

DEVELOPMENT OF A PILOT-SCALE MBBR–MBR WASTEWATER TREATMENT SYSTEM AS AN EXPERIENTIAL LEARNING PLATFORM FOR ENVIRONMENTAL ENGINEERING EDUCATION

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Abstract

Experiential learning has become an important approach in engineering education for bridging the gap between theoretical knowledge and real-world applications. This study presents the development and educational evaluation of a pilot-scale wastewater treatment learning platform based on an integrated Moving Bed Biofilm Reactor–Membrane Bioreactor (MBBR–MBR) system implemented at Thu Dau Mot University, Vietnam. The system was designed as a technology-supported learning environment that allows environmental engineering students to observe, operate, and analyze modern biological wastewater treatment processes in a controlled laboratory setting. The experimental system consists of several treatment units, including an equalization tank, an anoxic reactor, an MBBR aeration reactor, a membrane bioreactor unit, and a disinfection stage. In addition to evaluating the technical performance of the treatment system, the study assessed its educational effectiveness through student participation in system operation, environmental monitoring, and laboratory analysis. The treatment system demonstrated stable performance with high removal efficiencies for key pollutants, including 95.35% for COD, 95.41% for BODs, and 95.21% for total suspended solids. Survey results indicated that the majority of participating students reported improved understanding of biological wastewater treatment processes, enhanced laboratory skills, and increased engagement with course content. The findings suggest that integrating pilot-scale environmental technologies into university laboratories can significantly support experiential learning and improve student competencies in environmental engineering education. This study contributes to the development of technology-enhanced learning environments that combine engineering practice with educational innovation.

Keywords: experiential learning, environmental engineering education, Technology-enhanced learning, wastewater treatment, MBBR–MBR system.

1. Introduction

Environmental pollution caused by untreated domestic wastewater remains a significant environmental challenge in many developing countries. Effective wastewater treatment

systems are therefore essential for protecting aquatic ecosystems and public health (UNEP, 2016). At the same time, environmental engineering education faces increasing demands to equip students with practical skills that complement theoretical knowledge.

Traditional lecture-based instruction often limits students' ability to understand complex environmental processes. Numerous studies have shown that experiential learning and project-based teaching methods significantly improve student engagement, conceptual understanding, and problem-solving skills in engineering education (Faba & Díaz, 2020; Mahalakshmi & Rathidevi, 2024). Practical laboratory models that simulate real treatment systems can therefore play an important role in bridging the gap between theory and professional practice.

Wastewater treatment technologies such as Moving Bed Biofilm Reactor (MBBR) and Membrane Bioreactor (MBR) systems represent advanced biological treatment approaches widely applied in modern wastewater management. Integrating these technologies into a laboratory-scale system offers a valuable opportunity for students to observe biological processes, operate treatment units, and analyze environmental data in real time.

Although advanced wastewater treatment technologies such as MBBR and MBR systems have been widely studied for their engineering performance, relatively few studies have examined their integration into environmental engineering education as experiential learning platforms. Most existing studies in engineering education focus on theoretical instruction, simulation tools, or small laboratory demonstrations rather than operational pilot-scale treatment systems. As a result, students often have limited opportunities to interact directly with real wastewater treatment processes and operational equipment. Developing technology-enhanced learning environments that combine pilot-scale treatment systems with laboratory instruction may therefore provide a more effective approach for improving practical competencies in environmental engineering education.

Recognizing this need, Thu Dau Mot University developed a pilot-scale MBBR–MBR wastewater treatment model designed both as a functional treatment system and as an educational platform for environmental engineering students. The objectives of this study were therefore:

1. To design and operate a compact pilot-scale MBBR–MBR wastewater treatment system suitable for laboratory instruction.
2. To evaluate the technical performance of the integrated treatment system.
3. To assess the effectiveness of the system as an experiential learning platform for environmental engineering students.

By integrating engineering practice into the academic environment, the model aims to strengthen experiential learning and enhance the professional competencies of future environmental engineers.

2. Overview of biological wastewater treatment technologies

Biological wastewater treatment processes rely on microorganisms to degrade organic pollutants and convert them into biomass, carbon dioxide, and other stable products. Conventional activated sludge systems have been widely used for decades; however, these systems often require large reactor volumes and complex sludge management (Tchobanoglous et al., 2003).

The Moving Bed Biofilm Reactor (MBBR) technology improves treatment efficiency by introducing floating biofilm carriers into aeration tanks. These carriers provide large surface areas for microbial attachment, allowing higher biomass concentrations and stable treatment performance under variable loading conditions (Ødegaard, 2006).

Membrane Bioreactor (MBR) systems combine biological treatment with membrane filtration. The membrane module acts as a physical barrier that separates treated water from suspended solids and microorganisms, producing high-quality effluent with very low turbidity and pathogen content (Judd, 2010). Despite challenges such as membrane fouling, MBR technology has become increasingly popular due to its compact design and high effluent quality.

Hybrid systems integrating MBBR and MBR technologies have recently gained attention because they combine the operational stability of biofilm processes with the separation efficiency of membrane filtration. Such systems can achieve high organic matter removal while maintaining compact reactor configurations (Saidulu et al., 2021).

From an educational perspective, pilot-scale treatment models based on these advanced technologies can serve as powerful learning tools. By interacting directly with operational treatment units, students can better understand the complex relationships between biological activity, reactor design, and environmental performance.

3. Materials and Methods

3.1. System design and configuration

A laboratory-scale wastewater treatment model was constructed at Thu Dau Mot University to simulate a compact treatment train integrating MBBR and MBR technologies. The system consisted of six sequential treatment units: Influent collection tank, Equalization tank with aeration and mixing, Anoxic tank for denitrification, Aerobic MBBR tank containing biofilm carriers, Membrane bioreactor tank equipped with a hollow-fiber membrane module, Disinfection tank using sodium hypochlorite (Figure 1).

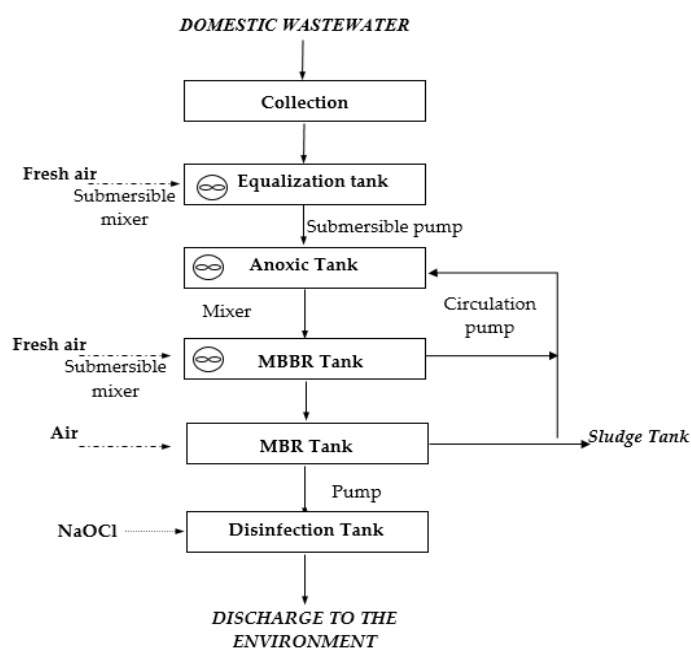


Figure 1. Schematic diagram of the pilot-scale MBBR–MBR wastewater treatment system

All tanks were fabricated from transparent acrylic to allow direct observation of biological processes during laboratory instruction.

The MBBR reactor contained polyethylene biofilm carriers with a filling ratio of approximately 30–40%. Continuous aeration maintained dissolved oxygen levels suitable for aerobic microbial activity. The membrane module in the MBR unit had a nominal pore size of 0.1 μm , allowing efficient separation of biomass and suspended solids.

3.2. Sampling and analytical methods

Water samples were collected from five points: influent, post-equalization, post-anoxic, post-MBBR, and final effluent (after MBR and disinfection). Sampling was conducted during the operation period. Each sample was analyzed for the following parameters:

Table 1. Analytical methods used for water quality analysis

No.	Parameter	Analytical method
1	Total Suspended Solids (TSS)	TCVN 6625:2000
2	Chemical Oxygen Demand (COD)	TCVN 6491:1999 (Closed reflux titrimetric method)
3	Biochemical Oxygen Demand (BOD ₅)	TCVN 6001-2:2008 (5-Day Incubation method)
4	Ammonium (NH ₄ ⁺ -N)	TCVN 6179-1:1996 (Nessler method – Spectrophotometry)
5	Total Phosphorus (TP)	TCVN 6202:2008 (Ascorbic acid spectrophotometric method)

All analytical procedures were carried out in accordance with the Vietnamese National Standards (TCVN), and aligned with internationally recognized scientific methodologies. Techniques employed included spectrophotometric analysis for nutrient and chemical parameters, titration for oxygen demand, gravimetric determination for suspended solids, and electrochemical methods for pH and dissolved oxygen measurements. All laboratory analyses were conducted at the Environmental Analysis Laboratory of Thu Dau Mot University, under strict adherence to quality assurance and quality control (QA/QC) protocols to ensure data accuracy and reproducibility.

The overall performance of the integrated wastewater treatment system was assessed based on its ability to meet the discharge criteria defined by Vietnamese environmental legislation. Specifically, the system was evaluated according to QCVN 14:2025/BTNMT – Column B, which stipulates the national technical regulation on domestic wastewater quality for effluents directly discharged into surface water bodies intended for domestic use.

3.3. Statistical analysis

All experiments and sample analyses were performed in triplicate to ensure statistical validity. Data were recorded using Excel and analyzed with basic statistical functions (mean, standard deviation) to evaluate treatment performance trends over time.

The following formulas were applied:

Mean ($\bar{x}$)

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

Standard Deviation (SD)

$$SD = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

Treatment Performance (%)

$$RE (\%) = \left(\frac{C_{Inlet} - C_{outlet}}{C_{Inlet}} \right) \times 100 \quad (3)$$

Where C_{Inlet} , C_{outlet} are the average concentrations of the parameter in the influent and effluent, respectively.

To determine the statistical significance of changes in water quality parameters before and after treatment, a one-way Analysis of Variance (ANOVA) was conducted using Statgraphics Centurion 19 software. A significance threshold of $\alpha = 0.05$ was applied, with p-values less than 0.05 indicating meaningful differences. This statistical method enhances the robustness of the performance assessment by minimizing the potential impact of random variability and experimental error, thereby improving the confidence in the observed treatment outcomes (Zar, 1999; Montgomery, 2017).

3.4. Educational evaluation

To evaluate the educational effectiveness of the learning platform, a structured questionnaire was administered to 32 fourth-year environmental engineering students who participated in laboratory activities using the pilot-scale treatment system during the Environmental Engineering Laboratory course.

The internal reliability of the questionnaire was evaluated using Cronbach's alpha to ensure the consistency of the survey items measuring student perceptions of learning outcomes.

The survey consisted of five Likert-scale questions (1 = strongly disagree to 5 = strongly agree) addressing:

- Understanding of wastewater treatment principles
- Laboratory skill development
- Confidence in environmental analysis
- Engagement in learning activities
- Perceived relevance to professional practice
- Participation in the survey was voluntary and anonymous.

4. Results and Discussion

4.1. Treatment performance of the pilot-scale MBBR–MBR system

The pilot-scale MBBR–MBR wastewater treatment model demonstrated stable performance during continuous operation under laboratory conditions. The system achieved high removal efficiencies for major pollutants typically present in domestic wastewater. Average removal efficiencies were 95.35% for COD, 95.41% for BOD₅, and 95.21% for TSS. Nutrient removal was also observed, with ammonium (NH₄⁺–N) reduced by 77.55% and total phosphorus (TP) by 97.98% (Figure 2).

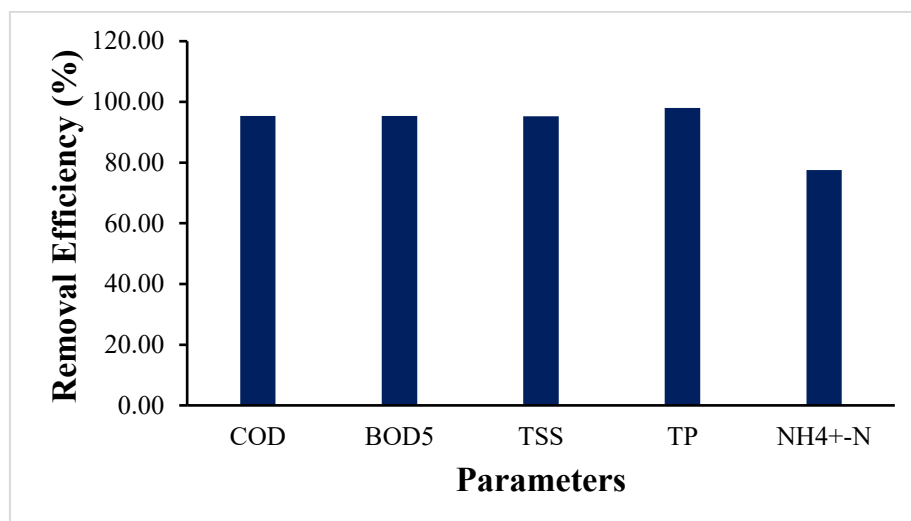


Figure 2. Pollutant removal efficiencies of the pilot-scale MBBR–MBR wastewater treatment system

The high removal efficiencies indicate effective biological degradation of organic matter within the MBBR reactor combined with efficient solid–liquid separation by the membrane filtration unit. The treated effluent consistently met the Vietnamese national technical regulation for domestic wastewater discharge.

These results are consistent with previous studies demonstrating the strong treatment capability of integrated MBBR–MBR systems for municipal wastewater treatment. For example, Martín-Pascual et al. (2016) reported COD removal efficiencies exceeding 90% under optimized operating conditions (Martín-Pascual et al., 2016). Similarly, Banti et al. (2023) demonstrated that biofilm carriers in hybrid systems enhance microbial activity and improve overall treatment stability (Banti et al., 2023).

From an educational perspective, the stable performance of the system is important because it allows students to observe clear treatment trends and understand how biological and membrane processes interact in modern wastewater treatment systems.

4.2. Educational value of the pilot treatment model

Beyond its technical performance, the primary objective of the system was to serve as an experiential learning platform for environmental engineering students. The transparent structure of the reactors and the modular system configuration enabled students to directly observe biological treatment processes such as aeration, biofilm development on carriers, and membrane filtration.

Students participated in several learning activities, including: operating the pilot treatment system, collecting wastewater samples at different treatment stages, conducting laboratory analyses for COD, BOD₅, and nutrient parameters, interpreting treatment performance data.

Through these activities, students gained hands-on experience with real environmental engineering processes that are typically difficult to demonstrate in conventional classroom settings.

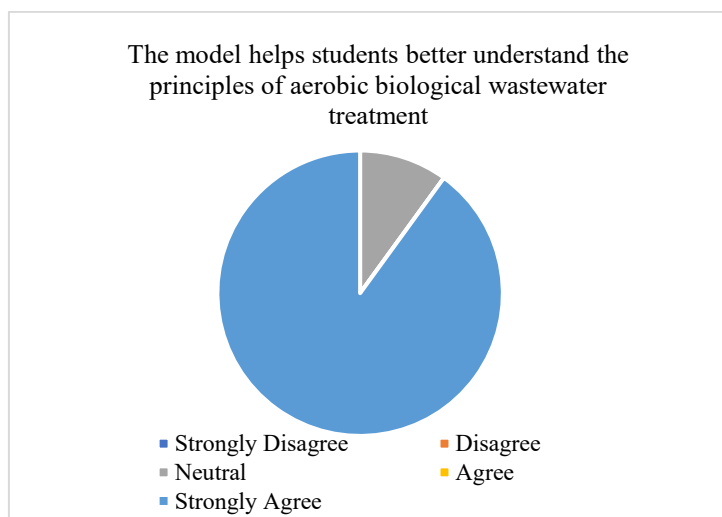


Figure 3. Student perceptions of improved understanding of wastewater treatment processes

Survey results from 32 participating students indicated improved understanding of biological wastewater treatment processes, enhanced laboratory skills, and increased engagement with course content (Figure 3). More than 90% of respondents agreed that the pilot system significantly improved their understanding of biological wastewater treatment processes. This highlights the effectiveness of learning through direct engagement. Throughout the semester, students were actively involved in all operational stages of the system from installation and setup, to operation, monitoring, sample collection and preservation, as well as laboratory analysis of key indicators (COD, BOD₅, TSS, NH₄⁺-N, TP). They also participated in performance evaluations relative to Vietnam's national discharge standards.

The results of the student survey indicate that the majority of participants perceived significant improvements in their understanding of wastewater treatment processes and laboratory skills (Table 2).

Table 2. Student perceptions of learning outcomes from the pilot-scale MBBR–MBR learning platform

Survey statement	Agree/Strongly agree (%)
Improved understanding of wastewater treatment processes	92
Improved laboratory skills	90
Increased confidence in environmental analysis	88
Increased engagement in learning activities	94
Relevance to professional practice	91

Students gained hands-on experience operating essential components such as pumps, aerators, and membrane filtration units, giving them practical exposure to how actual treatment systems function. As shown in Figure 4, 90% of the students reported increased confidence in conducting laboratory analyses and interpreting environmental data.

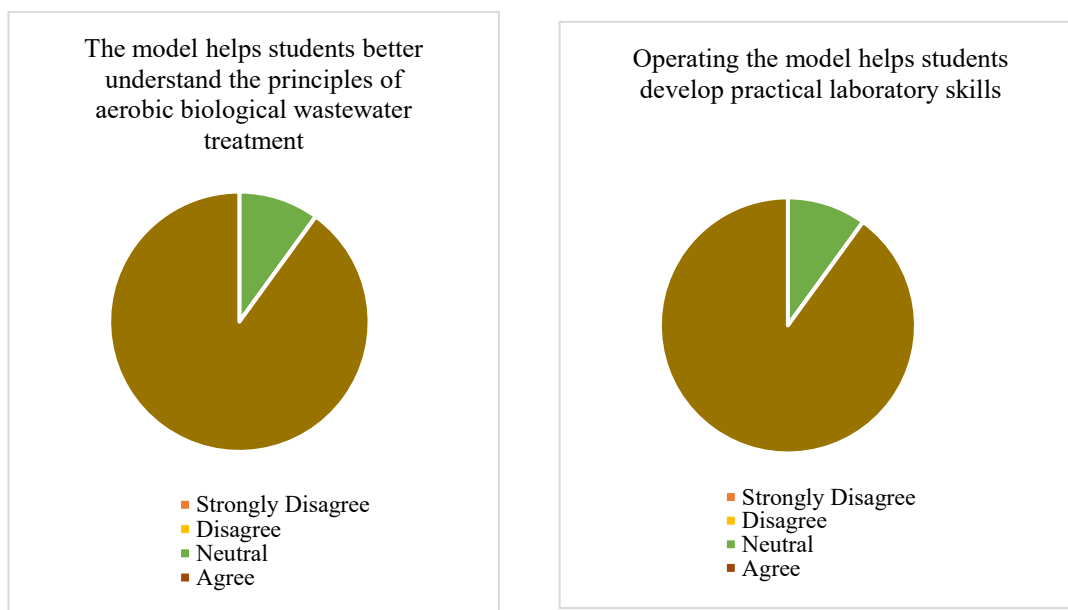


Figure 4. Student confidence in conducting environmental laboratory analysis

The model-based learning environment offered several pedagogical advantages. Firstly, it deepened students' theoretical understanding and functional knowledge of MBBR and MBR technologies. Secondly, it enhanced laboratory proficiency through real-time application of standard analytical techniques. Thirdly, it cultivated critical thinking and problem-solving abilities as students analyzed system data and diagnosed potential performance challenges.

Anonymous feedback further confirmed the model's educational value, with 90% of participants expressing greater engagement, confidence, and preparedness for professional roles in the field. Several students also indicated an increased interest in pursuing research or careers in water and wastewater treatment. These findings are consistent with existing literature emphasizing that hands-on, model-based learning significantly improves academic outcomes and practical skill development in engineering education.

The MBBR–MBR system served as a dual-function platform — not only simulating advanced treatment technologies effectively but also fostering essential competencies among future environmental professionals.

These findings are consistent with previous studies highlighting the effectiveness of project-based and experiential learning approaches in engineering education (Faba & Díaz, 2020). Hands-on laboratory models allow students to connect theoretical knowledge with real engineering applications, thereby improving engagement and learning outcomes.

4.3. Implications for environmental engineering education

The integration of pilot-scale wastewater treatment systems into university laboratories represents a promising pedagogical approach for improving environmental engineering education. Traditional lecture-based teaching methods often focus primarily on theoretical explanations of treatment processes, which can limit students' ability to understand the complexity of real environmental systems. In contrast, experiential learning approaches allow students to engage directly with real or simulated engineering

systems, thereby strengthening their conceptual understanding and practical competencies.

Experiential learning has been widely recognized as an effective pedagogical strategy in engineering education. A systematic review of project-based learning (PBL) in engineering programs found that experiential learning activities significantly enhance students' ability to apply theoretical knowledge to real-world engineering problems and improve their professional skills development. The review analyzed 54 studies and concluded that project-based learning environments can foster multidisciplinary collaboration, sustainability awareness, and problem-solving capabilities among engineering students (Lavado et al., 2024).

Similarly, studies in environmental engineering education have shown that hands-on laboratory projects improve student engagement and deepen their understanding of complex environmental processes. For example, a project-based learning course in environmental engineering required students to design and implement experimental treatment systems such as stormwater treatment and water purification processes. The results indicated that students gained stronger analytical skills and demonstrated improved comprehension of environmental engineering principles through active participation in experimental projects (Gude et al., 2015).

Another recent study examining active learning strategies in environmental engineering courses reported that combining project-based learning with interactive teaching tools significantly increased student engagement and academic performance. Over a five-year implementation period involving approximately 130 students annually, average final grades increased noticeably after introducing hands-on projects and interactive learning activities. These results highlight the importance of integrating practical experimentation into engineering education to enhance learning outcomes (Pedro et al., 2025).

Within this context, the pilot-scale MBBR–MBR wastewater treatment model developed in the present study provides several important educational benefits.

First, the transparent reactor design allows students to visually observe biological treatment processes such as aeration dynamics, biofilm formation on carrier media, and membrane filtration mechanisms. Visualization of these processes helps students better understand the interactions between microbial activity, hydraulic conditions, and pollutant removal efficiency.

Second, the system supports the development of essential environmental monitoring skills. Students can collect wastewater samples at different treatment stages and perform laboratory analyses for parameters such as chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), suspended solids, and nutrients. Through these activities, students become familiar with standard environmental laboratory techniques and data interpretation methods commonly used in professional environmental monitoring.

Third, the system promotes problem-solving and engineering design skills. Students can evaluate treatment performance, identify operational issues such as membrane fouling or aeration imbalance, and propose technical solutions. These activities reflect real engineering practice and encourage students to think critically about system optimization and environmental sustainability.

Another important advantage of experiential learning platforms is their potential to improve student motivation and engagement. Research in engineering education suggests

that students are more motivated when they work on projects with tangible real-world applications, particularly those addressing environmental and sustainability challenges. Such learning environments encourage students to take ownership of their learning process and develop stronger professional identities as future engineers (Lavado et al., 2024).

The implementation of pilot-scale treatment systems may be particularly valuable for universities in developing countries where access to full-scale wastewater treatment plants is limited. Laboratory-scale models provide a practical alternative that allows students to simulate real treatment processes within an academic environment. These systems can serve as experimental platforms for teaching, research, and innovation in environmental technologies.

Furthermore, experiential learning approaches align closely with modern educational trends emphasizing active learning, sustainability education, and interdisciplinary collaboration. Engineering programs worldwide are increasingly adopting experiential learning frameworks to prepare students for the complex environmental challenges associated with urbanization, industrialization, and climate change. By integrating pilot-scale environmental technologies into the curriculum, universities can enhance both the quality of engineering education and the readiness of graduates to address real environmental problems.

Overall, the findings of this study suggest that the integration of pilot-scale wastewater treatment systems into environmental engineering laboratories represents an effective strategy for improving experiential learning and developing practical engineering competencies. Future research should explore the long-term educational impacts of such learning platforms, including their influence on student learning outcomes, professional skill development, and career readiness.

All figures and tables in this article are the results of the authors' own research.

4.4. Limitations of the study

This study has several limitations. The educational evaluation was conducted with a relatively small sample size and focused primarily on short-term student perceptions. In addition, the study was implemented within a single environmental engineering program, which may limit the generalizability of the findings. Future research should investigate the long-term impacts of experiential learning platforms on student learning outcomes, professional skill development, and career readiness across different educational contexts.

5. Conclusion

This study presented the development and evaluation of a pilot-scale wastewater treatment learning platform based on an integrated Moving Bed Biofilm Reactor–Membrane Bioreactor (MBBR–MBR) system implemented at Thu Dau Mot University, Vietnam. The system was designed not only to simulate advanced biological wastewater treatment technologies but also to function as an experiential learning tool for environmental engineering education.

The experimental results demonstrated that the integrated treatment system achieved high pollutant removal efficiencies, with average reductions of 95.35% for chemical oxygen demand (COD), 95.41% for biochemical oxygen demand (BOD₅), and 95.21% for total suspended solids (TSS). Nutrient removal was also significant, confirming the technical

effectiveness and operational stability of the hybrid MBBR–MBR process under laboratory conditions. These results indicate that the pilot system can effectively replicate key treatment mechanisms commonly applied in modern municipal wastewater treatment plants.

More importantly, the study highlights the educational value of integrating pilot-scale environmental technologies into university teaching laboratories. The system enabled students to directly observe biological treatment processes, participate in system operation, collect wastewater samples, and perform environmental monitoring analyses. Survey results indicated that the majority of students perceived the learning platform as highly beneficial for improving their understanding of wastewater treatment processes and strengthening their laboratory and analytical skills.

The findings suggest that experiential learning environments supported by real or simulated engineering systems can significantly enhance student engagement and practical competency development in environmental engineering education. By connecting theoretical knowledge with hands-on experimentation, such learning platforms contribute to a deeper understanding of environmental technologies and better preparation for professional practice.

Furthermore, the implementation of pilot-scale treatment systems can provide an effective alternative for universities that have limited access to full-scale wastewater treatment facilities. These systems offer flexible platforms for teaching, student research, and technology demonstration within the academic environment.

Future research should further investigate the long-term impacts of experiential learning platforms on student learning outcomes and professional skill development. In addition, integrating digital monitoring tools, simulation software, or remote learning technologies could further enhance the educational effectiveness of such systems in engineering education.

Overall, the pilot-scale MBBR–MBR model developed in this study represents a valuable educational innovation that supports the integration of engineering technology and experiential learning in environmental engineering programs.

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