

# Performance evaluation of a compact integrated anoxic-aerotank membrane bioreactor system for domestic wastewater treatment

An The Huynh<sup>1\*</sup> , Trung Minh Dao<sup>2</sup>

<sup>1</sup> Department of Environmental Resources, Institute of Green and Sustainable Technology, Thu Dau Mot University, Ho Chi Minh City, Vietnam

<sup>2</sup> Institute for Environmental Science, Engineering and Management, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam

\* Corresponding author's e-mail: [anht@tdmu.edu.vn](mailto:anht@tdmu.edu.vn)

## ABSTRACT

This study aimed to evaluate the treatment performance of a compact integrated anoxic-aerotank membrane bioreactor (MBR) system designed for decentralized domestic wastewater treatment in a university campus environment. The experimental system was installed at Thu Dau Mot University (Vietnam) with a design capacity of 1.0 m<sup>3</sup>/day to investigate the effectiveness of combining biological treatment processes with membrane filtration under practical operating conditions. The treatment configuration consisted of an equalization tank, an anoxic reactor, an aerobic moving bed biofilm reactor (MBBR), and a submerged membrane bioreactor followed by a disinfection unit. Wastewater samples were collected at different treatment stages over a 50-day operational period. Key water quality parameters including BOD<sub>5</sub>, COD, TSS, NH<sub>4</sub><sup>+</sup>-N, total phosphorus (TP), and coliforms were analyzed to assess system performance and stage-based pollutant removal. The results demonstrated high treatment efficiencies, with overall removal rates reaching 96.2% for BOD<sub>5</sub> and COD, 99.5% for TSS, 92.5% for NH<sub>4</sub><sup>+</sup>-N, 86.7% for TP, and 99.6% for coliform bacteria. The final effluent quality satisfied the Vietnamese discharge standard QCVN 14:2008/BTNMT (Column A). Stage-based analysis revealed that the anoxic unit played a key role in nitrogen removal, while the aerobic MBBR process contributed mainly to organic matter degradation. The membrane bioreactor ensured effective solid-liquid separation and produced a stable high-quality effluent. The study demonstrates that the integrated anoxic-aerotank MBR configuration can provide an efficient and compact solution for decentralized wastewater treatment in institutional environments where land availability is limited. However, the study was conducted at laboratory scale, and further research is required to evaluate long-term operation, membrane fouling control, and energy consumption under large-scale conditions. The findings contribute new experimental data on compact hybrid biological membrane systems for campus-scale wastewater treatment and provide practical insights for the development of decentralized wastewater management solutions in developing countries.

**Keywords:** domestic wastewater, anoxic-aerotank MBR, membrane bioreactor, decentralized wastewater treatment.

## INTRODUCTION

Domestic wastewater generated within university campuses represents a unique subset of community wastewater with highly variable pollutant loads due to periodic occupancy, dining facilities, academic laboratories, and residential dormitories (Dwumfour et al., 2020; Cao et al., 2022; Ash et al., 2023; Litthavong et al., 2023;

El-Aassar et al., 2025). If not properly treated, such wastewater may pose significant environmental and public health risks when discharged directly into receiving water bodies, particularly in regions where centralized wastewater infrastructure remains limited. In Vietnam, the rapid expansion of universities and student populations has increased the urgency of developing compact and efficient on-site wastewater

treatment solutions suitable for campus environments such as Thu Dau Mot University.

Membrane bioreactor (MBR) technology has emerged as a promising solution for decentralized wastewater treatment due to its ability to combine biological degradation with membrane separation, producing high-quality effluent while requiring a relatively small footprint (Judd, 2010; Helmi et al., 2020; Gibas et al., 2021). By retaining high concentrations of biomass and effectively separating suspended solids, MBR systems can achieve superior removal of organic matter, nutrients, and pathogens compared with conventional activated sludge processes (Namdeti et al., 2025; Nguyen et al., 2017). Previous studies have demonstrated that integrated biological membrane systems can achieve high removal efficiencies for chemical oxygen demand (COD), ammonia nitrogen, total nitrogen, and phosphorus even under low carbon loading conditions. For instance, an AOA–MBR system achieved more than 94% COD removal and 98% ammonia nitrogen removal when treating low-carbon domestic wastewater (Nwachi et al., 2025).

Previous laboratory-scale investigations of MBR applications for residential wastewater have reported average removal efficiencies ranging from 89% to 95% for key pollutants such as BOD<sub>5</sub>, COD, total nitrogen (TN), and total phosphorus (TP), confirming the feasibility of MBR-based systems for municipal and small community wastewater treatment (Rahman et al., 2023). However, systematic studies evaluating the performance of compact decentralized wastewater treatment systems in university campus environments, particularly in Vietnam, remain scarce, particularly studies that integrate engineering design considerations with performance evaluation under practical operating conditions.

Hybrid biological treatment systems that combine suspended activated sludge and attached biofilm processes have been widely investigated because biofilm carriers can enhance microbial retention, improve nitrification efficiency, and increase system stability under fluctuating organic loading conditions (Meng et al., 2009; Zhang et al., 2019; Palmarin et al., 2019). Many hybrid configurations, including A2O–MBR and MBBR–MBR processes, have been successfully applied in municipal wastewater treatment plants to enhance nutrient removal and improve effluent quality.

However, most previous studies have focused primarily on large-scale municipal wastewater treatment facilities, while applications of compact

hybrid configurations for decentralized wastewater treatment in institutional environments such as university campuses remain relatively limited. In such environments, treatment systems must be compact, adaptable to fluctuating wastewater generation patterns, and capable of achieving high effluent quality under land-limited conditions.

Unlike conventional A2O–MBR or municipal-scale hybrid treatment systems, the proposed configuration integrates an anoxic reactor, an MBBR aerotank, and a membrane bioreactor into a compact modular system designed for decentralized wastewater treatment in land-limited environments.

Therefore, this study aims to experimentally evaluate the performance of a compact integrated anoxic-aerotank MBR system designed for decentralized domestic wastewater treatment in a university campus environment. Unlike conventional municipal wastewater treatment systems, the proposed configuration integrates an anoxic reactor, an MBBR aerotank, and a membrane bioreactor into a compact modular system suitable for environments with limited land availability and fluctuating wastewater generation patterns.

The main objective of this research is to assess the pollutant removal efficiency and operational performance of the integrated system under practical operating conditions. In addition, the study analyzes the contribution of individual treatment stages to the overall treatment efficiency in order to better understand the operational mechanisms of hybrid biological–membrane treatment processes.

It is hypothesized that the combination of suspended activated sludge, attached biofilm carriers, and membrane filtration can significantly enhance organic matter and nutrient removal while maintaining stable effluent quality. The results of this study are expected to provide experimental evidence supporting the application of compact hybrid wastewater treatment systems for decentralized wastewater management in institutional environments.

## MATERIALS AND METHODS

### Study site and wastewater characteristics

The experimental study was conducted at Thu Dau Mot University, located in Ho Chi Minh City, Vietnam. Domestic wastewater was collected from cafeterias and academic buildings. Composite

samples were collected over daily operating hours to compensate for variations in flow and pollutant loading resulting from student activity.

Influent wastewater quality was analyzed prior to treatment and characterized by high concentrations of organic matter, suspended solids, nutrients, and coliform bacteria (Table 1). These parameters guided the design and operational settings of the treatment system and form the basis for calculating removal efficiencies.

Table 1 summarizes the characteristics of influent domestic wastewater collected from Thu Dau Mot University. The wastewater exhibited relatively high concentrations of organic matter and suspended solids, with average BOD<sub>5</sub> and COD values of  $550 \pm 25$  mg/L and  $715 \pm 30$  mg/L, respectively, indicating a high organic load typical of wastewater generated from campus dormitories and cafeterias. Nutrient concentrations were also notable, particularly ammonium ( $40 \pm 3$  mg/L) and total phosphorus ( $15 \pm 0.6$  mg/L), which highlight the potential risk of eutrophication if discharged without adequate treatment. In addition, the high coliform density ( $2.4 \pm 0.1 \times 10^5$  MPN/100 mL) reflects significant microbiological contamination, emphasizing the necessity of an effective biological and disinfection process prior to discharge.

### System design and configuration

The laboratory-scale wastewater treatment system was designed and implemented at Thu Dau Mot University (Vietnam) to simulate a compact and efficient treatment process for domestic wastewater in a university campus environment. The system integrates biological treatment and membrane separation technologies, following the treatment sequence illustrated in (Figure 1).

Raw domestic wastewater generated from campus activities was first conveyed to a collection

tank, which served as the influent receiving unit. From this tank, wastewater was pumped into the equalization tank, where a submersible mixer and air injection were employed to homogenize the influent flow and pollutant concentrations, as well as to prevent solids settling and odor formation.

After equalization, wastewater was transferred to the anoxic tank, which was operated under oxygen-limited conditions. A mechanical mixer was installed to maintain uniform mixing without introducing dissolved oxygen. In this unit, nitrate reduction occurred through biological denitrification, utilizing organic carbon present in the wastewater as an electron donor. Internal circulation from the downstream aerobic treatment unit was provided by a circulation pump to supply nitrate-rich mixed liquor to the anoxic zone, thereby enhancing nitrogen removal efficiency.

The effluent from the anoxic tank flowed into the moving bed biofilm reactor (MBBR) tank, where aerobic biological degradation of organic matter and nitrification took place. The MBBR tank was equipped with free-floating biofilm carriers and supplied with continuous aeration through submerged air diffusers to maintain appropriate dissolved oxygen levels for aerobic microorganisms. The presence of attached biomass on carriers increased the effective biomass concentration and improved process stability under fluctuating loads.

Subsequently, treated wastewater entered the membrane bioreactor tank, which combined biological treatment with physical solid-liquid separation. A submerged membrane module was installed within the bioreactor, and treated water was extracted by suction pumping through the membrane. This configuration ensured near-complete retention of suspended solids and biomass, resulting in a high-quality effluent. Excess sludge generated during the process was intermittently

**Table 1.** Characteristics of influent domestic wastewater at Thu Dau Mot University

No.	Parameter	Unit	Influent concentration
1	pH	–	$8.5 \pm 0.1$
2	Biochemical oxygen demand (BOD <sub>5</sub> )	mg/L	$550 \pm 25$
3	Chemical oxygen demand (COD)	mg/L	$715 \pm 30$
4	Total suspended solids (TSS)	mg/L	$550 \pm 20$
5	Ammonium (NH <sub>4</sub> <sup>+</sup> -N)	mg/L	$40 \pm 3.0$
6	Total phosphorus (TP)	mg/L	$15 \pm 0.6$
7	Coliforms	MPN/100 mL	$(2.4 \pm 0.1) \times 10^5$

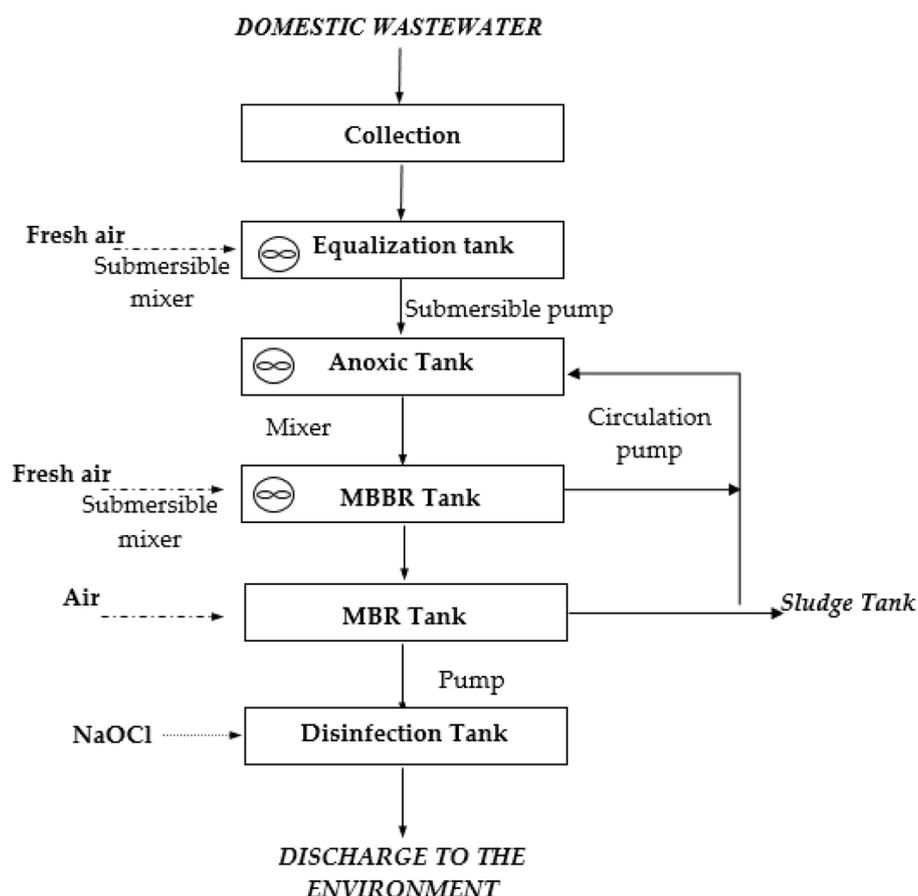


Figure 1. Design model diagram

withdrawn from the MBR tank and conveyed to a sludge storage tank for further handling.

Finally, permeate from the MBR unit was directed to the disinfection tank, where sodium hypochlorite (NaOCl) was dosed to inactivate pathogenic microorganisms before discharge. The disinfected effluent was then released into the environment in compliance with the applicable discharge standards.

The entire system was constructed using corrosion-resistant materials and mounted on a compact frame to facilitate observation, operation, and maintenance. The integrated configuration reflects a practical and space-efficient solution for on-site domestic wastewater treatment in university campuses and similar decentralized settings.

### Operational procedures

#### *Hydraulic loading and flow control*

The experimental system was operated at an average influent flow rate of 1.0 m<sup>3</sup>/day, corresponding to the design capacity of the laboratory-scale model. Raw domestic wastewater was

continuously introduced into the collection tank, which provided an initial hydraulic retention time (HRT) of approximately 60 minutes to stabilize short-term flow variations.

Subsequently, wastewater was transferred to the equalization tank, where an HRT of approximately 8 hours was maintained to homogenize influent characteristics and mitigate diurnal fluctuations in organic and hydraulic loading. From the equalization tank, wastewater flowed sequentially through the anoxic tank, MBBR tank, and MBR tank by means of controlled pumping.

Flow rates between treatment units were regulated using calibrated pumps and control valves to ensure stable hydraulic conditions for biological processes and membrane filtration. Excess sludge generated during system operation was periodically withdrawn from the MBR tank and conveyed to the sludge storage tank to maintain steady biomass concentrations (Figure 2).

#### *Biological treatment conditions*

The integrated treatment system consisted of three main biological units: an anoxic tank, an



Figure 2. Schematic diagram of the constructed experimental model device

aerobic MBBR, and a MBR. Each unit was operated under controlled conditions to facilitate sequential nitrogen transformation and efficient organic matter removal.

- Anoxic tank:

The anoxic tank was operated under oxygen-limited conditions to promote heterotrophic denitrification. Dissolved oxygen (DO) concentrations were maintained below 0.5 mg/L to prevent the inhibition of denitrifying bacteria. Mechanical mixing was applied to ensure uniform distribution of substrates and microbial biomass while avoiding oxygen intrusion into the reactor.

To enhance nitrogen removal, internal recirculation of mixed liquor from the downstream aerobic unit was implemented at a ratio of approximately 0.5:1 (recirculated flow to influent flow). This recirculation supplied nitrate-rich liquor to the anoxic zone, thereby facilitating the biological reduction of nitrate to nitrogen gas through denitrification processes.

- MBBR aerotank:

The MBBR served as the primary aerobic biological treatment unit responsible for the degradation of organic pollutants and nitrification. Free-floating biofilm carriers were introduced into the reactor at a filling ratio of approximately 30–40% of the working volume, providing a large specific surface area for the development of attached microbial communities.

Continuous aeration was supplied through fine-bubble diffusers to maintain dissolved oxygen concentrations within the range of 2.0–3.0 mg/L, which is favorable for aerobic microbial activity and nitrifying bacteria. The coexistence

of suspended activated sludge and attached bio-film biomass increased microbial retention and improved process stability under variable organic loading conditions. This hybrid configuration also enhanced nitrification efficiency by providing suitable microenvironments for different microbial populations.

- Membrane bioreactor:

The final treatment stage consisted of a submerged membrane bioreactor responsible for solid–liquid separation and polishing of the treated effluent. Mixed liquor suspended solids (MLSS) concentrations in the MBR tank were maintained at approximately 4000–4500 mg/L, allowing the retention of high biomass concentrations within the system.

A submerged membrane module was used to separate treated water from the mixed liquor. Permeate was withdrawn through the membrane using a suction pump operating under controlled transmembrane pressure (TMP). This membrane separation process effectively retained suspended solids, microorganisms, and colloidal particles, resulting in high-quality effluent.

To ensure stable membrane operation during the experimental period, routine operational procedures were implemented, including periodic membrane cleaning and continuous air scouring. These measures helped minimize membrane fouling and maintain consistent filtration performance throughout the experimental study (Table 2).

### Sampling and analytical methods

Water samples were collected at five representative locations along the treatment process,

**Table 2.** Operational parameters of the experimental system

Parameter	Value
Treatment capacity	1.0 m <sup>3</sup> /day
Equalization tank HRT	8 h
Anoxic tank HRT	2 h
MBBR tank HRT	6 h
MBR tank HRT	3 h
Total hydraulic retention time (HRT)	19 h
Dissolved oxygen in anoxic tank	< 0.5 mg/L
Dissolved oxygen in MBBR tank	2.0–3.0 mg/L
MLSS concentration in MBR	4000–4500 mg/L
Biofilm carrier filling ratio	30–40%
Internal recirculation ratio	0.5 : 1
Membrane type	Submerged membrane
Membrane pore size	0.1–0.4 μm

corresponding to the main treatment units shown in (Figure 1), to evaluate the performance of each treatment stage. The sampling points included: influent wastewater, post-equalization tank, post-anoxic tank, post-MBBR tank, and final effluent after MBR and disinfection.

Sampling was conducted during the stable operation period of the system. All samples were collected as grab samples using clean polyethylene bottles and immediately preserved at 4 °C prior to analysis. Each parameter was analyzed in triplicate to ensure data reliability and statistical validity.

The experimental system was operated continuously for a total period of 50 days. The first 20 days were considered as the start-up phase to allow microbial acclimation and biofilm development within the MBBR carriers and the activated sludge system. After this period, the system reached stable operational conditions,

and performance monitoring was conducted during the subsequent 30 days. Wastewater samples were collected twice per week during the stable operational phase, resulting in a total dataset of approximately 45 samples for each monitored parameter.

The collected samples were analyzed for key physicochemical parameters, including pH, total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD<sub>5</sub>), ammonium (NH<sub>4</sub><sup>+</sup>-N), and total phosphorus (TP). Analytical methods followed the Vietnamese National Standards (TCVN), as summarized in Table 3, which are consistent with internationally recognized analytical procedures.

All laboratory analyses were performed at the Environmental Analysis Laboratory of Thu Dau Mot University, following strict quality assurance and quality control (QA/QC) procedures, including instrument calibration, blank analysis, and replicate measurements to ensure data accuracy and reproducibility.

The overall performance of the integrated treatment system was evaluated based on its ability to meet the discharge limits specified in QCVN 14:2008/BTNMT (Column A), which regulates the quality of domestic wastewater discharged into surface water bodies used for domestic purposes. Experimental data were recorded and processed using Microsoft Excel, and basic statistical analyses, including calculation of mean values and standard deviations, were applied to assess treatment efficiency trends throughout the operational period.

### Performance evaluation

The treatment performance of individual unit processes as well as the overall integrated system was evaluated based on the removal efficiency of key physicochemical parameters. Removal

**Table 3.** Analytical methods used in this study

No.	Parameter	Analytical method
1	pH	TCVN 6492-1999
2	Total suspended solids (TSS)	TCVN 6053-1995
3	Chemical oxygen demand (COD)	TCVN 6491:1999
4	Biochemical oxygen demand (BOD <sub>5</sub> )	TCVN 6001-1995
5	Ammonium (NH <sub>4</sub> <sup>+</sup> -N)	TCVN 5988-1995
6	Total phosphorus (TP)	TCVN 6202:2008
7	Coliforms	TCVN 6187-1-1996

efficiency (RE) for each treatment stage was calculated using the following equation:

$$RE (\%) = \left( \frac{C_{In} - C_{out}}{C_{In}} \right) \times 100 \quad (1)$$

where:  $C_{in}$  (mg/L) represents the pollutant concentration at the inlet of a specific treatment unit, and  $C_{out}$  (mg/L) denotes the corresponding concentration at the outlet of that unit.

Removal efficiencies were determined for pH, BOD<sub>5</sub>, COD, TSS, NH<sub>4</sub><sup>+</sup>-N, and total phosphorus (TP) at each sampling point to assess the contribution of individual processes, including equalization, anoxic treatment, MBBR aeration, and membrane filtration. The cumulative performance of the system was evaluated using the final effluent quality after MBR and disinfection.

The effectiveness of the integrated wastewater treatment system was benchmarked against the Vietnamese National Technical Regulation on Domestic Wastewater (QCVN 14:2008/BT-NMT, Column A), which specifies discharge limits for effluents released into surface water bodies intended for domestic use. Compliance with this standard was used as the primary criterion to evaluate the suitability and reliability of the proposed treatment configuration for application in university campus environments.

### Statistical analysis

Experimental data were analyzed using descriptive statistical methods, including the calculation of mean values and standard deviations. These statistical indicators were used to evaluate the stability and variability of treatment performance during the operational period.

All statistical analyses were conducted using Microsoft Excel, which was considered adequate for handling the dataset size and experimental design of the laboratory-scale system. Because the primary objective of the study was to evaluate treatment performance and operational stability of the system rather than hypothesis testing, descriptive statistical analysis was considered sufficient for interpreting the experimental data.

## RESULTS AND DISCUSSION

### Overall treatment performance

The integrated wastewater treatment system combining anoxic treatment, aerobic biological processes, and membrane filtration demonstrated high efficiency in treating domestic wastewater generated within a university environment. The influent wastewater was characterized by elevated pollutant concentrations, including BOD<sub>5</sub> of 550 mg/L, COD of 715 mg/L, TSS of 550 mg/L, NH<sub>4</sub><sup>+</sup>-N of 40 mg/L, total phosphorus (TP) of 15 mg/L, and coliforms of  $2.4 \times 10^5$  MPN/100 mL, indicating a relatively high-strength domestic wastewater influenced by campus activities.

After passing through the complete treatment train, the effluent quality was markedly improved, as summarized in Table 4. The concentrations of BOD<sub>5</sub> and COD decreased from  $550 \pm 25$  mg/L and  $715 \pm 30$  mg/L in the influent to  $21 \pm 2.0$  mg/L and  $27 \pm 1.3$  mg/L in the final effluent, corresponding to overall removal efficiencies of 96.2% for both parameters. The TSS concentration was reduced from  $550 \pm 20$  mg/L to  $3 \pm 0.8$  mg/L, achieving a removal efficiency of 99.5%, indicating effective solid-liquid separation throughout the biological and membrane-based processes.

**Table 4.** Influent and effluent characteristics and overall removal efficiencies of the integrated treatment system

Parameter	Unit	Influent	Final effluent	Overall removal efficiency (%)	QCVN 14:2008/ BTNMT (Column A)
pH	–	8.5 ± 0.1	7.3 ± 0.2	–	5–9
BOD <sub>5</sub>	mg/L	550 ± 25	21 ± 2.0	96.2	30
COD	mg/L	715 ± 30	27 ± 1.3	96.2	100
TSS	mg/L	550 ± 20	3 ± 0.8	99.5	50
NH <sub>4</sub> <sup>+</sup> -N	mg/L	40 ± 3.0	3 ± 0.6	92.5	30
Total phosphorus (TP)	mg/L	15 ± 0.6	2 ± 1.0	86.7	6
Coliforms	MPN/100 mL	$(2.4 \pm 0.1) \times 10^5$	930 ± 20	99.6	3,000

Nutrient removal was also significant. The concentration of  $\text{NH}_4^+\text{-N}$  decreased from  $40 \pm 3.0$  mg/L to  $3 \pm 0.6$  mg/L, resulting in a removal efficiency of 92.5%, while TP was reduced from  $15 \pm 0.6$  mg/L to  $2 \pm 1.0$  mg/L, corresponding to an overall removal efficiency of 86.7%. In addition, the disinfection stage effectively reduced coliforms from  $(2.4 \pm 0.1) \times 10^5$  to  $930 \pm 20$  MPN/100 mL, achieving a removal efficiency of 99.6%.

The pH of the treated effluent remained stable of  $7.3 \pm 0.2$ , which is well within the permissible limits. Importantly, all monitored parameters in the final effluent complied with the discharge standards specified in QCVN 14:2008/BTNMT (Column A) for domestic wastewater, confirming the suitability of the proposed treatment system for practical application.

To place the obtained results in a broader context, the overall removal efficiencies achieved in this study were compared with those reported in selected international studies employing biological and membrane-based systems for domestic wastewater treatment. The comparison focuses on key parameters, including BOD<sub>5</sub>, COD, TSS,  $\text{NH}_4^+\text{-N}$ , and TP, which are commonly used indicators to evaluate the performance of wastewater treatment processes.

As shown in Table 5, the system investigated in this study achieved consistently high removal efficiencies for organic matter, suspended solids, and nutrients. In particular, the removal efficiencies of BOD<sub>5</sub> and COD (both 96.2%) are higher than those reported for conventional laboratory-scale MBR systems treating domestic wastewater (Rahman et al., 2023). The TSS removal efficiency (99.5%) indicates

excellent solid–liquid separation performance, reflecting the effectiveness of membrane filtration in the final treatment stage.

Compared with hybrid MBBR–MBR and pilot-scale MBBR systems, the proposed system demonstrates comparable or superior performance in terms of organic matter removal, while also achieving higher nutrient removal efficiencies, especially for  $\text{NH}_4^+\text{-N}$  (92.5%) and TP (86.7%). Importantly, the final effluent quality in this study fully complied with the discharge limits specified in QCVN 14:2008/BTNMT (Column A), highlighting the applicability of the proposed configuration for decentralized domestic wastewater treatment under stringent regulatory requirements.

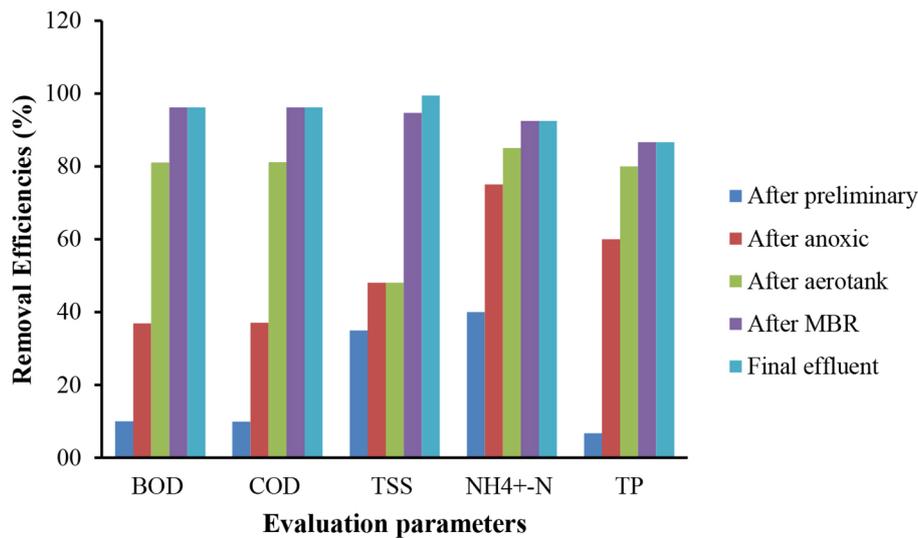
### Contribution of treatment stages based on removal efficiencies

The contribution of each treatment stage to the overall performance of the system was evaluated based on the cumulative removal efficiencies of key pollutants, including BOD, COD, TSS,  $\text{NH}_4^+\text{-N}$ , and TP. As shown in (Figure 3). The stepwise variation in removal efficiency clearly demonstrates the distinct and complementary roles of individual treatment units.

During the preliminary treatment stage, relatively low removal efficiencies were observed for organic matter, with BOD and COD removals of 10.0% and 9.9%, respectively. In contrast, this stage contributed significantly to suspended solids and ammonium reduction, achieving 34.9% TSS removal and 40.0%  $\text{NH}_4^+\text{-N}$  removal, mainly due to physical separation and partial settling. The removal of TP was limited (6.7%), indicating

**Table 5.** Comparison of pollutant removal efficiencies between the proposed anoxic-aerotank MBR system and previous studies

Study	System type	Key removal (%)	Notes and source
This study (Thu Dau Mot University)	Anoxic-Aerotank-MBR	BOD <sub>5</sub> : 96.2 COD: 96.2 TSS: 99.5 $\text{NH}_4^+\text{-N}$ : 92.5 TP: 86.7	Final treated effluent compliant with QCVN 14:2008/BTNMT (Column A)
Membrane bioreactor	MBR -domestic wastewater	BOD <sub>5</sub> : 94.6 COD: 92.6 TSS: 89.4 TN: 64.6 TP: 79.2	Laboratory MBR with submerged membranes treating domestic wastewater (Rahman et al., 2023)
Hybrid MBBR-MBR	MBBR-MBR hybrid	BOD <sub>5</sub> : 88 COD: 80–90	Reported in compact municipal wastewater treatment studies; indicates high efficiency comparable to conventional systems (Wang et al., 2023)
Pilot-scale MBBR	MBBR	BOD <sub>5</sub> : 98 COD: 85–90	Greywater MBBR pilot, confirms strong organic removal potential (Wang et al., 2023)



**Figure 3.** Cumulative removal efficiencies of major pollutants across different treatment stages

that preliminary treatment primarily serves as a load equalization and protection step for downstream biological processes.

The anoxic treatment stage showed a substantial increase in overall treatment performance. At this stage, cumulative removal efficiencies reached 36.9% for BOD, 37.1% for COD, and 48.0% for TSS. Notably, the anoxic process played a critical role in nutrient removal, achieving 75.0% NH<sub>4</sub><sup>+</sup>-N removal and 60.0% TP removal, which can be attributed to effective denitrification and phosphorus uptake under anoxic conditions.

Following anoxic treatment, the aerobic biological treatment stage (aerotank) became the dominant contributor to organic matter degradation. The cumulative removal efficiencies of BOD and COD increased sharply to 81.1%, confirming the effectiveness of aerobic biodegradation. Nutrient removal was further enhanced, with NH<sub>4</sub><sup>+</sup>-N and TP removals reaching 85.0% and 80.0%, respectively. However, the cumulative TSS removal remained unchanged at 48.0%, indicating that suspended solids were primarily retained in the system and required a physical separation process for effective removal.

The membrane bioreactor stage played a decisive role in polishing the effluent and achieving high overall treatment efficiency. After the MBR, cumulative removal efficiencies increased to 96.2% for BOD and COD, 94.7% for TSS, 92.5% for NH<sub>4</sub><sup>+</sup>-N, and 86.7% for TP. The membrane ensured effective solid–liquid separation and biomass retention, resulting in a sharp improvement in effluent clarity and stability.

The experimental system was operated for a total period of 50 days, including an initial start-up and stabilization phase followed by a stable operational period. During the first 20 days, the system gradually reached stable biological activity and membrane filtration conditions. The subsequent 30 days were considered the stable operational period during which wastewater samples were regularly collected and analyzed for performance evaluation. During this stable phase, no severe membrane fouling was observed, and the transmembrane pressure remained within a normal operational range, indicating stable membrane performance throughout the monitoring period.

In the final effluent, the cumulative TSS removal further increased to 99.5%, while the removal efficiencies of BOD, COD, NH<sub>4</sub><sup>+</sup>-N, and TP remained stable, indicating that the system had already reached optimal treatment performance at the MBR stage. Overall, the results confirm that the integrated anoxic-aerotank MBR system enables synergistic pollutant removal, with biological processes responsible for organic matter and nutrient transformation and membrane filtration ensuring consistent compliance with discharge standards.

The staged analysis also highlights the complementary roles of biological degradation and membrane filtration, which together ensure stable effluent quality and high pollutant removal efficiency.

### Significance and implications

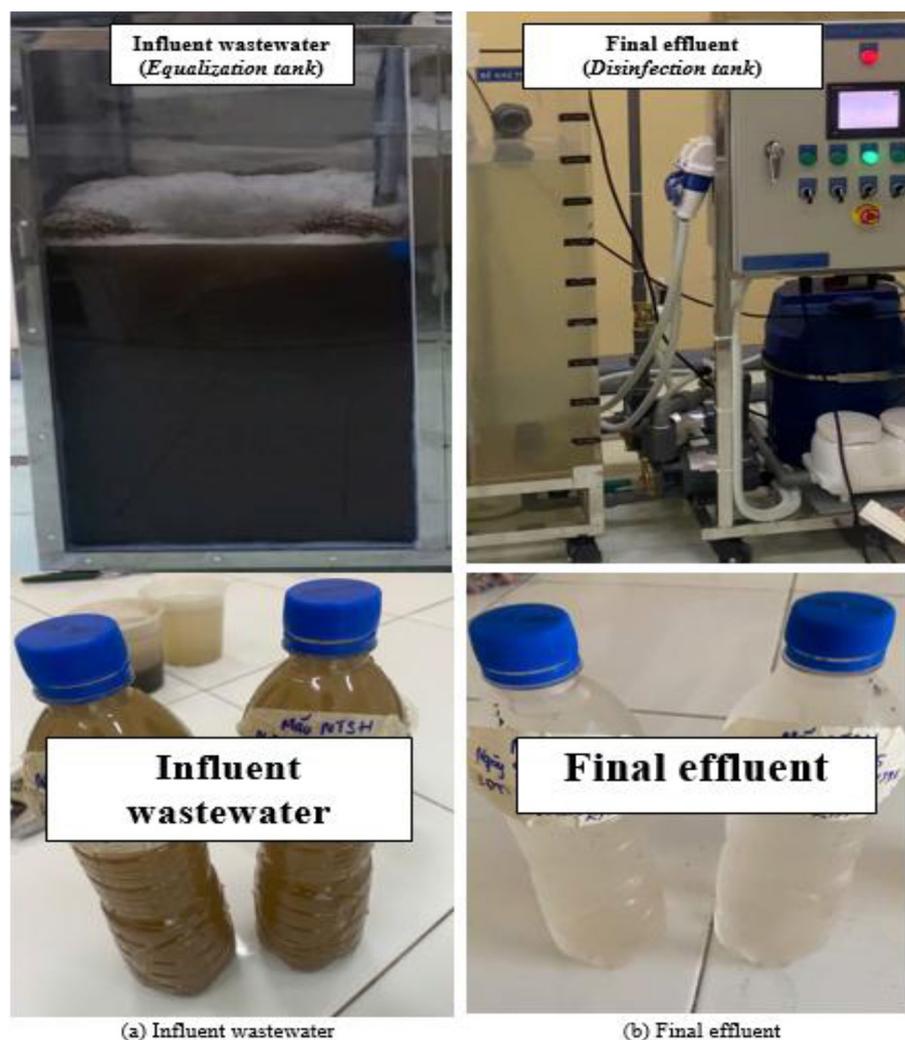
The high overall removal efficiencies achieved by the integrated anoxic-aerotank MBR

system demonstrate its effectiveness as a compact and decentralized solution for treating domestic wastewater in university campus environments. The system consistently achieved high removal performance for major pollutants, including organic matter (BOD<sub>5</sub> and COD), suspended solids (TSS), nutrients (NH<sub>4</sub><sup>+</sup>-N and TP), and microbial contaminants (coliforms). As a result, the final effluent fully complied with the Vietnamese national discharge standard QCVN 14:2008/BTNMT (Column A), indicating that the treated wastewater is suitable for discharge into receiving water bodies with strict environmental protection requirements (Figure 4).

The treatment performance observed in this study is consistent with recent advances in hybrid biological–membrane wastewater treatment systems. Previous studies have demonstrated that the integration of MBBR technology with MBR processes can significantly improve pollutant removal

efficiency due to the synergistic interaction between attached biofilm and suspended biomass. For instance, Zhang et al. (2019) reported that a combined MBBR–MBR process achieved COD and NH<sub>4</sub><sup>+</sup>-N removal efficiencies of up to 97%, highlighting the advantages of hybrid configurations in enhancing effluent quality and reducing membrane fouling. Similarly, Namdeti et al. (2025) reported that an anaerobic–anoxic–oxic membrane bioreactor system achieved COD and NH<sub>4</sub><sup>+</sup>-N removal efficiencies of 94.31% and 98.82%, respectively, when treating low-carbon domestic wastewater. These findings support the effectiveness of sequential biological processes combined with membrane filtration, similar to the treatment configuration implemented in the present study.

The high treatment efficiency observed in this study can be attributed to the synergistic interaction between suspended activated sludge and attached biofilm within the MBBR unit. The



**Figure 4.** Wastewater treated using an experimental model: (a) influent wastewater, (b) final effluent

biofilm carriers provide a large specific surface area that promotes microbial attachment and growth, particularly for nitrifying bacteria, thereby enhancing nitrification efficiency and overall system stability under fluctuating organic loading conditions. In addition, the submerged membrane module in the MBR unit plays a crucial role in retaining biomass within the bioreactor, resulting in high mixed liquor suspended solids (MLSS) concentrations. This biomass retention improves biological degradation performance and contributes to the extremely high removal efficiency of suspended solids observed in the final effluent.

The practical implications of this research are particularly relevant for decentralized wastewater management in areas with limited land availability and infrastructure, such as university campuses, small communities, and peri-urban developments. The compact footprint, high treatment efficiency, and operational stability of the integrated system suggest that it can serve as an effective alternative to large centralized treatment plants. Furthermore, the high effluent quality achieved by the system indicates its potential suitability for non-potable water reuse applications, such as landscape irrigation or campus facility cleaning, where stringent water quality requirements must be satisfied.

Although the experimental system was operated at a laboratory scale with a design capacity of 1.0 m<sup>3</sup>/day, the treatment configuration can be scaled up for practical decentralized wastewater treatment applications. The design of the integrated anoxic-aerotank MBR system was based on conventional biological treatment principles and membrane bioreactor design parameters commonly applied in wastewater treatment practice.

When scaling up the system, the hydraulic retention time applied in this study can be maintained by proportionally increasing reactor volumes according to the design flow rate. For example, a treatment plant designed to treat 100 m<sup>3</sup>/day of domestic wastewater would require approximately 100 times the reactor volume used in the experimental model while maintaining similar biological operating conditions.

Similarly, the required membrane surface area can be determined based on the design membrane flux. For submerged membrane bioreactor systems, typical membrane flux values range from 10 to 25 L·m<sup>-2</sup>·h<sup>-1</sup> under stable operating conditions. Therefore, the membrane area required for larger treatment capacities can be estimated proportionally according to the influent flow rate.

Energy consumption in membrane bioreactor systems is mainly associated with aeration for biological oxidation and membrane scouring (Judd, 2010; Meng et al., 2009). Previous studies have reported that energy consumption in municipal and decentralized MBR systems typically ranges from 0.6 to 1.2 kWh·m<sup>-3</sup>. The modular configuration adopted in this study allows flexible system expansion by installing additional parallel treatment units, which further enhances the suitability of the proposed treatment configuration for decentralized wastewater management in institutional environments such as university campuses. The results obtained in this study provide additional experimental evidence supporting the applicability of compact hybrid biological membrane systems for decentralized wastewater treatment, particularly in institutional environments in developing countries.

## CONCLUSIONS

This study evaluated the treatment performance of an integrated anoxic-aerotank-MBR system for domestic wastewater generated within a university campus environment. The results demonstrate that the proposed treatment configuration is highly effective in removing organic matter, suspended solids, nutrients, and microbial contaminants, achieving stable effluent quality that fully complies with QCVN 14:2008/BTNMT (Column A) discharge standards.

The system achieved high overall removal efficiencies of 96.2% for BOD and COD, 99.5% for TSS, 92.5% for NH<sub>4</sub><sup>+</sup>-N, 86.7% for total phosphorus, and 99.6% for coliforms. Analysis of stage-by-stage performance revealed that preliminary treatment mainly contributed to suspended solids and ammonium reduction, while the anoxic stage played a critical role in nutrient removal. The aerobic biological treatment was the dominant process for organic matter degradation, and the membrane bioreactor provided effective solid-liquid separation and effluent polishing, ensuring consistent and high-quality treated water.

Comparative analysis with selected international studies confirmed that the treatment efficiencies achieved in this study are comparable to, or higher than, those reported for conventional MBR and hybrid MBBR-MBR systems treating domestic wastewater. The synergistic integration of biological processes and membrane filtration

was identified as the key factor contributing to the superior performance of the system.

Overall, the findings indicate that the integrated anoxic-aerotank MBR system represents a technically feasible and reliable solution for decentralized domestic wastewater treatment, particularly in institutional settings such as universities where land availability is limited and stringent discharge requirements must be met. Future research should focus on long-term operational stability, membrane fouling control, energy consumption optimization, and the potential for treated wastewater reuse, especially for non-potable applications in urban and campus environments.

### Acknowledgments

The authors would like to express their sincere gratitude to Thu Dau Mot University for providing the facilities and financial support necessary to conduct this study. This research is funded by Thu Dau Mot University, Ho Chi Minh City, Vietnam under grant number DT.24.3-358.

### REFERENCES

- Ash, K. T., Li, Y., Alamilla, I., Joyner, D. C., Williams, D. E., McKay, P. J., et al. (2023). SARS-CoV-2 raw wastewater surveillance from student residences on an urban university campus. *Frontiers in Microbiology*, 14, 1101205.
- Cao, T. N. D., Bui, X. T., Le, L. T., Dang, B. T., Tran, D. P. H., Vo, T. K. Q., Vo, T. D. H. (2022). An overview of deploying membrane bioreactors in saline wastewater treatment from perspectives of microbial and treatment performance. *Bioresour. Technol.*, 363, 127831.
- Dwumfour, A. B., Nyarko, K. B., Essandoh, H. M., Awuah, E. (2020). Domestic greywater flows and pollutant loads: A neighbourhood study within a university campus in Ghana. *Scientific African*, 9, e00489.
- El-Aassar, A. H. M., Isawi, H., Ali, M. E., Shawky, H. A., Mito, M. T., Oterkus, S., Oterkus, E. (2025). Development and testing of a novel compact system for municipal wastewater treatment and irrigation using advanced technologies. *Scientific Reports*, 15, 43388.
- Gibas, C., Lambirth, K., Mittal, N., Juel, M. A. I., Barua, V. B., Brazell, L. R., et al. (2021). Implementing building-level SARS-CoV-2 wastewater surveillance on a university campus. *Science of the Total Environment*, 782, 146749.
- Helmi, A., Gallucci, F. (2020). Latest developments in membrane (bio) reactors. *Processes*, 8(10), 1239.
- Judd, S. (2010). *The MBR book: principles and applications of membrane bioreactors for water and wastewater treatment*. Elsevier.
- Litthavong, S., Chittima, C., Mesak, M., Sansanee, C. (2023). Treatment of domestic wastewater using membrane bioreactor (MBR) pilot plant: A case study of wastewater from kklung hok's treatment pond and the environmental research and training centre (ERTC), Pathumthani, Thailand. *Souphanouvong University Journal Multidisciplinary Research and Development*, 9(1), 260–267.
- Meng, F., Chae, S. R., Drews, A., Kraume, M., Shin, H. S., Yang, F. (2009). Recent advances in membrane bioreactors (MBRs): membrane fouling and membrane material. *Water research*, 43(6), 1489–1512.
- Namdeti, R., Lakkimsetty, N. R., Rao, G. B., Thandlam, A. K., Karu, C. V., Doddamani, D., et al. (2025). Membrane bioreactors: Integration of biological processes with membrane technology for wastewater treatment. *Journal of Membrane Science and Research*, 11(2), e720042.
- Nguyen, M. K., Nguyen, H. L., Nhi, T. T. T. (2017). Research on treating residential wastewater using membrane bioreactor (MBR) technology. *Can Tho University Journal of Science*, 52, 72–79.
- Nwachi, C., Nwakaeze, E. A., Romanus, I. I. (2025). Development of membrane bioreactors (MBR) for sustainable urban wastewater treatment. *Path of Science*, 11(5), 2009–2016.
- Palmarin, M. J., Young, S. (2019). Comparison of the treatment performance of a hybrid and conventional membrane bioreactor for greywater recclamation. *Journal of Water Process Engineering*, 28, 54–59.
- Rahman, T. U., Roy, H., Islam, M. R., Tahmid, M., Fariha, A., Mazumder, A., et al. (2023). The advancement in membrane bioreactor (MBR) technology toward sustainable industrial wastewater management. *Membranes*, 13(2), 181.
- Wang, K., Xu, X., Ma, X., Cheng, X., Zhang, Y., Ma, J. (2023). Ceramic membrane bioreactor for low carbon source wastewater treatment: Process design, performance and membrane fouling. *Environmental Science: Water Research & Technology*, 9(1), 116–124.
- Zhang, H., Duan, L., Yao, M., Wei, J. (2019). Study on performance and membrane fouling of MBBR–MBR combined process for treatment of domestic wastewater. *Journal of Environmental Engineering and Technology*, 9(3), 245–251.