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Starting from the "Micro": Innovating Microbiology Laboratory Teaching to Cultivate Innovative Talents

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Abstract

This article focuses on the reform of microbiology laboratory teaching and the cultivation of innovative talents. It analyzes the limitations of traditional teaching methods in terms of mode, content, resources, and faculty, proposing a reform philosophy centered on students, strengthening innovation capacity building, and emphasizing interdisciplinary integration. It innovates teaching content by optimizing basic experiments, expanding comprehensive experiments, and conducting research-based experiments. Teaching methods are improved through project-based learning, information technology tools, and heuristic/inquiry-based teaching, while a diversified process-oriented evaluation system is constructed. Practical cases from a university demonstrate significant post-reform improvements in student lab report quality, participation in innovation projects, and scientific research capabilities. The article also analyzes challenges faced in reform—resources, faculty, student disparities, and evaluation implementation—offering targeted solutions. Finally, it envisions the future integration of teaching with cutting-edge technologies and industry needs, alongside personalized and intelligent development directions, providing references for the construction of microbiology laboratory courses in universities.

Keywords: Microbiology Laboratory; Teaching Reform; Cultivation of Innovative Talents; Project-Based Learning; Diversified Evaluation.

1. Introduction

In the current context of rapid life sciences development, microbiology, as a core foundational discipline, has laboratory teaching that serves not only as a crucial vehicle for applying theoretical knowledge but also as an important platform for cultivating students' scientific thinking, practical abilities, and innovative literacy (Qin *et al.*, 2025). With the advancement of "Emerging Engineering Education" and "New Agricultural Science" initiatives, societal demand for innovative talents possessing interdisciplinary perspectives and the ability to solve complex practical problems is becoming increasingly urgent (Ju *et al.*, 2024). However, traditional microbiology laboratory teaching models are increasingly revealing limitations—a teaching inertia that emphasizes verification over inquiry, operation over thinking, and results over process, making it difficult to stimulate students' initiative and creativity (Deng *et al.*, 2021).

Therefore, based on contemporary needs, promoting the reform of microbiology laboratory teaching and constructing a teaching system centered on fostering innovation capability has become a significant task for talent cultivation in life sciences majors at universities. This article, considering the current state of microbiology laboratory teaching, explores how to systematically integrate the goal of cultivating innovative talents throughout the entire laboratory teaching process from the dimensions of teaching philosophy, content design, methods, and evaluation system, providing practical references for the development of microbiology laboratory courses in universities.

2. Analysis of the Current State of Microbiology Laboratory Teaching

2.1. Characteristics and Limitations of the Traditional Teaching Model

Traditional microbiology laboratory teaching commonly adopts a "teacher-led, student-followed" model, characterized by a "three-centered" approach: centered on the teacher, the textbook, and the experimental results (Shangkun, 2020). In specific teaching, instructors typically prepare materials in advance, explain principles and procedures, and sometimes even predefine expected results. Students merely follow established procedures to perform operations, record data, and write reports, making the process more akin to "mechanical replication" than "active inquiry". While this model helps students master basic laboratory skills such as aseptic technique, culture medium preparation, and microbial isolation and purification, it exhibits significant shortcomings in fostering innovation capability (Zhu N. *et al*., 2022). On one hand, students remain in a passive state of knowledge reception for extended periods, lacking opportunities for independent thinking and problem-solving, hindering the development of a scientific research mindset characterized by "problem identification — experimental design — hypothesis verification — summary and reflection". On the other hand, the teaching process overlooks individual student differences, with uniform experimental requirements and evaluation standards stifling personalized development and innovative awareness, leading students to "know the how but not the why", and making it difficult to translate laboratory skills into innovative practical abilities.

2.2. Issues in Existing Teaching Content and Methods

Teaching content suffers from a "three excesses and three deficiencies" problem: an excess of verification experiments and a deficiency of inquiry experiments; an excess of classical experiments and a deficiency of cutting-edge experiments; an excess of single-discipline experiments and a deficiency of interdisciplinary integrated experiments. For example, in one domestic university's microbiology laboratory curriculum, verification experiments like "Isolation and Identification of *E. coli*" and "Fermentation and Activity Assay of Amylase" account for over 70% of projects, while experiments involving cutting-edge fields like microbiomics, synthetic microbiology, and microbial resource development constitute less than 10% (Pan *et al*., 2022). This content setup disconnects the experimental scenarios students encounter from actual industry needs, making it difficult for them to understand the application value of microbiology in environmental remediation, biomedicine, food processing, and other fields, thereby reducing learning interest.

In terms of teaching methods, traditional "cramming" instruction still dominates, lacking diversity and interactive approaches. In the classroom, teachers primarily explain key experimental points via blackboard or PPT, with students listening passively. During experiments, teacher guidance is mainly "error-correcting", with little effort to guide students in considering the rationality of experimental design or the scientific control of variables. After experiments, student reports often follow a fixed format of "procedure + data + conclusion", lacking reflection on the experimental process and suggestions for innovative improvements (Jiang *et al*., 2025). This monotonous teaching approach not only fails to stimulate student enthusiasm but also fosters a "focus on operation, neglect of thinking" learning habit, constraining the development of innovation capability.

2.3. Challenges in Teaching Resources and Faculty Development

Insufficient teaching resources are a major constraint on reform. On one hand, laboratory equipment updates lag, with some universities still using basic instruments like traditional optical microscopes and constant temperature incubators, lacking modern equipment such as high-throughput sequencers, real-time quantitative PCR instruments, and bioinformatics analysis platforms. This prevents students from accessing cutting-edge technologies (Song *et al*., 2025). On the other hand, limited experimental funding, coupled with the high cost of consumables like culture media, reagents, and strains used in microbiology experiments, poses challenges. Furthermore, some experiments require long-term cultivation and observation, demanding significant laboratory space and time, which limited budgets struggle to support for inquiry-based and comprehensive experiments (Ren *et al*., 2021). Additionally, laboratory manuals are updated slowly, with some content still reflecting knowledge systems from a decade ago, failing to incorporate new advances and methods in the field, resulting in a disconnect between teaching content and disciplinary progress.

Faculty development faces dual challenges. Some teachers lack research backgrounds and innovative teaching concepts, having long been engaged in traditional laboratory instruction and accustomed to a "follow-the-rules" mode, resulting in insufficient mastery of new teaching methods like project-based learning and inquiry-based teaching (Zhou *et al*., 2024). Simultaneously, heavy teaching loads—often in a "large-class teaching" format where one instructor guides 20-30 students—make it difficult to address individual needs and leave little time or energy for teaching reform research. Moreover, university evaluation systems predominantly prioritize research outcomes, offering insufficient incentives for teaching reform, which dampens teacher enthusiasm for participating in reforms.

3. Teaching Reform Philosophy Under the Goal of Cultivating Innovative Talents

3.1. Shift to a Student-Centered Teaching Philosophy

"Student-centeredness" is a core concept of modern education and the fundamental guideline for reforming microbiology laboratory teaching. This philosophy requires breaking away from the traditional "teacher-led" model, placing students at the heart of teaching activities, and shifting from "teaching students to learn" to "guiding students to learn actively" (Liao *et al*., 2024). In setting teaching objectives, it is essential to design personalized learning goals based on students' majors, interests, and career plans—for instance, focusing on applications in food preservation and safety testing for food science majors, and on roles in wastewater treatment and soil remediation for environmental science majors. During the teaching process, fully respect students' central role, encouraging them to independently pose questions, design experimental schemes, and conduct investigative activities. Teachers should act as "guides" and "collaborators", helping students solve problems encountered during experiments through questioning, inspiration, and feedback, thereby cultivating independent thinking skills. In allocating teaching resources, provide diverse learning resources such as open laboratories, online learning platforms, and scientific literature databases to meet personalized learning needs and stimulate initiative and creativity.

3.2. Core Position of Fostering Innovation Capability

Innovation capability is the core competency of innovative talents, and its cultivation must permeate the entire process of laboratory teaching. Fostering innovation capability in microbiology labs does not require students to achieve major research breakthroughs but aims to develop innovative thinking, awareness, and practical abilities (Jiang *et al.*, 2025). This specifically includes: the ability to identify problems from experimental phenomena and real-life situations; the ability to formulate reasonable hypotheses and design scientific experimental plans based on problems; the ability to apply acquired knowledge and skills to analyze anomalies and propose solutions; and the ability to summarize, analyze results, reflect on shortcomings, and suggest improvements. To achieve this goal, innovation capability cultivation must be integrated into teaching content, methods, and the evaluation system—for example, by increasing inquiry-based experiments, adopting project-based learning, and incorporating innovation thinking indicators, forming an integrated "teaching — practice — evaluation" system for fostering innovation capability.

3.3. Interdisciplinary Integration as a Teaching Approach

Microbiology is closely linked to biology, chemistry, medicine, environmental science, food science, and other disciplines. Interdisciplinary integration is a crucial pathway for cultivating students' comprehensive literacy and innovation capability. In laboratory teaching, it is necessary to break down disciplinary barriers, organically combine microbiological knowledge with that of other fields, and design interdisciplinary experimental projects to broaden students' knowledge base and thinking horizons (Wu *et al.*, 2021). For example, integrating biology and chemistry knowledge to design an experiment on "Isolation, Purification, and Activity Assay of Microbial Enzymes" allows students to master multidisciplinary experimental skills. Combining environmental science and microbiology knowledge to design an experiment on "Analysis of Microbial Community Structure in Activated Sludge from Municipal Wastewater Treatment Plants" enables students to use high-throughput sequencing and bioinformatics analysis to explore the relationship between microbial communities and treatment efficiency. Integrating food science and microbiology knowledge in an experiment like "Development of Probiotic Fermented Dairy Products" helps students master fermentation techniques and food quality testing methods, understanding the link between microbes and food quality. Through interdisciplinary experiments, students can build a complete knowledge system and develop the ability to solve practical problems using multidisciplinary knowledge, laying the foundation for cultivating innovative talents.

4. Innovative Design of Microbiology Laboratory Teaching Content

4.1. Optimizing Basic Experiments

Basic experiments are the core, aiming to help students master fundamental experimental skills and theoretical knowledge. Optimization involves not simply reducing items but integrating innovative elements while retaining core skills to guide active thinking (Li *et al.*, 2025). Specific approaches include:

1. **Selecting Key Experiments, Focusing on Core Skills:** Based on disciplinary characteristics and professional needs, select representative basic experiments such as aseptic technique, microbial isolation and purification, morphological observation and identification, and culture medium preparation and sterilization to ensure students master core skills. Remove redundant or outdated items, such as merging "Observation of Yeast Budding" with "Microbial Morphology Observation" to avoid resource waste.
2. **Integrating Problem-Based Learning to Guide Active Thinking:** Incorporate "question chains" into basic experiments, guiding students to think about design principles before the experiment, observe phenomena and analyze causes during the experiment, and reflect on shortcomings afterward. For instance, in the "Isolation and Identification of *E. coli*" experiment, pose questions like: "Why use LB medium for *E. coli* culture?", "How to confirm the isolated colony is *E. coli*?", "What are potential causes of contamination and how to avoid them?". This prompts students to consult literature and analyze principles, fostering problem awareness and thinking skills.
3. **Adding Variable Exploration to Cultivate Innovative Thinking:** Appropriately introduce variable exploration in basic experiments, allowing students who have mastered basic operations to try changing conditions like temperature, pH, or medium composition, observe outcome variations, and explore the impact of variables. For example, in the "Amylase Fermentation and Activity Assay" experiment, set different fermentation temperatures and measure enzyme activity to analyze temperature's effect. This helps students understand the science and rigor of experimental design, fostering innovative thinking and design capabilities.

4.2. Expanding Comprehensive Experiments

Comprehensive experiments bridge basic labs and research practice, aiming to cultivate students' ability to comprehensively apply knowledge and skills to solve practical problems (Wang *et al.*, 2020). Design should combine disciplinary frontiers and industry needs, selecting themes with practical application value and emphasizing systematic and complex content.

1. **Designing Experiments Around "Microbial Resource Development":** This is a key research area and industry hotspot. An experiment like "Screening and Application of Functional Microorganisms from Soil" can be designed, where students isolate strains producing cellulase, antibiotics, or degrading heavy metals

from campus soil, identify them via morphology, physiology, biochemistry, and molecular biology, determine functional activity through shake-flask fermentation, and finally write a report with application suggestions. This covers multiple steps, comprehensively exercising experimental skills and problem-solving abilities.

2. **Designing Experiments Around "Microbes and Environmental Remediation":** With growing environmental concerns, microbial applications in remediation are expanding. An experiment like "Experimental Study on Microbial Remediation of Petroleum-Contaminated Soil" can simulate contaminated soil, inoculate different degrading agents, set varying conditions, and measure degradation rates and community changes to analyze effects and propose optimized plans. This combines knowledge from environmental science and microbiology, cultivating interdisciplinary thinking and practical skills.
3. **Designing Experiments Around "Microbes and Food Safety":** Food safety is crucial. An experiment on "Rapid Detection and Traceability of Foodborne Pathogens" can involve sampling meat and dairy products, detecting pathogens using traditional culture and qPCR methods, comparing sensitivity/specificity, and conducting traceability analysis via gene sequencing. Covering multiple areas, this helps students master cutting-edge detection technologies and enhance practical problem-solving skills.

4.3. Implementing Research-Based Experiments

Research-based experiments are core to cultivating scientific research thinking and innovation capability, aiming to let students experience the complete research process, shifting from "passive knowledge reception" to "active knowledge creation" (Yan *et al.*, 2022). Implementation should follow principles of "autonomy, inquiry, and openness", allowing students to choose topics, design plans, conduct research, and write reports independently.

1. **Topic Selection Guidance:** Teachers can suggest topics based on research hotspots or their own projects. Encourage students to propose topics based on interest or real-life observations. Teachers must guide the selection process to ensure scientific merit, feasibility, and innovation.
2. **Proposal Design:** Students design detailed plans through literature review and group discussion. Teachers review proposals, pointing out issues in design rigor, variable control, etc., and guide revisions.
3. **Experimental Implementation:** Conducted in open labs, students schedule time and select equipment/reagents autonomously. Teachers provide technical support and safety guidance. Students are encouraged to record data promptly, identify problems, and adjust plans accordingly.
4. **Data Analysis and Report Writing:** Students analyze data using statistical methods and bioinformatics tools, draw conclusions, and write reports following academic paper format. Teachers evaluate reports from various perspectives, provide feedback, and organize defenses for students to present and discuss findings.

5. Reform and Innovation in Teaching Methods and Tools

5.1. Application of Project-Based Learning Method

Project-based learning (PBL) is a student-centered method using projects as vehicles, focusing on knowledge construction and ability development through completing projects (Meng *et al.*, 2025). Applying PBL in microbiology labs transforms the course into a series of project tasks.

1. **Project Design:** Design challenging, practical projects based on objectives and student level. For junior students, design projects like "Microbiology Lab Safety Management"; for seniors, projects like "Development and Promotion of Probiotic Beverages" or "Development and Application of Microbial Fertilizers".
2. **Team Formation:** Divide students into 4-6 person groups with diverse backgrounds and skills. Appoint a leader for coordination. Teachers guide plan development and role assignment.
3. **Project Implementation:** Students work according to plan. Teachers organize regular progress reports, address issues, and encourage inter-group collaboration.
4. **Project Evaluation:** Upon completion, groups submit outputs and present defenses. Teachers organize self, peer, and teacher assessments based on completion, teamwork, innovation, etc., linking results to grades to motivate participation.

5.2. Utilization of Information Technology Teaching Tools

The development of information technology has provided a new path for experiment teaching, which can break the limitations of time and space, enrich content and forms, and improve teaching effects (Guo *et al.*, 2022).

1. **Virtual Simulation Platforms:** For experiments that are long, costly, or hazardous, use 3D modeling and VR to simulate real scenarios.
2. **Online Learning Platforms:** Integrate resources like videos, manuals, literature, virtual labs, Q&A, and assignment submission/feedback. Include discussion forums for experience sharing.
3. **Big Data Analytics:** Collect and analyze student data to identify learning patterns and weaknesses, enabling personalized instruction and teaching effectiveness evaluation.

5.3. Heuristic and Inquiry-Based Teaching

Heuristic and inquiry-based teaching are important methods for cultivating innovative thinking and inquiry ability (Xiao *et al.*, 2021). Their core is to guide students to think actively, explore independently, and stimulate learning interest and creativity.

1. **Creating Problem Situations:** Before experiments, use cases or phenomena to pose questions and stimulate interest.
2. **Guiding Independent Inquiry:** During experiments, avoid giving direct answers; guide students to discover principles through observation, operation, and analysis. Encourage hypothesis generation and testing for unexpected results.
3. **Organizing Group Discussions:** Facilitate discussions for students to share ideas, methods, and data, broadening perspectives and fostering collaboration and communication skills.

6. Reform and Improvement of the Laboratory Teaching Evaluation System

6.1. Construction of Diversified Evaluation Indicators

Traditional evaluation mainly relies on experimental report scores, with a single indicator, making it difficult to fully reflect students' abilities and literacy (Zhang *et al.*, 2023). It is necessary to construct a diversified evaluation indicator system to evaluate learning outcomes from multiple dimensions.

1. **Experimental Operation Ability:** Assess standardization, proficiency, and safety awareness via observation or video review.
2. **Lab Report Quality:** Evaluate not only completeness, accuracy, and analysis but also innovative thinking and reflective capabilities.
3. **Innovative Thinking and Ability:** Assess through innovative ideas, designs, problem-solving, and participation in projects/competitions.
4. **Teamwork Ability:** For comprehensive/research experiments, evaluate role, task completion, communication, and contribution via peer/teacher assessment.

6.2. Strengthening Process-Oriented Evaluation

Traditional evaluation focuses on results and ignores processes, leading students to pay more attention to reports than operations and inquiry (Wei *et al.*, 2020). It is necessary to strengthen process-oriented evaluation, integrate evaluation into the entire teaching process, provide timely feedback and promote improvement.

1. **Pre-Lab Preparation Evaluation:** Use quizzes, note checks, or presentations to assess understanding of principles, procedures, and equipment.
2. **In-Process Evaluation:** Observe and record operation standardization, data recording, and problem-solving during experiments.
3. **Post-Lab Summary Evaluation:** Evaluate outcomes, analysis, and reflection through report grading, presentations, and displays.

6.3. Student Self-Assessment and Peer Assessment

Students' self-evaluation and mutual evaluation can cultivate reflection ability, critical thinking and team collaboration ability, and are important components of the evaluation system (Zhu Y. *et al.*, 2021).

1. **Self-Assessment:** Students complete self-evaluation forms after each experiment, reflecting on performance, report quality, and learning gains.
2. **Peer Assessment:** Within groups, students assess each other's contributions, task quality, and collaboration using structured forms, guided by teachers for objectivity.

7. Challenges and Countermeasures in Teaching Reform

7.1. Difficulties and Problems in the Reform Process

1. **Insufficient Teaching Resources:** High costs of equipment/reagents for comprehensive/research experiments and lack of lab management personnel hinder reform.
2. **Inadequate Teacher Capacity and Time:** Reform demands higher expertise and teaching skills, but teachers may lack research experience, training in new methods, and time due to heavy workloads.
3. **Student Disparities in Foundation and Engagement:** Variations in knowledge base, skills, and motivation lead to difficulties and low participation in complex experiments; some students remain passive.
4. **Implementation Difficulties of Evaluation System:** Process-oriented evaluation requires significant teacher time; objectivity of self/peer assessment is hard to ensure; lack of standardized weighting for diverse indicators affects fairness.

7.2. Targeted Solutions and Suggestions

In response to the above problems, combined with the actual situation of universities, the following measures and suggestions are put forward:

1. **Secure Resources Through Multiple Channels:** Increase funding, establish partnerships with enterprises/other universities for resource sharing, optimize lab management using student assistants.
2. **Enhance Teacher Training and Capacity:** Develop systematic training programs, establish incentives

linking reform achievements to promotion/performance, support teaching reform research projects.

3. **Implement Tiered Instruction to Stimulate Engagement:** Group students by level, design differentiated experiments, create mentorship programs, and use awards to motivate.
4. **Optimize Evaluation Processes for Fairness and Effectiveness:** Develop clear evaluation standards and guidelines, utilize IT for efficient assessment management, establish feedback mechanisms, and regularly refine the system based on feedback.

8. Conclusion and Outlook

8.1. Summary of Achievements in Microbiology Laboratory Teaching Reform

Systematic reform has yielded significant results. Philosophically, shifts to student-centeredness, ability-focus, and interdisciplinary integration have stimulated initiative and creativity. Content-wise, the three-tier system optimized basics, expanded comprehensives, and introduced research-based experiments, aligning with frontiers and needs, fostering practical and research innovation abilities. Methodologically, PBL, IT tools, and heuristic/inquiry-based teaching enriched forms and improved effectiveness. The evaluation system became diversified and process-oriented, comprehensively assessing student development. Practice shows reform significantly enhanced student innovation capability and research literacy, strongly supporting innovative talent cultivation.

8.2. Prospects for Future Cultivation of Innovative Talents

With the development of life sciences and technological progress, the reform of microbiology experiment teaching still needs to be continuously deepened to meet the new needs of cultivating innovative talents.

1. **Integration with Cutting-Edge Technologies:** Incorporate gene editing, single-cell sequencing, metagenomics, etc., into teaching to enhance technical application and innovation capabilities.
2. **Alignment with Industry Needs:** Strengthen industry-academia cooperation, design projects based on real needs, involve industry experts, and enhance vocational skills and practical abilities.
3. **Personalization and Intelligence:** Leverage big data and AI for personalized learning paths and intelligent tutoring systems, providing real-time guidance and customized recommendations.

The reform of microbiology experiment teaching is a long-term and arduous task that requires the joint efforts of universities, teachers, students and all sectors of society. In the future, through continuous deepening of reforms and continuous innovation of teaching philosophy, content, methods and evaluation systems, more high-quality innovative talents with solid professional foundations, strong innovative abilities and practical abilities will be cultivated, making greater contributions to the development of China's life science field and the progress of social economy.

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