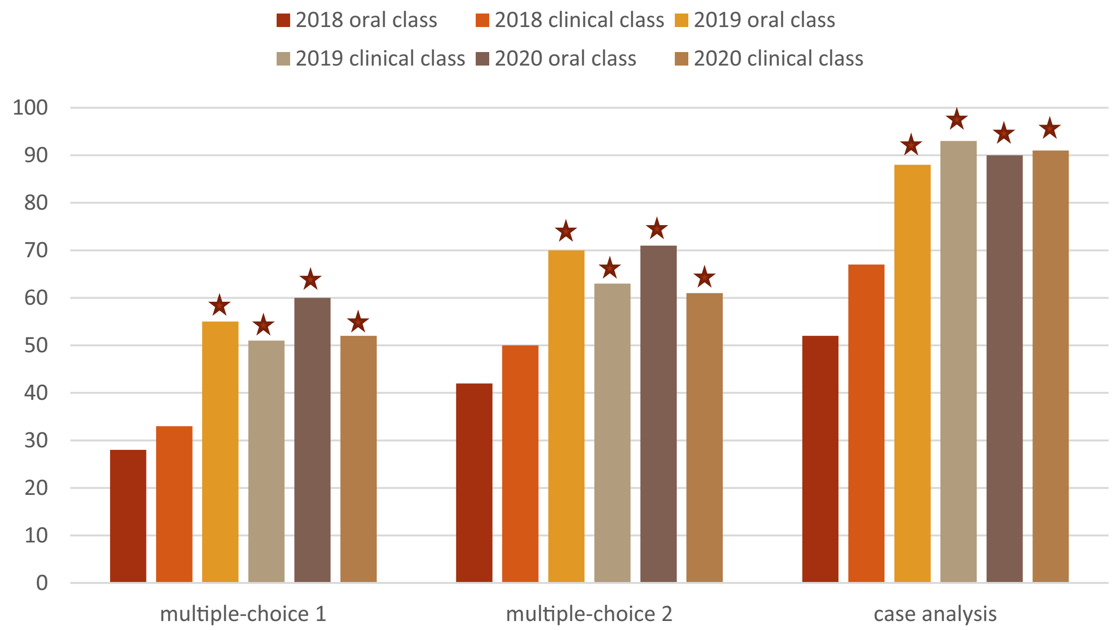


FIGURE 12
Score rate of students comparing experimental group and control group.

learning quality (Diwakar et al., 2015). In addition, more than 90% of students asked to add additional virtual activities on the platform to cover all chapters of the curriculum.

Learners prefer to conduct experiments in virtual laboratories rather than real laboratories, as it is easier to understand and implement with the help of advanced software. Moreover, virtual labs can help learners become more actively participated in learning, which can improve their academic performance as a result (Diwakar et al., 2015).

In another question, students are invited to make suggestions on promoting practical online learning environment.

◇ Enriching the experimental content;
◇ Improving the fluency and compatibility of the software;
◇ Appropriately increasing the class hours of virtual simulation experiments.

In fact, we will continue to improve the virtual laboratory in the future based on the given suggestions.

5.3 Impact on learning outcomes

We take the oral and clinical classes in 2019 and 2020 as the experimental group and the oral and clinical classes in 2018 as the control group. We designed three questions related to the experimental content in the theoretical examination at the end of classes. As can be seen from Figure 12, the score rate of the experimental group was significantly higher than that of the control group.

Due to the contribution to improved academic performance, the creation of virtual learning environments can serve as a solution for maintaining laboratory activities. Learners prefer to do experiments in virtual laboratories, which is easier to understand and implement. Facts have proved that the use of online virtual laboratory activities is beneficial to learners' skills, knowledge and problem-solving abilities.

It is also important to note that the virtual laboratory could be used as a supplement to higher education institutions or as a pre-laboratory exercise. Studies from Zacharia and Michael (2016), Wang and Tseng (2018), and Kapici et al. (2019) show that he combination of virtual laboratory and real laboratories is more effective than using one experimental method alone. The reason is that learners have acquired some practical skills and experience/ability in virtual experiments, which can be further strengthened in hand-on experiments.

5.4 Achievements and application

Reform effect. After 9 years of teaching reform, satisfactory results have been achieved. All the resources of virtual experiment course and teaching services are free to universities and social learners. By October 2022, the platform has reached over 10,200 users and 16,000 online experiments, with 93% completion rate and 71.5% passing rate of experiments. We have successfully won the support of 11 national teaching reform projects, including the national first-class undergraduate courses.

Promotion effect. The virtual laboratory has received numerous visitors from universities, enterprises and institutions all over the country, including more than 20 universities such as Xi 'an Jiaotong University, Harbin Institute of Technology, Renmin University of China, Sun Yat-sen University, Shanghai International Studies University. Enterprises and institutions include Huawei, Tianjin Radio and Television Station, Tianjin Stomatological Hospital, etc. The annual number of visitors has reached 600.

6 Conclusion

Experimental teaching is very important for science education, however, traditional laboratory have some problems in the teaching-learning procedures. This paper presented the development of virtual experiments which cannot be done due to the limitation of laboratory conditions. Virtual experiment uses computer simulation to illustrate practical laboratory activities and can be operated via the web.

In this paper, we adopted an instructional design model ADDIE as the main method. This paper also introduces the techniques and tools used to develop virtual learning environment: Virtual laboratory with VR and AR equipment was used to create immersive and interactive practical environment; virtual experiment projects of various subjects provided learners highly simulated operating objects and experience, and the virtual experiment learning management platform was used for hosting and deployment all the digital resources that supported management, tracking and reporting of online experiment activities.

Forty-one virtual-simulation-experiment projects were developed, they cover 18 disciplinary fields (engineering, science, literature, medicine, etc.) in 14 colleges of Nankai University. One of these projects was tested by learners taking microbiology course in medical college. In this project, information technology and intelligent technology is used to create virtual environment with vision, hearing and touch, so that the learner can enter an interactive three-dimension clinical laboratory. Virtual experimentation can keep up with the trend of medical development, overcoming the gap between theory and clinical learning. Moreover, it is helpful for medical education to cultivate the clinical thinking and has a unique practical role in experimental teaching. For 2 years, undergraduates of two majors conducted 4 virtual experiment activities in the project, opening up a new learning perspective that traditional laboratories cannot fully explore.

In a word, the learners gave a positive evaluation on the effectiveness and practicability of the virtual experiment; in addition, learners like the experience of virtual laboratory, because it improved their perception of theory, enhanced their practical skills, and increased their problem-solving ability. On the other hand, the developed virtual learning environment has been proved to improve learners' interest and motivation, and raise the efficiency of teaching and learning.

Due to the weakness of traditional laboratories, virtual experiments have emerged as a model of online-learning with a bright future for higher education. At the same time, a few studies have proved virtual laboratories can ensure that the learning effect is as good as that of the traditional hands-on laboratories. Furthermore, they are also powerful tools to realize the sustainability of higher education.

Finally, the general framework is proposed, which provided a software and hardware platform for virtual simulation experiments of many scientific and technical courses. We are working on the development of more quantitative virtual activities as a complement to the theoretical courses, gradually forming a new virtual experimental learning mode.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

NZ: Writing – original draft. YL: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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