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Innovative Experimental Teaching Reform for Environmental Engineering Majors Based on Research Achievement Transformation

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Abstract: To implement the goal of connotative development in application-oriented undergraduate institutions and promote experimental teaching reform, the research achievement of "biochar carrier-enhanced anaerobic reactor start-up and granular sludge cultivation" was transformed into an undergraduate innovative experimental teaching project. By constructing a four-module experimental teaching system, a comprehensive and design-oriented experimental project suitable for environmental science and engineering majors was developed. Using a laboratory-scale anaerobic sequencing batch reactor (ASBR), agricultural waste-derived biochar was employed as the carrier material, achieving the experimental teaching transformation of anaerobic ammonium oxidation (anammox) nitrogen removal technology. Pilot research and preliminary teaching practice have shown that this project effectively fills the content gap in the existing Water Pollution Control Engineering experimental curriculum in the field of low-carbon-source wastewater nitrogen removal, significantly reduces experimental teaching costs, and enhances the high-level, innovative, and challenging nature of experimental teaching, providing a referable pathway for the transformation of research achievements into experimental teaching in application-oriented undergraduate institutions.

Keywords: Innovative Experiment; Achievement Transformation; Experimental Teaching; Reform.

1. Introduction

Experimental teaching is an important component of higher engineering education and a key link in cultivating students' practical ability, innovative spirit, and engineering literacy [1]. However, for a long time, experimental teaching in environmental engineering majors at domestic universities has generally suffered from outdated content, monotonous modes, and disconnection from disciplinary frontiers [2]. Taking the Water Pollution Control Engineering course as an example, existing experimental content is mostly dominated by verification experiments such as conventional activated sludge process and biofilm process, where students follow predetermined steps and the experimental results have "standard answers", making it difficult to stimulate students' research interest and innovative potential [3].

Meanwhile, with the in-depth advancement of the "dual carbon" strategy and the urgent demand of the wastewater treatment industry for low-carbon and high-efficiency technologies, anaerobic ammonium oxidation (anammox) technology has become a research hotspot in the field of biological nitrogen removal from wastewater due to its advantages of no organic carbon source requirement, low energy consumption, and low sludge yield [4-6]. However, this technology has not yet been systematically introduced into the undergraduate experimental teaching system, making it difficult for students to access and master this frontier technology during their studies, resulting in a certain disconnect from actual industry needs.

As an application-oriented undergraduate institution, Chengdu Technological University has always adhered to student-centered education and actively promoted teaching reform and quality improvement projects [7]. The university's Teaching Reform and Quality Improvement Project Guidelines explicitly propose to deepen the reform of experimental teaching methods and approaches, improve the quality of experimental teaching, and further cultivate students' practical and innovative abilities. Against this background, how to effectively transform the frontier research achievements of the research group into undergraduate experimental teaching content and construct innovative, comprehensive, and challenging experimental teaching projects has become an important issue that needs to be addressed urgently.

This project aims to transform the research group's achievements into operable undergraduate innovative experimental teaching projects, constructing the "Bacteria-Char Coupled ASBR Reactor High-Efficiency Low-Consumption Water Purification Experiment" teaching system. Specific objectives include: (1) supplementing and updating existing experimental content to fill the gap in low-carbon-source wastewater nitrogen removal experiments; (2) enhancing the high-level, innovative, and challenging nature of experimental teaching, and cultivating students' engineering design and problem-solving abilities; (3) reducing experimental risks, time costs, and economic costs, and improving the safety and environmental protection level of experiments; (4) exploring effective mechanisms and pathways for transforming research achievements into experimental teaching, providing reference for similar institutions.

2. Necessity and Feasibility Analysis of Project Construction

2.1. Problems in Existing Experimental Teaching

Through systematic review and analysis of the existing

Water Pollution Control Engineering experimental curriculum, the following prominent problems were identified: (1) Outdated experimental content with a lack of frontier technologies. Existing experiments are dominated by verification experiments of conventional activated sludge process and biofilm process, lacking experimental content on frontier nitrogen removal technologies such as anammox, and unable to reflect the latest developments in the discipline; (2) Single nature of experiments with insufficient cultivation of innovative abilities. Traditional experiments are mostly verification experiments where students follow predetermined steps, lacking space for independent design and exploration, making it difficult to cultivate students' innovative thinking and engineering problem-solving abilities; (3) Fragmented experimental system with a lack of systematicity. Each experimental project is independent of each other without organic connections, making it difficult for students to form a complete understanding of the engineering technology chain; (4) Complex equipment, high costs, and high operational risks. Continuous-flow reactors have complex equipment, large volumes, require continuous aeration, have high energy consumption and noise, and involve extensive use of organic solvents, posing certain safety risks.

2.2. Feasibility of Research Achievement Transformation

This project relies on the research group's years of scientific research accumulation and has a good foundation for transformation: (1) Solid preliminary research achievements. The research group has achieved a series of research results in biochar carrier preparation, ASBR reactor optimization, and anammox granular sludge cultivation, including published research papers and authorized invention patents; (2) Mature experimental conditions. The project team currently has more than 20 sets of ASBR, CRI, EGSB and other reactors with effective volumes of 2~10 L, with rich experience in reactor construction and operation; (3) Strong faculty team. The project team consists of 3 teachers (1 professor, 2 associate professors), 2 enterprise engineers, 1 graduate assistant, and 5 undergraduate assistants, forming a collaborative team of "university teachers + enterprise experts + graduate students + undergraduates"; (4) Sufficient funding guarantee. The university provides funding matching and workload recognition, providing strong support for project implementation.

3. Project Construction Content and Technical Route

3.1. Overall Technical Route

This project follows the overall approach of "research achievement extraction→pedagogical transformation→ modular reorganization→practical verification→ optimization and improvement", and is promoted in four stages (Figure 1).

As shown in Figure 1, the project technical route includes four stages: Stage I (3 months) is the biochar carrier preparation and characterization stage, completing biomass pyrolysis, grinding and sieving, and characterization analysis of BET specific surface area, SEM morphology, and FTIR functional groups; Stage II (3 months) is the ASBR reactor construction and commissioning stage, completing organic glass reactor processing, temperature control system installation, stirring device commissioning, and influent/effluent system connection; Stage III (3 months) is the Anammox sludge inoculation and acclimation stage, completing inoculated sludge seeding, gradual increase of nitrogen loading, biochar addition, and monitoring of granular sludge formation; Stage IV (3 months) is the water purification performance evaluation and optimization stage, completing preparation of low C/N simulated wastewater, sequencing batch five-stage operation control, influent/effluent nitrogen and COD monitoring, sludge property evaluation, and economic analysis.

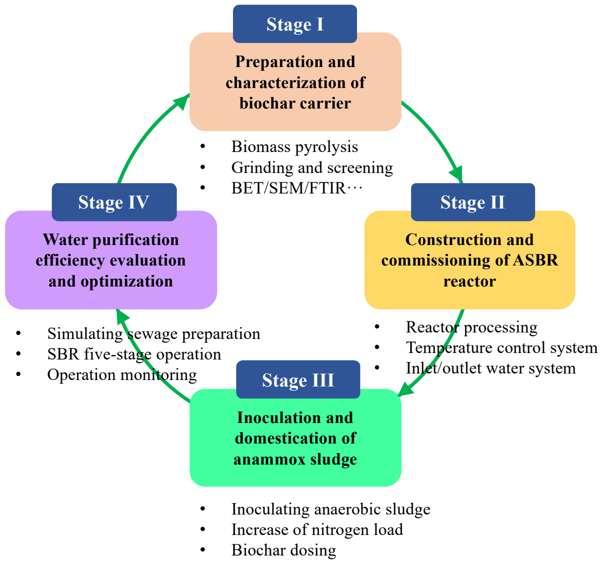

Fig 1. Technical route of the innovative experimental teaching project

3.2. Construction of the Four-Module Experimental Teaching System

This project constructs a four-module experimental teaching system of "material preparation→reactor construction→operation control→performance evaluation", with a total of 16 class hours (4 class hours, 4 modules), offered to sophomore to senior undergraduate students majoring in environmental science and engineering.

Module I: Biochar Material Preparation and Characterization (4 class hours). Students use waste crop straw, animal manure, and other materials as raw materials, conduct limited-oxygen pyrolysis at 400~700 °C, and after grinding and sieving (0.1~0.5 mm), characterize the biochar using BET specific surface area determination, SEM morphology observation, and FTIR functional group analysis [8-10]. This module cultivates students' material preparation and characterization abilities, enabling them to master biomass pyrolysis principles and material characterization methods.

Module II: ASBR Reactor Construction and Commissioning (4 class hours). Students independently design an organic glass cylindrical reactor (effective volume 2 L, height-to-diameter ratio 3: 1), install a temperature control system (35±1 °C), a mechanical stirring device (60~200 r/min), and an automatic influent/effluent control system, and conduct airtightness testing and operational commissioning [11,12]. This module cultivates students' reactor design and assembly abilities, enabling them to master reactor structural design principles and basic mechanical processing knowledge.

Module III: Anammox Sludge Inoculation and Acclimation (4 class hours). Students inoculate anaerobic sludge from wastewater treatment plants, gradually increase the nitrogen loading (0.1→0.5 kg N/m^3/d), add biochar carriers at a ratio of 20% of the seed sludge dry weight, monitor the granular sludge formation process, and evaluate sludge properties (particle size distribution, settling velocity, VSS/TSS) [13]. This module cultivates students' microbial cultivation and acclimation abilities, enabling them to master anaerobic microbial growth laws and sludge granulation mechanisms.

Module IV: Water Purification Performance Evaluation and Optimization (4 class hours). Students prepare low C/N simulated wastewater, conduct sequencing batch five-stage (influent-reaction-settling-effluent-idle) operation control, monitor influent/effluent nitrogen and COD, calculate removal rates, conduct nitrogen balance analysis and Monod kinetic equation fitting, and carry out economic evaluation [14,15]. This module cultivates students' data analysis and engineering evaluation abilities, enabling them to master wastewater treatment performance evaluation methods and economic analysis skills.

3.3. Key Technical Parameters

Reactor design parameters include: organic glass cylindrical material, 2 L effective volume, 3: 1 height-to-diameter ratio, 60~200 r/min adjustable stirring paddle, 35±1 ℃ constant temperature water bath temperature control, automatic control system, etc.

Biochar carrier parameters include: waste straw/animal manure raw materials, 400~700 ℃ limited-oxygen pyrolysis temperature, 1.5~3 h pyrolysis time, 0.1~0.5 mm particle size, 20% of seed sludge dry weight addition amount, preparation cost below 50 CNY/batch, etc.

Operation control parameters include: NH_4^+-N 100~200 mg/L, NO_2^--N 130~260 mg/L, 1: 1.32 substrate ratio, 12~24 h HRT, 7.0~8.0 pH, below 0.5 mg/L DO, etc.

The evaluation index system covers four dimensions: water quality indicators (COD removal rate, NH_4^+-N removal rate, TN removal rate, effluent compliance rate), sludge property indicators (granular sludge particle size distribution, settling velocity, VSS/TSS, granulation rate), economic and operational indicators (nitrogen loading removal rate, operating energy consumption, material cost, start-up period), and teaching effectiveness indicators (student satisfaction, ability improvement, paper output, competition awards).

4. Project Characteristics and Innovations

4.1. Research Feeding Back into Teaching with Frontier Content

This project directly transforms the research group's scientific papers and patent achievements in the field of biochar carrier anaerobic reactors into undergraduate experimental teaching, introducing the frontier "bacteria-char coupling" technology into undergraduate experimental teaching, achieving "research feeding back into teaching". The biochar preparation, granular sludge cultivation, and other technologies that students are exposed to are all research hotspots in the past five years, effectively solving the problem of disconnection between experimental teaching content and disciplinary frontiers.

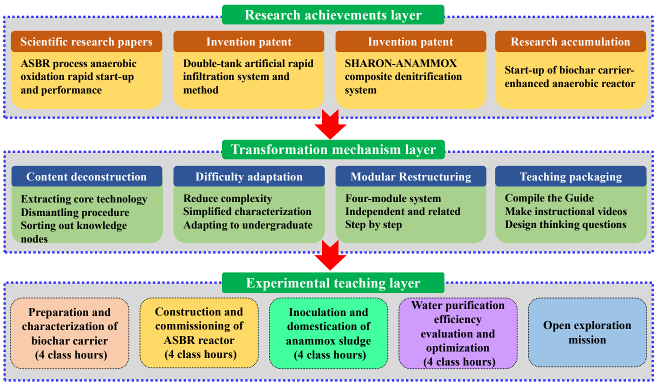

Fig 2. Mechanism and pathway of research achievement transformation

As shown in Figure 2, the project has established a systematic research achievement transformation mechanism, including four stages: content deconstruction (extracting core technologies, disassembling operational steps, sorting out knowledge nodes), difficulty adaptation (reducing operational complexity, simplifying characterization methods, adapting to undergraduate level), modular reorganization (four-module experimental system, independent yet interconnected, progressive), and pedagogical packaging (writing guidebooks, producing teaching videos, designing discussion questions), forming a complete transformation pathway from research to teaching.

4.2. Low-Carbon and Eco-friendly Concept Aligned with the Dual Carbon Strategy

Anammox technology requires no organic carbon source and large-scale aeration, saving 62.5% oxygen consumption and 100% carbon source addition [16]; biochar raw materials are derived from agricultural waste, embodying the circular economy concept of "waste treating waste". The experimental process has zero aeration noise and low energy consumption, aligning with the "dual carbon" strategic goals [17].

In terms of economy, the equipment cost of this project is controlled within 2000 CNY/set, 75% lower than conventional processes; the material cost is about 35 CNY/batch, 77% lower than conventional processes; the operating energy consumption is 37.5% of conventional processes; and the organic carbon source addition is zero. In terms of environmental protection, the aeration noise index of this project is only 10 (conventional process is 80), the greenhouse gas emission index is 35 (conventional process is 85), the agricultural waste resource utilization index reaches 95 (conventional process is 20), and the experimental safety risk index is 25 (conventional process is 60).

4.3. Engineering Application Training to Cultivate Systematic Thinking

This project breaks through the fragmentation of traditional unit operation experiments and constructs a complete chain of "materials→equipment→process→evaluation". Students not only learn reactor operation but also master the whole process of biochar material preparation and characterization, reactor design and processing, and process start-up and regulation, cultivating systematic thinking.

4.4. Low Cost and High Adaptability for Easy Promotion

The ASBR reactor has a simple structure (no need for complex components such as three-phase separators and water distribution systems), and the 2 L bench scale is convenient for laboratory implementation; the self-made biochar cost is less than 50 CNY/batch; the sequencing batch operation is flexible and suitable for teaching schedule arrangements. The project results can be promoted to similar majors in local universities.

4.5. Both Innovative and Challenging

The experiment sets open-ended tasks where students can independently choose different raw materials to prepare biochar or modify them, design different addition ratios, and optimize operation cycles. The experimental results have uncertainty, truly reproducing the scientific research exploration process and avoiding “standard answer” style teaching.

5. Student Competency Development System

5.1. Knowledge Foundation Layer

This project is based on theoretical knowledge such as microbiology, reaction engineering, environmental monitoring, water pollution control engineering, and materials science learned by students. Through experimental teaching, it consolidates and deepens students’ understanding and mastery of this knowledge. Specific contents include: anaerobic microbial cultivation and acclimation techniques, nitrogen speciation transformation analysis (determination of NH_4^+-N, NO_2^--N, NO_3^--N), sludge property evaluation (particle size distribution, settling velocity, VSS/TSS), etc.

5.2. Competency Development Layer

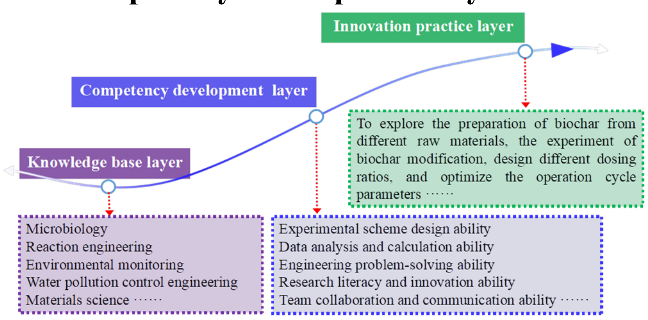

Fig 3. Student competency development system

As shown in Figure 3, the project constructs a three-level progressive competency development system of “Knowledge base layer-Competency development layer-Innovative practice layer”. In the competency development layer, five aspects of abilities are emphasized: (1) Experimental scheme design ability. Students independently design biochar preparation schemes and optimize reactor operation parameters, cultivating experimental scheme design ability; (2) Data analysis and calculation ability. Students conduct removal rate calculations, nitrogen balance analysis, and Monod equation fitting, cultivating data analysis and calculation ability; (3) Engineering problem-solving ability. Students propose regulation strategies for problems such as sludge loss and slow start-up, cultivating engineering problem-solving ability; (4) Research literacy and innovation ability. Students write papers, apply for patents, and participate in competitions, cultivating research literacy and innovation ability; (5) Team collaboration and communication ability. 2~3 people work in division of labor to complete reactor operation and management, cultivating team collaboration and communication ability.

5.3. Innovative Practice Layer

In the innovative practice layer, the project encourages students to carry out exploratory research, including: exploring biochar preparation from different raw materials (waste crop straw, municipal excess sludge, animal manure, etc.), conducting biochar modification treatment experiments, designing different addition ratios, and optimizing operation cycle parameters. These open-ended tasks make the experimental results uncertain, truly reproducing the scientific research exploration process.

6. Outcomes and Teaching Application

The project produced five types of outcomes: (1) Experimental teaching project guidebook. Writing the Bacteria-Char Coupled ASBR Reactor High-Efficiency Low-Consumption Water Purification Experiment Guidebook, including experimental objectives and principles, experimental materials and instruments, experimental steps (16 class hours), data processing and discussion questions, safety regulations, etc; (2) Self-made experimental equipment. Developing 1 set of ASBR teaching experimental device (effective volume 2 L), including organic glass reactor body, constant temperature system, mechanical stirring device, automatic influent/effluent control system, and gas collection device, with equipment cost controlled within 2000 CNY/set; (3) Digital teaching resources. Producing 1 experimental teaching video (biochar preparation, reactor assembly, operation), including ASBR five-stage operation parameter regulation animation, and constructing an online learning platform; (4) Teaching application. For junior undergraduate students majoring in environmental science and engineering (supporting experiment for Water Pollution Control Engineering course or open experiment), officially included in the open plan starting from the 2026~2027 academic year, accepting approximately 30~50 students per year to conduct experiments. Prior to formal inclusion, the project team has completed a full-cycle pilot run with undergraduate assistants, verifying the feasibility of the four-module system and refining the experimental protocols; (5) Student achievement cultivation. Guiding students to write research papers or apply for patents based on experimental data, publishing 1 teaching reform paper and 1 academic research paper during the project construction period, and guiding students to participate in and win 3~5 provincial-level or above discipline competition awards.

The project adopts a diversified assessment method: experimental operation (40%) + experimental report (30%) + design optimization scheme (20%) + team collaboration (10%), with additional innovation ability bonus points. Through the combination of process evaluation and result evaluation, the learning effects and competency improvement of students are comprehensively assessed.

7. Project Comparative Analysis

Table 1 systematically compares the differences between this project and traditional experimental projects from 10 dimensions including experimental content, experimental nature, experimental system, equipment scale, material cost, operating energy consumption, carbon source demand, experimental safety, student competency development, and teaching effectiveness. The results show that this project has significant advantages in introducing frontier technologies, cultivating innovation ability, constructing systematic systems, reducing costs and energy consumption, and improving safety and environmental protection levels, fully demonstrating the value and significance of innovative experimental project construction.

Table 1. Comparison of traditional and innovative experimental projects

Dimension	Traditional Project	This Project	Improvement
Experimental Content	Conventional activated sludge and biofilm verification experiments	Integrated design experiment on anaerobic ammonia oxidation-biochar coupling	Introduces cutting-edge nitrogen removal technology; fills the gap in low-carbon-source wastewater nitrogen removal experiments
Experimental Nature	Verification experiment with predetermined procedures	Comprehensive and design-oriented experiment; students independently design solutions	Shifts from “passive acceptance” to “active exploration”; fosters innovative thinking
Experimental System	Fragmented content; experiments are independent of each other	Complete technical chain: “Materials→Equipment→Process→Evaluation”	Builds a systematic experimental system; cultivates engineering systems thinking
Equipment Scale	Continuous-flow reactor; complex equipment and high cost	ASBR sequencing batch reactor (2 L bench-scale)	Simple equipment; cost reduced by 75%; easy to implement in laboratory settings
Material Cost	Commercial activated carbon, etc., ~150 CNY/batch	Biochar self-prepared from agricultural waste, ~35 CNY/batch	Material cost reduced by 77%; embodies the “waste-to-treat-waste” concept
Operating Energy Consumption	Requires continuous aeration; high energy consumption	Anaerobic process requires no aeration; saves 62.5% oxygen consumption	Significantly reduces operating costs; aligns with “dual carbon” goals
Carbon Source Requirement	Requires addition of organic carbon source (e.g., sodium acetate)	Anaerobic ammonia oxidation requires no organic carbon source	Saves 100% carbon source addition; reduces experimental cost and safety risks
Experimental Safety	High aeration noise; extensive use of organic solvents	No aeration noise; biochar pyrolysis conducted under ventilation conditions	Enhances experimental safety and environmental protection; reduces safety risks
Student Competency Development	Single-operation skill training	Solution design, data analysis, engineering problem-solving, scientific research innovation	Multi-dimensional competency synergistic development; enhances comprehensive literacy
Teaching Effectiveness	Experimental results have “standard answers”	Experimental results have uncertainty; authentically reproduces the scientific research exploration process	Stimulates research interest; cultivates a truth-seeking and pragmatic scientific attitude

8. Summary

Based on the research group’s accumulated scientific research and pilot teaching validation, this project successfully transformed the research achievement of “Biochar carrier-enhanced anaerobic reactor start-up and granular sludge cultivation” into an undergraduate innovative experimental teaching project, developed comprehensive and design-oriented experimental projects suitable for environmental science and engineering majors, established a systematic research achievement transformation mechanism, and effectively filled the content gap in the existing Water Pollution Control Engineering experimental curriculum in the field of low-carbon-source wastewater nitrogen removal. The project has significant economic and environmental protection advantages, constructs a three-level progressive competency development system of “Knowledge base layer-Competency development layer-Innovative practice layer”, and effectively enhances students’ abilities in experimental scheme design, data analysis, engineering problem-solving, scientific research innovation, and team collaboration. Future work will be deepened from the following aspects: (1) continuously optimizing the experimental guidebook and teaching videos, and improving digital teaching resources; (2) exploring a blended teaching model combining virtual simulation and physical experiments; (3) expanding biochar raw material types and modification methods to enrich the exploratory and open-ended nature of experiments; (4) strengthening school-enterprise cooperation and introducing more real engineering cases; (5) establishing a long-term mechanism for transforming research achievements into experimental teaching, continuously converting the latest research achievements into experimental teaching content.

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