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Application of Scanning Electron Microscopy in Biology Experimental Teaching

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Abstract
This study elucidates the critical role of scanning electron microscopy (SEM) in university-level laboratory teaching and scientific research. It further proposes a comprehensive teaching framework encompassing theoretical principles, sample preparation, instrument operation, and accurate interpretation of microstructural surface morphology. By integrating pre-class self-study with on-site instruction, the teaching model enables students to develop a deeper understanding of SEM, enhances their operational competence, strengthens their grasp of biological concepts, stimulates curiosity in microscopic biological structures, and ultimately improves instructional quality and talent cultivation.

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1. Introduction

The exploration of microscopic structures is of fundamental importance in higher education, aiding students in understanding the natural world, discovering functional mechanisms, optimizing material properties, and facilitating practical applications. Light microscopy remains a standard tool for observing biological structures in teaching settings, allowing visualization of cellular morphology, tissue arrangement, and organ-level features. Such observations form the basis for comprehending physiological traits and developmental mechanisms. However, light microscopy has inherent limitations in surface morphology characterization due to insufficient magnification, inadequate resolution, and limited contrast, hindering students from accurately acquiring fine structural details.

Scanning electron microscopy (SEM), a pivotal analytical instrument across materials science, life sciences, physics, and geology, offers high resolution, large depth of field, broad magnification range, and relatively straightforward sample preparation. It is widely employed for microscopic morphological characterization and chemical composition analysis, providing an essential avenue for investigating the microcosmic world. SEM-based instruction enables students to directly observe surface morphology, structural features, and chemical composition, thereby strengthening their research capabilities and innovative thinking. Nevertheless, the high cost, limited availability, operational complexity, and maintenance demands of SEM present significant challenges. Academic institutions must therefore determine how to maximize SEM utilization—balancing undergraduate teaching needs with graduate-level research—while ensuring safe and effective instrument management.

Drawing on recent experience in managing large-scale analytical instruments for educational purposes, this study examines the role of SEM in experimental teaching and scientific innovation. By identifying key challenges in SEM instruction, we propose effective pedagogical strategies to enhance teaching efficiency and provide a scientific basis for integrating SEM into biology-oriented laboratory courses.

2. Challenges in SEM-Based Experimental Teaching

SEM teaching primarily targets undergraduate and graduate biology majors who possess basic theoretical knowledge of analytical instruments but lack hands-on experience. According to the curriculum requirements, students must understand SEM principles, routine maintenance, operational precautions, and basic sample testing procedures.

However, SEM is a sophisticated, high-value instrument whose components are highly sensitive to improper use, resulting in apprehension among students who fear damaging the equipment. The fully enclosed and automated nature of SEM further limits students' ability to visualize internal instrument structures, preventing them from fully comprehending its operational principles.

To address these challenges, including the enhancement of conceptual understanding, the reduction of students' hesitancy in instrument operation, and the cultivation of problem-solving abilities, a blended learning model integrating pre-class preparation with interactive laboratory instruction was implemented. This model significantly improves student engagement and contributes to the cultivation of scientific innovation.

3. Optimization of Instructional Content Design (Blended Learning Model)

3.1. Pre-class Preparation

SEM encompasses broad technical content and numerous specialized terminologies. Its enclosed, automated structure necessitates high-quality pre-class preparation to meet instructional objectives within limited teaching hours. A detailed syllabus was created outlining learning goals and specifying essential theoretical principles, technical terminology, maintenance knowledge, and safety considerations. Instrument structure, operational workflows, and sample preparation techniques were developed into videos, animations, and slide presentations accessible via online platforms.

Students may review these materials flexibly and repeatedly, engage in peer discussion, and enter the classroom with a foundational understanding and targeted questions—thereby accelerating the transition to hands-on operation and improving learning efficiency.

3.2. Interactive On-site Instruction

Informed by the disciplinary characteristics of biological science education, we developed an instructional framework that integrates theoretical instruction with practical engagement. Instructors demonstrate SEM operation while articulating key concepts and prompting critical thinking. Students observe in real time, practice instrument operation, and participate in small-group discussions to deepen understanding. Small-group instruction (4–6 students each) ensures that every student operates the SEM and completes imaging tasks. Students are encouraged to design their own experimental procedures based on research objectives, while instructors monitor progress, address questions, and correct operational errors. After the experiment, students conduct group-based data analysis, evaluate imaging quality, identify sources of error, and suggest improvements. Instructors conclude with a synthesis of key techniques and recommendations for optimizing future instructional practices.

3.3. Project-Based Learning

In the cultivation of students' scientific and technological innovation competencies, a series of instructional measures has been implemented to ensure a close integration of theoretical teaching with authentic research activities. Students are encouraged to participate in extracurricular research initiatives, including undergraduate innovation projects and academic competitions such as the "Challenge Cup." These activities provide highly practical platforms for applying classroom knowledge to real scientific problems.

Within these projects, and under faculty supervision, students consult relevant literature, gain an understanding of project background and research progress, and clarify the objectives of their experiments. They then formulate detailed testing protocols, including sample selection, preparation methods, instrument operation strategies, and data-analysis plans. Subsequently, students conduct experimental investigations, document procedures and observations, analyze the resulting data, develop evidence-based conclusions, and reflect on their research process before producing a final project report. Through the use of scanning electron microscopy, students are able to observe and analyze microstructural and surface morphological features of samples, thereby acquiring practical competence with advanced instruments and learning to adjust operational parameters according to specific experimental goals to obtain accurate and reliable results. More importantly, students develop the ability to integrate multiple characterization techniques to address complex scientific questions. For example, by combining SEM with energy-dispersive X-ray spectroscopy (EDS), they obtain compositional information from microscopic regions of samples. This multi-technique analytical approach enriches the breadth and depth of sample characterization and significantly enhances students' overall analytical capability. Through these practices, students learn to evaluate research samples from multiple perspectives and to propose innovative solutions based on comprehensive material evidence. Such hands-on engagement not only strengthens their scientific creativity but also improves their research competence and overall academic maturity. During the course of these projects, students progressively transition from novice experimenters to independent, research-oriented problem solvers.

A multi-level evaluation system was established to assess the effectiveness of this training approach in fostering scientific and technological innovation. During the in-person teaching phase, students' proficiency in instrument operation, their ability to select appropriate imaging conditions, and the creativity demonstrated in solving practical problems serve as direct indicators of their progress. Additionally, periodic research-progress reports provide an effective means of monitoring students' autonomy and development of innovative thinking. Regular discussions of research results and encountered challenges allow instructors to provide targeted guidance, helping students refine both their experimental designs and innovative strategies. These evaluative measures not only reflect the degree to which students have mastered technical skills but also reveal their capacity for creative thinking and problem-solving when confronted with real scientific questions.

Ultimately, students participating in these projects achieved outstanding results in undergraduate innovation programs and the "Challenge Cup" competition, demonstrating the effectiveness of the course in cultivating scientific and technological innovation. Moreover, students consistently reported substantial improvement in data analysis, experimental design, and the ability to solve complex problems. These outcomes are reflected not only in students' subjective feedback but also in their subsequent research performance, further validating the effectiveness of this instructional model.

3.4. Virtual Simulation Experiments

A virtual SEM simulation platform was developed to support students who lack immediate access to the physical instrument. This platform typically incorporates modules such as instrument overview, sample preprocessing, operational simulation, and data analysis. Students can perform simulated experiments independently, while the system records their procedural accuracy, operational sequence, and time spent, serving as part of the evaluation system. Virtual simulation not only enhances teaching efficiency and provides abundant practice opportunities, but also reduces operational risks and instructional costs, offering a new pedagogical pathway for integrating high-value instruments into undergraduate education.

4. Conclusion

The incorporation of advanced analytical instruments into laboratory teaching represents an essential component of modern higher education. Traditional experimental teaching models and outdated equipment are increasingly incompatible with contemporary training goals. Integrating SEM into biology laboratory teaching constitutes a bold and effective pedagogical innovation. The approach not only deepens theoretical understanding and fosters creativity, but also significantly enhances students' experimental proficiency and overall scientific literacy. Furthermore, it strengthens students' engagement with their discipline and stimulates intellectual curiosity. Utilizing SEM in undergraduate teaching also substantially increases instrument utilization, maximizing educational value and supporting the development of high-quality scientific talent.

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