Reform of Environmental Microbiology Laboratory: Innovation and Practice under Limited Resources

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Abstract: Environmental microbiology laboratory instruction is a core practical course that supports the three main career directions in wastewater, waste gas, and solid waste treatment and disposal. However, in many universities, this course is plagued by a number of persistent problems, including limited hardware resources, an overemphasis on confirmatory experiments, inadequate cultivation of students' comprehensive abilities, and a rigid one-dimensional evaluation system. To solve these issues, this paper takes Chengdu Technological University as a case study. The proposed reform restructures the experimental teaching content around a foundational plus inquiry-based framework, integrates virtual and actual teaching methods, transforms the instructional setting by leveraging research teams and an undergraduate mentorship system, and introduces a diversified, process-oriented evaluation system. These measures effectively resolve the tension between resource constraints and the quality of student development. Practical results demonstrate that the reform significantly enhances students' active participation and overall competence, and thus offers a useful reference for experimental teaching reforms at similar institutions.

Keywords: Environmental Microbiology; Experimental Teaching Reform; Limited Resources; Inquiry-based Experiments; Multiple-Criteria Asessment

1. Introduction

With the introduction of a series of policies such as the "Dual Carbon" strategy and the "Ecological Civilization Construction" initiative, numerous industries in China have been continuously exploring and advancing along the path of green development and transformation [1]. They have achieved a range of accomplishments. Environmental Science and Engineering is a key discipline that underpins green transformation and development. The demands of the industry have in turn forced reforms in the talent cultivation plans and objectives of higher education institutions [2]. Many universities are no longer confining themselves to traditional pollution control technologies. Instead, they aim to cultivate practical, interdisciplinary, and innovative talents capable of solving complex environmental problems [3]. This developmental direction requires students to possess stronger hands-on practical skills and systematic thinking abilities.

Environmental microbiology laboratory is a core foundational course for the Environmental Science and Engineering major. It serves as the practical extension of the theoretical course "Environmental Microbiology" and also forms the basis for the three subsequent specialized courses in wastewater, waste gas, and solid waste treatment [4]. Student' mastery of professional skills in this laboratory course directly affects their ability to design and operate key processes for low-cost, high-efficiency pollutant removal and resource recovery in real scenarios.

Chengdu Technological University is a university jointly established by the Sichuan Provincial Department of Education and the Sichuan Provincial Commission of Economy and Information Technology, and has defined its institutional positioning as "local, application-oriented, and open". Taking the core foundational course in the Environmental Science and Engineering program as an example, which is a Sichuan Provincial First-Class Discipline at Chengdu Technological University, this paper explores reforms in the teaching model of environmental microbiology laboratory courses. Given limited experimental

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equipment and resources, these reforms address the challenges of water pollution control and resource recovery, aiming to cultivate students' practical abilities and innovative thinking. At the same time, this study provides a reference for experimental teaching reforms at similar institutions and supports local universities in cultivating engineering and technical talent in areas such as wastewater treatment and ecological restoration.

2. Analysis of the Current State of Instruction and Prominent Issues

The Environmental Microbiology Laboratory course at Chengdu Technological University has been in operation for nine years. Through classroom observations, faculty discussions, and research visits, we have continuously monitored and reflected on the teaching process and identified the following prominent issues.

2.1 Limited Hardware Resources Hinder the Development of Practical Skills

Currently, Chengdu Technological University has one Environmental Science and Engineering Laboratory equipped with 10 analytical balances, 3 autoclaves, and 8 optical microscopes. Assuming three students per group, the lab can accommodate 20–30 students conducting experiments simultaneously. However, there are currently nearly 400 students enrolled in the Environmental Science and Engineering program across the college, all of them need to conduct laboratory experiments simultaneously for courses such as Instrumental Analysis, College Chemistry, and Water Pollution Control Engineering. Furthermore, the university typically organizes laboratory sessions in concentrated lab weeks, meaning that for most courses, laboratory instruction takes place during Weeks 18–19, with experiments conducted on a weekly basis. Consequently, the limited hardware resources available within a short timeframe constrain students' hands-on skills. Furthermore, like other universities, some instruments lack professional maintenance during use, or students operate them improperly, further reduce the number of available experimental equipment sets. The university's limited funding makes it difficult to support one-on-one independent hands-on training for every student in the classroom. Peer communication is promoted under the group-based teaching model. However, the practical opportunities are unbalanced for everyone. Some students will be inclined to free-ride, obtaining good grades without active involvement. This kind of behavior will also have the side effect of lowering the overall hands-on competence of the student body.

2.2 Outdated and Unchallenging Experimental Content

Environmental microbiology courses ask students to learn simple practical skills. These include the following: culture medium preparation, sterilization, inoculation, streak plating, microscope operation, etc. For this reasons, previous teaching contents are mainly basic and confirmatory experiments [5]. Instructional videos for these basic laboratory skills are important and useful supplements in any biology classroom, and are strongly recommended to students' learning in biologic sciences. These operations are widely available online. However, few of these videos are high quality, specifically aimed, and/ or well adapted to the local teaching environment and platforms. Students relying solely upon video-based learning are prone to a disconnection between visual familiarity and hands-on competence. They may understand the procedure in theory, but fail to do. When they are asked to perform for the actual manipulations, it is hard to argue that foundational experiments can usually offer enough experimental equipment and time for hands-on practice, with instructors offering guidance during the turning points, so students can acquire the corresponding skills by hard practice. These skills serve as a prerequisite for conducting design-based and comprehensive experimental instruction. However, with foundational experiments accounting for over 80% of the 22 teaching hours, students' practical work remains superficial. Besides, their thinking lacks depth, which is detrimental to the cultivation of innovative thinking and problem-solving abilities.

2.3 Lack of Critical Thinking Training and Disconnect from Job Requirements

Today, when faced with questions posed by teachers, students have developed a strong inclination to use artificial intelligence tools to help them solve problems. Typically, in class, when a teacher asks a question, students will send the question to AI software such as

Doubao or DeepSeek, convert the AI-generated results into their own words to answer, and the feedback on classroom interaction is relatively positive. However, when students are asked to apply their learned knowledge to explain existing phenomena, they often show low engagement and low response rates. For example, when a teacher asked about the nutritional composition and functions of two types of solid culture media described in the lab manual (composed of different proportions of beef extract, peptone, sodium chloride, and agar), or inquired about possible reasons why the solid culture medium prepared by the previous group had failed to solidify, students hesitated to respond. The root cause lies in the fact that, throughout the entire teaching process, students lack training in systematic thinking. Specifically, the process of identifying problems, analyzing problems, and solving problems trained insufficiently. All questions must be posed by the teacher, rather than students identifying problems on their own based on observed phenomena during practical exercises, considering potential causes, and determining how to avoid them in subsequent procedures. This results in students being unable to analyze real-world problems from a theoretical perspective during future internships or work, and they struggle to identify critical technical steps. Overall, they exhibit poor ability to apply knowledge, and thus provide employers with the impression that they are poor in expertise, no clear thinking, and poor communication skills.

2.4 Limited Assessment Methods and Insufficient Formative Assessment

There are same pattern by surveying different universities. Most institutions take records of attendance and final experimental reports. Instructors are the unique evaluators in this system. In this model, some critical aspects of students' performances are ignored. These are in-lab engagement, collaborating writings, following the standard operating procedures, and creating thinking. Given the large amount of group assignments, instructors have limited time to guide individually. They are not available to monitor each students' online activity. Therefore, instructors need an assistant to help them track students' in-class progress and assignments. Consequently, some students who operate weakly get higher grades by coping from others [6], which lead to most students discouraged, especially for that work hard in practice. They feel less motivated to learn as a result. However, they are hesitant to tell these incidents directly to the instructor, because their reluctance stems from concern about embarrassing their peers.

3. Specific Measures for Teaching Reform

There are practical teaching challenges in Environmental microbiology laboratory. The teaching team has implemented systematic reform measures. The reform addresses four key dimensions. These include course content, teaching methods, laboratory facilities, and evaluation approaches.

3.1 Restructuring of Course Content: A Dual-Track Approach Combining Foundations and Inquiry

The teaching team reviewed the existing course content carefully. They also drew on the curriculum reform experience of Shihezi University. Based on this review, they divided the content into two major sections. These are foundational experimental modules and inquiry-based experimental modules [7].

The foundational laboratory modules were designed to preserve and refine core basic skills training. This design enables students to master general skills in environmental microbiology. Through curriculum reorganization, the teaching team identified five key general skills. These include the classification and preparation of culture media. They also include proper operation of autoclaves. Another skill is inoculation and cultivation techniques for activated sludge. The Gram staining method for bacteria is also included. Finally, students need to understand and use optical microscopes. These skills correspond to various instructional components. They cover experimental preparation, safety protocols, core procedures, observation and identification, and practical application. Through mastering these skills, students become able to prepare sterile media. They can isolate and culture target microorganisms. They can classify and identify bacteria. They basically cover the entire process from pre-experiment preparation to post-experiment analysis, avoiding the low-level repetitive training. This allows students to spend more time improving their design and analytical skills in the subsequent inquiry-based experiments rather than worry about whether they performed the basic procedures correctly. At the same time, surveys and visits to employers such as environmental protection companies, wastewater treatment plants, and environmental monitoring stations have revealed that these skills are essential for entry-level technical positions. During the daily operation of wastewater treatment plants, operators need to observe and identify microbial species in activated sludge regularly by using optical microscopes, for example, the presence of rotifers shows that the treatment plant is operating effectively [8]. Environmental monitoring departments need to carry out testing for fecal coliforms, which requires skills in the preparation and sterilization of culture media [9]. Therefore, mastering foundational laboratory skills can shorten the adjustment period for students when they later enter related fields of work and lay the groundwork for scientific research training, thereby reflecting the orientation toward cultivating applied talent. The experimental topics for the inquiry-based laboratory module are directly derived from the teaching team's research projects. Currently, the teaching team is focused on the research areas of bioremediation technologies and resource recovery, and has developed experimental teaching content such as "The Effects of Environmental Factors on Cyanobacterial Growth and Physiological Characteristics" and "The Effects of Various Factors (pH, DO, Temperature) on Activated Sludge Settling Performance and Microbial Colony Morphology." Typically, students work in groups. The instructor provides the experimental materials and, early in the process, assigns tasks through the Wisdom Tree platform, encouraging students to visit the laboratory on their own to familiarize themselves with the available equipment and reagents. Based on this, students independently design and conceptualize the experimental objectives and protocols. They are required to complete the corresponding experiments, data collection, and data organization within two days according to their designed experimental plan. The preliminary design proposals must undergo joint review by an AI evaluation system and the teaching team before they can be implemented. Taking "The Effects of Environmental Factors on Cyanobacterial Growth and Physiological Characteristics" as an example, instructors post assignments on the Wisdom Tree platform, requiring each group of 5–6 students to independently design an experimental protocol focusing on "the effects of environmental factors (temperature, pH, light, nutrients, etc.) on cyanobacterial growth." Before the experiment begins, students visit the Environmental Science and Engineering Laboratory to familiarize themselves with available equipment—including light-controlled incubators, spectrophotometers, microscopes, and pH meters—as well as experimental reagents such as BG11 medium, cyanobacterial cultures, and pH adjusters, in preparation for designing their protocols. The teams conducted literature reviews and group discussions. They found out the effects of some influential factors and their corresponding degree. These factors were pH 5.0, 7.0, 9.0 and a control group. In addition, the indices of cyanobacteria's growth ability were also recognized. These indices were OD680 and chlorophyll a content. Then, they worked out certain operating procedures and divided the work among people. This distribution enabled them to finish the experiment in two days. Each group submitted their preliminary plan to the Wisdom Tree website. The website used an artificial intelligence system to assess the plan. The evaluation included several aspects such as the comprehensiveness, scientific accuracy, practicability and safety. The system also gave comments on the plan. The experiment could be carried out only after the class team had given the final approval. The experimental procedure consisted of several stages. Firstly, the students prepared the culture medium with different pH values. Secondly, they added the same quantity of algal culture into the medium. Thirdly, they put the cultures in a light-controlled incubator. Fourthly, they took samples every four hours to detect OD680, pH and chlorophyll a content. Fifthly, they disinfected and disposed of the leftover algal solutions. Lastly, they cleaned all the instruments. After finishing the experiment, each group summarized their data. Then, they made Power Point presentations to report. They showed their research results and discussed the important points. The teacher and students from other groups asked questions. Furthermore, they made on-site assessments. During the process, some groups chose other influential factors like light intensity and nutrient salts and did parallel experiments. Therefore, during the presentation, the students learnt from each other. They gained a clear idea about the factors which influenced the growth of cyanobacteria. By means of this method, the course obtained remarkable teaching achievements with a small amount of resource investment.

3.2 Innovation in Teaching Methods: Integrating Virtual Simulation with Hands-On Training

To address the practical challenges of insufficient equipment during the foundational training phase—which made it difficult to support “one-on-one” hands-on training for students—the teaching team established a teaching model that combines comprehensive online learning with efficient offline practical training to significantly improve students' hands-on training efficiency. First, the teaching team developed digital instructional resources. Grounded in the course content, these resources consist of high-quality video materials—collected and curated from public websites—that are highly relevant to the experiments and feature clear explanations. Additionally, while guiding students through experiments, the team independently filmed and recorded a series of highly targeted videos covering topics such as standard operating procedures for optical microscopes, as well as the classification and preparation of culture media. These videos specifically address common issues that have arisen during experiments conducted by students in previous cohorts, such as how to select culture media, how to determine inoculation methods, and which steps are prone to introducing contamination. This text explicitly deals with the problems that students often encounter in their work. By doing so, it makes the content more interesting for the students. It is more efficient than merely explaining the right methods. The teaching staff have put these electronic materials on the Wisdom Tree website. The students can study them many times before the class. Virtual simulation-based experimental instruction serves to supplement the shortcomings of traditional laboratory teaching. It is also an integral part of contemporary higher education informatization [10]. The teaching team adopted this approach following the example of other universities. Students can complete basic procedures entirely online. These procedures include identifying microscope components. They also include performing virtual inoculation and simulating culture medium preparation. Virtual simulation is not intended to replace digital videos. Instead, it serves as a key tool for assessing the effectiveness of video-based learning. By practicing hands-on in the virtual environment, students work through the procedures. They memorize common pitfalls during this process. This practice reduces the error rate when students conduct experiments directly in the laboratory. This approach breaks down the constraints of time and space, enabling students to develop a clear understanding of the procedures before entering the laboratory. Consequently, it significantly reduces the time spent on basic instruction during in-person experiments, improves laboratory efficiency and students' ability to get up to speed quickly, and frees up more class time for inquiry-based experiments.

3.3 Reform of Teaching Facilities: Leveraging Research Teams and the Undergraduate Mentoring System

To address the issues of limited laboratory capacity and insufficient student engagement resulting from centralized scheduling, the teaching team developed two types of solutions. First, they formed interdisciplinary teaching teams. Through preliminary research, faculty members within the college whose primary research areas are environmental microbiology and environmental ecology were integrated into a core teaching team. Priority was given to identifying sub-projects within faculty research topics that could serve as innovation and entrepreneurship training projects for undergraduates. Students were encouraged to apply for national, provincial, and university-level innovation and entrepreneurship training projects based on these sub-projects. Upon project approval, students could engage in one year of effective research training. Projects were carried out in faculty laboratories under faculty supervision, and the resulting outcomes could be submitted to academic competitions, thereby enhancing students' comprehensive practical skills. On the other hand, to provide comprehensive guidance to students, the college was the first in the university to implement the “Undergraduate Mentor System.” Modeled after graduate education, this system assigns students to academic advisors upon entering their major in their freshman year to guide their academic and personal development. It allows students from freshman through senior year to join faculty research groups, fostering a mentorship model where upperclassmen guide underclassmen. This has largely enabled junior students to mentor sophomores in specific experimental procedures. The faculty team has transformed established research projects into formal experimental teaching programs. The online reservation system provides regular access to laboratory sessions. Scheduling has shifted from a centralized to a decentralized model, which has boosted lab utilization and eased resource strain. Each session requires the presence of at least one faculty advisor or lab instructor to safeguard students.

The laboratory sessions are now available through the online reservation system. This system has been modified from centralized control to individual booking. The new method has improved the utilization of laboratories and reduced the burden on resources. A teacher or laboratory instructor should be present during each session to ensure the safety of the students.

3.4 Restructuring the Teaching Evaluation System: Multi-Stakeholder and Full-Process Assessment

As stated before, the evaluations given by one stakeholder are not sufficient to accurately represent the true teaching results. After investigation, the teaching group has classified the evaluation standards into five aspects: research training and academic contests (5%), online resource study (15%), writing laboratory reports (30%), practical laboratory skill examination (30%) and group presentations and defences (20%). The achievements accomplished by the students in the innovation and entrepreneurship training programs can also be considered in the course evaluation, and the pre-class learning records can be automatically recorded through the Wisdom Tree system. The evaluation framework incorporates AI-powered assessment, instructor evaluation, and peer evaluation. AI-powered assessment is used to collect data on students' online learning activities, providing quantifiable baseline data. The writing of lab reports is primarily evaluated by instructors. During peer evaluations of experimental procedures and group presentations, students may assign comprehensive scores based on the standardization of others' procedures, the soundness of their experimental designs, the logical coherence of their presentations, and their performance during on-site defense. Students may not evaluate their own work or that of others presenting on the same topic. The faculty team evaluates simultaneously with the students, and the final grade is composed of 50% faculty evaluation and 50% peer evaluation. Throughout the assessment process, instructors should focus on three key areas: whether students can proactively identify issues worth further investigation during the experiment; whether they can reasonably interpret and analyze the recorded experimental data; and whether they can communicate effectively and divide tasks appropriately within the team. These three dimensions align precisely with the learning objectives of this teaching reform—namely, the cultivation of the abilities to identify, analyze, and solve problems.

4. Results and Reflections on the Teaching Reform

The teaching team has completed a full cycle of instruction based on the new teaching reform plan, and the reform has yielded preliminary results. In terms of students' practical skills, the use of carefully selected instructional videos, step-by-step guides for common problems, and the introduction of virtual simulation experiments have significantly reduced the error rate in students' practical operations. At the same time, thanks to our college's undergraduate mentorship program—which was the first of its kind implemented university-wide—we have secured funding for over 40 innovation and entrepreneurship training projects annually, ranking first in the entire university. Students have the opportunity, starting from their freshman year, to work alongside upperclassmen in research groups under the professional guidance of faculty mentors. As a result, the standardization of students' practical assessments has improved by more than 30%. Furthermore, classroom observations and extracurricular discussions have revealed that students are particularly interested in inquiry-based experiments; they believe such designs provide them with greater room for creativity and have come to understand the important role of environmental microorganisms in pollution control and resource recovery. Compared to the previously rather dull classroom environment, the new teaching approach—which incorporates student group presentations—has enabled a comprehensive and systematic review of the entire experimental design process, with a strong emphasis on the key modules of problem identification, analysis, and resolution. Overall, students' logical thinking and communication skills have improved significantly, and their research literacy and comprehensive abilities have steadily increased. Through the exploration of an appointment-based access system and the sharing of research laboratories, the average equipment usage time has increased, effectively alleviating the resource bottlenecks caused by fixed class schedules and improving the efficiency of limited resources.

Of course, a number of challenges were also identified during the implementation of this round of reforms. Inquiry-based experiments stress individual planning and thinking. Each group carries out its own experiment. When the groups perform experiments at the same time, some problems occur. The students may gather around the equipment stations and form a queue. Moreover, different groups have varying abilities in operating the equipment. These difficulties intensify the restrictions on the resource utilization. Thus, when checking the experimental designs of each group, the teachers should take into account several aspects. These aspects are the availability of instruments and the abilities of the students. Therefore, it is more difficult to prepare the lessons and organize the class. Whereas in previous verification-based experiments the entire class proceeded in unison, the introduction of inquiry-based experiments requires teachers to respond promptly and individually to each group's experimental plans, progress, and specific questions, significantly increasing the pressure on teachers to manage the classroom. Furthermore, students have reported that the early stages of class cover too much material and consume excessive time; they suggest distinguishing between required and optional content to allow for student autonomy. Additionally, some images on the virtual simulation platform differ from the laboratory equipment used on campus, requiring some time for students to adapt when transitioning from the online to the in-person phase. Overall, this round of reforms has achieved preliminary success, but further optimization is needed in areas such as experimental workflow design, classroom management and coordination, tiered learning content, and the adaptability of tools and platforms.

5. Conclusion

Addressing issues such as limited teaching resources in university laboratories and students' relatively weak practical skills, this paper takes the environmental microbiology laboratory instruction at Chengdu Technological University as a case study. By restructuring the two categories of instructional content like "fundamental experiments" and "inquiry-based experiments", and adopting a blended "online + offline" approach that integrates virtual and physical learning, the paper leverages the undergraduate mentorship system pioneered by our college. Through the scheduled use of research and teaching laboratory facilities, a diversified formative assessment system has been established that encompasses research training, academic competitions, online learning, lab reports, practical assessments, and group presentations, and by incorporating diverse evaluation sources such as AI-powered assessment, instructor evaluation, and peer evaluation. This approach has largely resolved issues such as students' weak practical skills, insufficient critical thinking training, and lack of innovative and comprehensive practical abilities. All of which were constrained by limited resources. Students' adherence to operational standards, sense of belonging to their discipline, and proactive learning attitudes have significantly improved, while their logical thinking and communication skills have been effectively honed, laying a solid foundation for their future employment. The insights gained from this reform initiative can serve as a reference for experimental teaching reforms at similar institutions of higher education.

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