Hue University Journal of Science: Natural Science
Vol. 134, No. 1B, 61–71, 2025

pISSN 1859-1388
eISSN 2615-9678

Treatment of urban wastewater discharged into Tinh Tam lake using hydrogen peroxide-supplemented aerated biofilter system

Dang Thi Thanh Loc, Le Van Tuan*

Faculty of Environment, University of Sciences, Hue University, Vietnam

* Correspondence to Le Van Tuan <levantuan@hueuni.edu.vn>

(*Received: 16 April 2025; Revised: 30 May 2025; Accepted: 02 June 2025*)

Abstract. This study investigates the application of a hydrogen peroxide-supplemented aerated biofilter system (ABF-H_2O_2) for the treatment of urban domestic wastewater from the Tinh Tam Lake catchment area, located within the Imperial Citadel of Hue City, Vietnam. In the absence of centralised treatment facilities, untreated sewage from a combined sewer system is directly discharged into this ecologically and historically significant lake. A laboratory-scale ABF-H_2O_2 reactor was designed and operated over 45 days, treating both synthetic and actual urban wastewater. Key operational parameters included organic loading rate, hydraulic retention time, and H_2O_2 dosage. The system achieved removal efficiencies of 69–81% for chemical oxygen demand and 88–94% for five-day biochemical oxygen demand. Ammonium (NH_4^+–N) removal reached 87% under low-loading conditions but declined to 27% at higher organic loading rates. H_2O_2 supplementation improved dissolved oxygen availability, supporting microbial activity and treatment stability under elevated stress. Microscopic analysis revealed a diverse and well-adapted microbial community, including protozoa and metazoa. These results highlight the potential of the ABF-H_2O_2 approach as a sustainable and decentralised wastewater treatment solution for urban heritage areas such as the Imperial City of Hue City.

Keywords: aerated biofilter, hydrogen peroxide, decentralized wastewater treatment, Tinh Tam Lake, urban sewage

1 Introduction

Urbanisation in Hue City has driven the implementation of various environmental improvement initiatives aimed at restoring water quality and preserving ecological assets. In the southern districts, international collaboration—particularly with the Japan International Cooperation Agency (JICA)—has facilitated the development of modern wastewater collection and treatment systems. These interventions have yielded measurable improvements in the Huong, Nhu Y, and Loi Nong Rivers, as well as in key urban canals [1]. However, the northern area, especially the historic Imperial Citadel, remains largely unserved by centralised wastewater treatment infrastructure.

Within this heritage-protected zone, domestic wastewater is primarily pre-treated through septic tanks before being discharged into a combined sewer system, which conveys both sewage and stormwater. This mixture is eventually routed to nearby regulatory lakes, including Tinh Tam Lake—a culturally and ecologically vital waterbody located at the heart of the Imperial City [2]. Although the combined sewer network offers some dilution, pollutant loads remain elevated because of continuous discharges and the limited treatment capacity of the existing infrastructure. Studies have shown

that only 56% of the total domestic water consumption in the Citadel area reaches the outlet at Tinh Tam Lake, indicating considerable leakage, exfiltration, and in-sewer losses [2, 3].

In Hue, untreated domestic wastewater typically contains 70–240 mg·L^{-1} of COD, 30–120 mg·L^{-1} of BOD_5, 20–55 mg·L^{-1} of T–N, and 2–5 mg·L^{-1} of T–P [2, 3]. These concentrations far exceed the country's national discharge standards [4]. When such high-strength wastewater is discharged into shallow and enclosed urban lakes like Tinh Tam, it poses severe risks of eutrophication, dissolved oxygen depletion, and long-term degradation of surface water quality. In Hue, domestic wastewater alone contributes more than 84% of the total nitrogen and phosphorus loading to urban surface water bodies [5].

Because of spatial constraints and the need for preserving historical and cultural heritage, the development of large-scale, centralised treatment systems in the Citadel area is not feasible. As a result, decentralised and on-site wastewater treatment technologies are increasingly considered viable and context-appropriate alternatives. Among these, the aerated biofilter (ABF) system has garnered attention owing to its small spatial footprint, operational simplicity, and low sludge generation [6–10]. However, ABF performance can be constrained because of suboptimal oxygen transfer, particularly under conditions of high organic loading or aeration failure. These issues may result in incomplete degradation of organic matter and inhibited nitrification [11–13].

Recent studies suggest that supplementing ABF systems with H_2O_2—a potent yet environmentally benign oxidant—can enhance aerobic biological treatment processes. H_2O_2 decomposes into water and oxygen while generating hydroxyl radicals (•OH), which facilitate the breakdown of refractory organic compounds and promote ammonium oxidation. At appropriate dosages, H_2O_2 improves dissolved oxygen (DO) availability, stimulates redox reactions and stabilises microbial activity under stress conditions [11–13].

Several studies have reported that H_2O_2-supplemented activated sludge systems achieve high removal efficiencies for COD, BOD_5, and ammonium (typically in a range of 75–95% for COD, 80–94% for BOD_5, and 60–85% for ammonium, under optimised conditions: 50–100 mg/L H_2O_2, pH 6–8, temperature 25–35 °C, and hydraulic retention times of 6–8 h) [6–8].

In light of these findings, the present study aims to design and evaluate a laboratory-scale ABF-H_2O_2 treatment system for actual urban wastewater collected from the sewer network discharging into Tinh Tam Lake. The system's efficiency in removing COD, BOD_5, and NH_4^+–N under varying loading conditions is assessed, with particular attention to its applicability in heritage-sensitive, space-constrained urban environments.

2 Materials and methods

2.1 Wastewater and activated sludge

Synthetic wastewater (SWW) was prepared during the initial start-up and stabilisation phase to ensure consistent influent quality and promote microbial acclimatisation. The formulation consisted of 5–10 mL of glucose solution (30 g·L^{-1}) to gradually increase BOD_5 and COD levels, 5 mL of CH_3COONH_4 (20 g·L^{-1}), 10 mL of $NaHCO_3$ (50 g·L^{-1}), 2.5 mL of KH_2PO_4 (7.2 g·L^{-1}), and 1 mL of a mixed salt solution containing NaCl (1 g·L^{-1}), KCl (1.4 g·L^{-1}), $CaCl_2{\cdot}2H_2O$ (1.9 g·L^{-1}), and $MgSO_4{\cdot}7H_2O$ (2 g·L^{-1}). Tap water used for dilution was aerated for over 24 hours to eliminate residual chlorine. Each batch of ~18 litres was

pISSN 1859-1388
eISSN 2615-9678

stored at 4 °C in the dark and used within 3 days to preserve consistency.

Urban wastewater (UWW) was collected from the primary sewer discharging into Tinh Tam Lake, located at the intersection of Tinh Tam and Doan Thi Diem Streets (coordinates: 16°28′36.2″N, 107°34′40.5″E), in alignment with previous studies by Quynh Anh et al. [2] and Watanabe et al. [3]. Samples (~25 L each) were taken during the dry season (May–June 2023) to minimise dilution effects from precipitation. The samples were transported to the laboratory under refrigerated conditions and used within 3-days after collection. Before use, the samples were filtered through a 0.8 mm mesh screen to remove coarse solids. All influent parameters were analysed within 24 hours.

Fig. 1. Sampling location and experimental materials: (a) Hue Imperial Citadel and Tinh Tam Lake; (b) Primary sewer outlet discharging into Tinh Tam Lake; (c) Wastewater sampling container; (d) 0.8 mm mesh filter; (e) Raw activated sludge; (f) Cultivated sludge; (g) Polyethylene biofilm carrier employed in the ABF system

Activated sludge was obtained from the aeration tank of the Phu Bai wastewater treatment plant in Hue City and enriched under laboratory conditions using a nutrient medium comprising a beef extract-peptone solution (5 mL·L^{-1}, prepared from 10 g peptone and 5 g NaCl per litre), 5 mL·L^{-1} of $NaHCO_3$ solution (21 g·L^{-1}), and the same mineral salt mix as used in the SWW preparation. The enrichment culture was maintained under continuous aeration at 28 ± 2 °C and a controlled pH of 7.0 ± 0.2. For system inoculation, the sludge was concentrated with centrifugation at 6,000 rpm for 5 min. A total wet sludge weight of 162 g corresponded to a suspended solids (SS) concentration of approximately 2,700 mg·L^{-1}, which was deemed appropriate for establishing a robust microbial community within the ABF system.

2.2 Experimental setup

The ABF system was constructed and continuously operated under laboratory conditions (Fig. 2). Wastewater was introduced into the system through a perforated, rotatable inlet pipe designed to enhance air-water contact, facilitate passive oxygen transfer, and ensure even distribution across the surface of the biofilm carrier medium. The experimental system consisted of the following components: a biofilter reactor, an influent tank, a settling tank for treated effluent, an air pump, a peristaltic pump for flow control, a flow meter, piping, and pH and DO sensors.

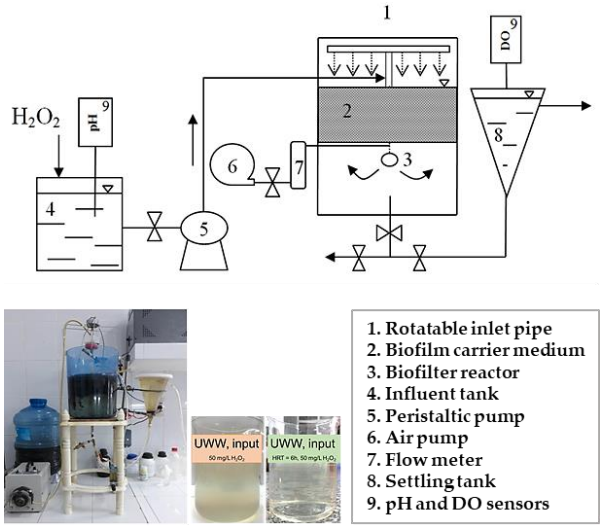

Fig. 2. Schematic diagram of the laboratory-scale ABF system used for SWW or UWW treatment

The biofilter reactor was fabricated from transparent acrylic in a cylindrical shape, with a total volume of 10 L and an effective working volume of 6 L. A fixed bed of biofilm-supporting material—polyethylene mesh weighing ~32.3 g

(dry weight)—was centrally positioned within the reactor, occupying a volume of roughly 3 L. This arrangement stabilised the hydraulic distribution and provided a favourable surface area for microbial attachment and biofilm formation.

The influent, either synthetic or urban wastewater, was introduced into the reactor via a peristaltic pump. The flow rate was adjusted with a calibrated flow meter. Aeration was provided continuously at a rate of 0.6–1.0 $L \cdot min^{-1}$ to maintain aerobic conditions throughout the reactor volume (Fig. 2).

2.3 Experimental operation

The ABF system was operated continuously across eight experimental phases, comprising three phases with synthetic wastewater (SWW; Phases I–III) and five phases with actual urban wastewater (UWW; Phases IV–VIII). The detailed operational parameters for each phase are provided in Table 1.

During Phases I and II, the system was operated under low organic loading conditions (organic loading rate, OLR ≤ 0.50 kg-COD $m^{-3} \cdot day^{-1}$) without the addition of H_2O_2. In Phase III, H_2O_2 was introduced at a dosage of 50 $mg \cdot L^{-1}$ to evaluate its effect on microbial activity. Although the organic loading remained stable, the measured COD in Phase III showed a slight increase compared with that in Phase II (534 vs. 503 $mg \cdot L^{-1}$), likely owing to analytical interference. This discrepancy is attributed to the residual H_2O_2 reacting with the dichromate reagent during COD analysis—a known issue in bio-oxidative treatment systems [11, 12].

From Phase IV onwards, the system was transitioned to treat real UWW collected from the main sewer discharging into Tinh Tam Lake. The organic loading rate was gradually increased from 0.243 to 1.140 kg-COD $m^{-3} \cdot day^{-1}$ by adjusting the influent flow rate (0.25–1.0 $L \cdot h^{-1}$) and reducing hydraulic retention time (HRT) from 24 to 6 h. H_2O_2 was reintroduced only in Phase VIII (50 $mg \cdot L^{-1}$) to assess its effectiveness under high organic loading conditions.

Aeration was maintained at 1.0 $L \cdot min^{-1}$ during SWW treatment and reduced to 0.6 $L \cdot min^{-1}$ for all UWW phases. Throughout the experiment, pH and temperature were consistently maintained at 7.0 ± 0.2 and 28 ± 2 °C, respectively.

2.4 Analytical methods

The analytical parameters included pH, DO, COD, BOD_5, SS, VSS, NH_4^+–N, NO_3^-–N, and T–N. All measurements were conducted in accordance with the Standard Methods for the Examination of Water and Wastewater [14].

pH was measured on-site immediately after sampling with an ECO Testr pH2 meter. Other parameters were analysed in the laboratory using the following equipment: ECO Testr pH2, DO 6+ Meter (Oakton), a BOD incubator with 300 mL Winkler bottles, a Velp Eco 25 digestion block, a Genesys 10S UV–VIS spectrophotometer, a SARTORIUS analytical balance, and a vacuum filtration system.

BOD_5 was measured by using the five-day closed incubation method (5210B), COD with the dichromate reflux method (5220C), and SS and VSS were determined gravimetrically with methods 2540D and 2540E, respectively. NH_4^+–N, NO_3^-–N, and T–N were analysed according to methods 4500–NH_3 F, 4500–NO_3^- E, and 4500–N C, respectively. Orthophosphate (PO_4^{3-}–P) was determined with the ascorbic acid method (4500–P E) [14]. Sludge samples were examined under an Olympus CX33 optical microscope (Olympus Corporation, Japan).

pISSN 1859-1388
eISSN 2615-9678

Table 1. Operational conditions of the ABF-H_2O_2 system across eight experimental phases using synthetic and urban wastewater

Phases	Synthetic WW			Urban WW				
	I	II	III	IV	V	VI	VII	VIII
COD (mg·L^{-1})	50 ± 10	503 ± 15	534 ± 5	243 ± 11	259 ± 12	230 ± 10	256 ± 31	275 ± 10
OLR (kg-COD m^{-3}·day^{-1})	0.25	0.50	0.53	0.243	0.341	0.467	1.013	1.140
H_2O_2 (mg·L^{-1})	0	0	50	0	0	0	0	50
Duration (days)	7	7	7	4	5	4	5	6
Flow rate (L·h^{-1})	0.25	0.25	0.25	0.25	0.33	0.5	1.0	1.0
HRT (h)	24	24	24	24	18	12	6	6
Aeration rate (L·min^{-1})	1	1	1	0.6	0.6	0.6	0.6	0.6
pH	7 ± 0.2	7 ± 0.2	7 ± 0.2	7 ± 0.2	7 ± 0.2	7 ± 0.2	7 ± 0.2	7 ± 0.2
Temperature (°C)	28 ± 2	28 ± 2	28 ± 2	28 ± 2	28 ± 2	28 ± 2	28 ± 2	28 ± 2

2.5 Data processing

Experimental data were processed with Microsoft Excel. The OLR and the removal efficiencies for COD, BOD_5, and NH_4^+–N were calculated with standard equations.

The OLR (kg-COD m^{-3}·day^{-1}) was determined according to Eq. 1 [13]

$$OLR = \frac{Q \times C_0}{V} \times 10^{-3} \quad \text{(Eq. 1)}$$

where Q is the influent flow rate (m^3·day^{-1}); C_0 is the influent COD (mg·L^{-1}); V is the working volume of the reactor (m^3).

The removal efficiency (H, %) of each parameter was calculated according to Eq. 2

$$H = \left(\frac{C_0 - C}{C_0}\right) \times 100 \quad \text{(Eq. 2)}$$

where C_0 is the influent concentration (mg·L^{-1}); C is the effluent concentration (mg·L^{-1}) of COD, BOD_5, or NH_4^+–N.

3 Results and discussion

3.1 Performance of the ABF system treating synthetic wastewater

During the start-up phase, the COD removal efficiency was used as a primary indicator to evaluate the initial adaptability and biological activity of the activated sludge in the ABF system. The reactor was operated continuously across three distinct phases, each with progressively increasing influent COD concentrations: 250 ± 10 mg·L^{-1} (Phase I), 503 ± 15 mg·L^{-1} (Phase II), and 534 ± 5 mg·L^{-1} (Phase III). Across all the three phases, the system consistently achieved high COD removal efficiencies ranging from 91 to 96%, reflecting strong microbial acclimation and effective aerobic oxidation under stable operational conditions (HRT = 24 h; pH = 7.0 ± 0.2; DO maintained at 2.5–3.2 mg·L^{-1} through continuous aeration at 1.0 L·min^{-1}).

In Phase I, the system achieved a removal efficiency of 96% within the first seven days, reducing effluent COD to 10 ± 5 mg·L^{-1}. This significant improvement reflected effective

biofilm formation and active organic matter degradation.

In Phase II, despite the COD load being doubled, the system maintained a high removal efficiency of 91%, with average effluent COD at 48 ± 13 mg·L^{-1}. This suggests that the microbial community had firmly colonised the biofilm carriers and was metabolically robust under increased organic loading (OLR = 0.5 kg-COD m^{-3}·day^{-1}). In Phase III, H_2O_2 was added at a concentration of 50 mg·L^{-1} to evaluate its effect on system performance. Although the influent COD increased slightly, likely owing to interference from residual H_2O_2 in the dichromate assay, the system still achieved a high removal efficiency of 92%, with effluent COD at 45 ± 10 mg·L^{-1}. These results are summarised in Figure 3.

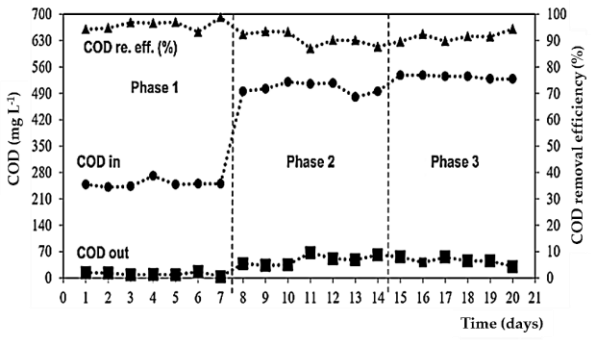

Fig. 3. Profiles of influent and effluent COD concentrations and corresponding removal efficiency in the ABF system treating SWW

The addition of H_2O_2 did not result in a substantial improvement in COD removal efficiency. In low-strength, readily biodegradable wastewater, the primary function of H_2O_2 is to enhance oxygen availability and stabilise DO levels, rather than to significantly accelerate COD degradation. Nevertheless, maintaining >90% removal efficiency under oxidative conditions confirms that the microbial community was both resilient and well-adapted to the presence of H_2O_2. Additionally, H_2O_2 contributed to odour suppression [12, 13] and improved operational stability benefits that are particularly valuable in preparing the system for subsequent treatment of urban wastewater, which typically contains a more complex and recalcitrant mixture of pollutants [6].

The consistently high treatment performance observed during the synthetic wastewater phase established a robust operational baseline, facilitating a smooth transition to the treatment of actual UWW in subsequent experimental phases.

3.2 Characteristics of urban wastewater

UWW was collected from the main sewer discharging into Tinh Tam Lake, an area without a centralised treatment system. Consequently, the influent exhibited a notable accumulation of organic matter and nutrients prior to environmental discharge. The measured quality parameters are summarised in Table 2.

The wastewater sampled from the main discharge outlet into Tinh Tam Lake exhibited typical characteristics of untreated domestic effluent. The average BOD_5 concentration was 129 ± 20 mg·L^{-1}, exceeding the regulatory threshold established by QCVN 14:2008/BTNMT Column B (50 mg·L^{-1}) by approximately 2.7 times. Similarly, the NH_4^+–N concentration averaged 33 ± 9 mg·L^{-1}, 3.3 times higher than the permitted limit of 10 mg/L [15]. These values reflect a substantial organic and nutrient load, posing a significant risk to the receiving water body in the absence of adequate treatment.

pISSN 1859-1388
eISSN 2615-9678

Table 2. Physico-chemical characteristics of UWW discharged into Tinh Tam Lake

Parameter	Unit	Measured range	Mean ± SD	QCVN 14:2008 (Column B)
Colour	–	Gray	–	–
Odour	–	Offensive	–	–
pH	–	6.7–7.3	7.0 ± 0.3	5–9
SS	$mg·L^{-1}$	85–120	103 ± 15	100
BOD_5	$mg·L^{-1}$	99–160	129 ± 20	50
COD	$mg·L^{-1}$	210–363	256 ± 32	–
BOD_5/COD	–	0.3–0.6	0.51 ± 0.06	–
NH_4^+–N	$mg·L^{-1}$	20–46	33 ± 9	10
NO_3^-–N	$mg·L^{-1}$	0.06–0.14	0.07 ± 0.05	–
T–N	$mg·L^{-1}$	29–69	50 ± 12	–

The BOD_5/COD ratio of 0.51 ± 0.06 suggests that a major portion of organic matter is biodegradable, which is favourable for aerobic biological treatment. However, the remaining fraction likely consists of more recalcitrant organics that may require additional oxidative support. In addition, the NH_4^+–N to T-N ratio (~0.66) indicates that nitrogen is predominantly present in reduced inorganic forms. If not properly removed, these species can contribute to eutrophication in the receiving ecosystem.

The wastewater also exhibited a grey colour, strong odour, and high turbidity. After pre-filtration, the SS concentration was 103 ± 15 $mg·L^{-1}$, slightly exceeding the national limit of 100 $mg·L^{-1}$. These observations are consistent with the findings of Watanabe et al. [3], who reported comparable concentrations in the same catchment: COD ≈ 184 ± 53 $mg·L^{-1}$; SS ≈ 36.5 ± 6.6 $mg·L^{-1}$; TN = 35.7 ± 8.2 $mg·L^{-1}$. Sampling was conducted during the dry season, minimizing dilution from rainfall and thereby reflecting the intrinsic characteristics of the domestic wastewater.

3.3 Performance of the ABF system in treating urban wastewater

Organic pollutant (COD, BOD_5) removal

The ABF system was operated continuously through five sequential phases for UWW, with OLR progressively increased from 0.243 to 1.14 kg-COD $m^{-3}·day^{-1}$. The highest COD removal efficiency (81 ± 4%) was observed in Phase IV, after which the removal performance gradually declined in response to the increasing OLR, reaching a minimum of 69 ± 5% in Phase VII. This reduction is attributable to the combined effects of decreasing HRT from 24 to 6 h, and the accumulation of refractory organic compounds can overload the surface of the biofilm carriers and impair treatment performance.

Notably, the addition of 50 $mg·L^{-1}$ H_2O_2 in Phase VIII led to a recovery in COD removal efficiency, reaching 80 ± 2%. This improvement highlights the role of H_2O_2 as an effective supplemental oxygen source, which enhances microbial respiration and promotes aerobic oxidation, particularly under high organic loading conditions. BOD_5 removal followed a similar trend to COD, though with greater stability across phases. Influent BOD_5 concentrations ranged from 114 to 157 $mg·L^{-1}$, with removal efficiencies of 91–94% achieved in Phases IV and V. As the OLR exceeded 0.341 kg-COD $m^{-3}·day^{-1}$ (Phase VI onward), a slight decline in BOD_5 removal efficiency was observed; however, overall performance remained strong, supported by the stable metabolic activity of the attached microbial community.

In Phase VIII, despite the highest OLR of 1.14 kg-COD $m^{-3}·day^{-1}$, the system maintained a BOD_5 removal efficiency of 91% following H_2O_2

supplementation. These findings indicate that the ABF system, when integrated with advanced oxidation processes (AOPs), demonstrates strong resilience and adaptability under high organic loading conditions [10, 12, 13].

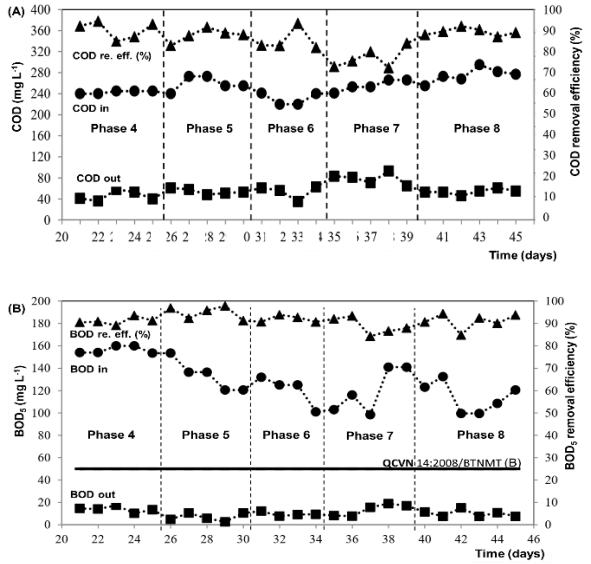

Fig. 4. (a) COD and (b) BOD_5 removal dynamics in the ABF system treating urban wastewater

In all operational phases, the effluent BOD_5 concentrations remained below 50 mg·L^{-1}, in compliance with the Vietnamese National Technical Regulation QCVN 14:2008/BTNMT – Column B. The system's ability to maintain high treatment performance under elevated OLR conditions, even with a reduced HRT of just 6 h, underscores the potential of the ABF-H_2O_2 approach for treating high-strength urban wastewater.

Ammonium removal and nitrification

The performance of the ABF system in removing NH_4^+–N and promoting nitrification (as indicated by nitrate formation, NO_3^-–N) was assessed across five phases under gradually increasing OLRs. The highest NH_4^+–N removal efficiency (87 ± 14%) was achieved in Phase IV, under favourable conditions, including a relatively low OLR and an HRT of 24 h. During this phase, the influent and effluent NH_4^+–N concentrations were 42.6 ± 3.0 mg·L^{-1} and 5.2 mg·L^{-1}, respectively. These conditions supported a stable aerobic environment with adequate DO levels (1.5–2.0 mg·L^{-1}), facilitating effective nitrification by autotrophic ammonia-oxidizing microorganisms.

As the OLR increased in subsequent phases, ammonium removal efficiency progressively declined: dropping to 72 ± 8% in Phase V, 59 ± 6% in Phase VI, and reaching a minimum of 27 ± 14% in Phase VIII. The sharp decrease in Phase VIII occurred despite the supplementation of 50 mg·L^{-1} H_2O_2, indicating that the oxidative support was insufficient to overcome the limitations imposed by high organic load and short HRT (6 h). The observed decline is likely attributed to DO depletion (<1.0 mg·L^{-1}) and intensified microbial competition, where heterotrophic bacteria—favoured under high OLRs—outcompete nitrifiers for both oxygen and biofilm surface area.

Effluent NO_3^-–N concentrations exhibited a consistent downward trend, from 34 ± 4 mg·L^{-1} in Phase IV to just 0.15 ± 0.12 mg·L^{-1} in Phase VIII, corroborating the observed suppression of nitrification under elevated loading conditions. Although H_2O_2 supplementation can enhance oxygen supply, it appears that most of the generated oxygen was rapidly consumed by heterotrophs, thereby limiting the availability of nitrifying bacteria.

Nitrification in the ABF system was most effective within a moderate loading range (0.243–0.467 kg-COD m^{-3}·day^{-1}) and at longer HRTs (12–24 h). Beyond this range, particularly above 1.0 kg-COD m^{-3}·day^{-1}, nitrification efficiency declined significantly. Under such conditions, further enhancements, such as intensified aeration, or integration of post-nitrification units may be necessary to ensure stable nitrogen removal.

pISSN 1859-1388
eISSN 2615-9678

Table 3. Ammonium removal efficiency and nitrate accumulation under different OLRs

Phase	OLR(kg-COD $m^{-3}·day^{-1}$)	NH_4^+–N Inlet ($mg·L^{-1}$)	NH_4^+–N Outlet ($mg·L^{-1}$)	NH_4^+–N removal efficiency (%)	NO_3^-–N Inlet ($mg·L^{-1}$)	NO_3^-–N Outlet ($mg·L^{-1}$)
IV	0.243	42.6 ± 3.0	5.2	87 ± 14	–	34 ± 4
V	0.341	41.8 ± 5.0	11.2 ± 2.0	72 ± 8	–	31.4 ± 1.0
VI	0.467	40.2 ± 4.0	16.3 ± 2.0	59 ± 6	–	21 ± 6
VII	1.013	24.6 ± 3.0	15.7 ± 2.0	36 ± 12	–	4.67
VIII	1.14	29.8 ± 2.0	21.8 ± 4.0	27 ± 14	–	0.15 ± 0.12

Note: Values are presented as mean ± standard deviation (n = 3); "–" indicates measurements below the detection limit.

3.4 Characteristics of activated sludge in ABF system

The stable development of activated sludge played a critical role in maintaining the overall treatment performance of the ABF system. Over the 46-day operational period, the total sludge mass increased from 162 g (corresponding to SS ≈ 2700 $mg·L^{-1}$) to 271.3 g (SS ≈ 4500 $mg·L^{-1}$), with an average sludge yield of approximately 2.02 $g·day^{-1}$. The volatile suspended solids to total suspended solids ratio (VSS/SS) increased from 0.44 ± 0.03 to 0.85 ± 0.07, indicating a substantial enrichment in biologically active biomass, including bacteria, algae, and protozoa.

Microscopic examination of the sludge samples collected during various operational phases revealed a diverse and well-established microbial community. Dense biofilms composed of cyanobacteria, filamentous fungi, and biofilm-forming filamentous bacteria were observed to adhere to the carrier surfaces. In addition, a variety of higher trophic organisms were present, including rotifers, flagellates, ciliates (e.g., *Paramecium*), amoebae, nematodes, and oligochaetes. The presence of these organisms is widely recognised as a reliable biological indicator of stable aerobic conditions and effective treatment performance [9, 13, 16].

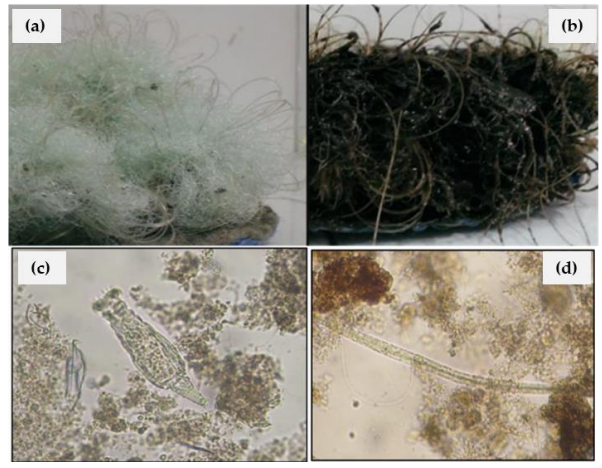

Fig. 5. Development of biofilm and microbial community structure in the ABF system: (a) Clean PE fiber carrier prior to inoculation; (b) Carrier after biofilm development with dense sludge accumulation; (c) Presence of rotifers and protozoa under optical microscopy, indicating aerobic stability; (d) Filamentous bacteria contributing to biofilm structure in activated sludge

Previous studies have demonstrated that the presence of protozoa and metazoa in activated sludge not only enhances organic matter degradation but also improves sludge settleability, reduces excess sludge production, and contributes to greater process stability [16]. These higher organisms help regulate bacterial populations, consume excess bacteria, and facilitate more efficient nitrogen cycling. The strong attachment of biofilm to the polyethylene

carrier media further reflects the system's capacity to retain biomass and resist washout, even under fluctuating organic loading conditions.

4 Conclusion

This study provides preliminary scientific and experimental insights into the potential application of an ABF-H_2O_2 system for the decentralised treatment of urban domestic wastewater from Tinh Tam Lake, located in Hue City, Vietnam. Over a 45-day operational period, the ABF system demonstrated stable and effective treatment performance. The COD removal efficiencies ranged from 69 to 81%, while the BOD_5 removal remained consistently high at 88–94%, even under increasing organic loading rates. The addition of H_2O_2 effectively enhanced DO availability, thereby sustaining microbial activity and supporting aerobic oxidation processes under high-load conditions. The NH_4^+–N removal was clearly influenced by the organic loading rate, reaching a peak efficiency of 87% under low-load conditions but declining to 27% at higher OLRs. Microscopic observations confirmed the presence of a diverse and well-established microbial community, including higher trophic organisms such as protozoa and metazoa—recognised indicators of stable aerobic environments and biological treatment effectiveness. Taken together, these findings affirm that the ABF-H_2O_2 system offers a technically feasible and environmentally sustainable solution for decentralised urban wastewater treatment. However, as this study was conducted at a laboratory scale, further pilot-scale validation is needed to assess scalability and long-term performance under real-world conditions, including hydraulic variability and operational stability.

References

1. Tuan LV, Loc DTT, Chung DT, Hung TC, Tam TTM, Tung TQ, et al. Temporal Variation in Water Quality of the Nhu Y River, Thua Thien Hue Province, during the Period 2010–2020. Journal of Research and Development. 2022;9(182),26–38.
2. Anh TNQ, Hidenori H, Shigeo F, Lieu PK, Hieu DV, Tanaka S. Sewer discharge characteristics and water balance in dry season in Hue, Vietnam. Vietnam Journal of Science and Technology. 2016;54(2A):265-272.
3. Watanabe R, Hidenori H, Hidenari Y, Van LT, and Fujii S. Exfiltration and infiltration effect on sewage flow and quality: a case study of Hue, Vietnam. Environmental Technology. 2021;42(11):1747-57.
4. Ministry of Natural Resources and Environment. Report on National Environmental Status 2022; Hanoi: Ministry of Natural Resources and Environment; 2022.
5. Tung TQ, Lieu PK, Hang HTM, Tuan LV. Estimation of nitrogen and phosphorus loads from main wastewater sources in Hue City. Vietnam Journal of Science and Technology. 2015;53(3A): 133-138.
6. Ribarova I, Vasilaki V, Katsou E. Review of linear and circular approaches to on-site domestic wastewater treatment: Analysis of research achievements, trends and distance to target. Journal of Environmental Management. 2024;367:121951.
7. Koul B, Yadav D, Singh S, Kumar M, Song M. Insights into the Domestic Wastewater Treatment (DWWT) Regimes: A Review. 2022;14(21):3542.
8. Sha C, Shen S, Zhang J, Zhou C, Lu X, Zhang H. A Review of Strategies and Technologies for Sustainable Decentralized Wastewater Treatment. 2024;16(20):3003.
9. Cheng H, Li W, Zhang C, Dai Z, Dai H, Chen H, et al. Innovation of a biofilm system for odor mitigation and enhanced nitrogen removal in decentralized sewage treatment: Performance and microbial community analysis. Journal of Water Process Engineering. 2025;69:106767.
10. Rasool T, Abdul R, Iffat N, Rahat U, and Ahmed S. Efficiency of a locally designed pilot-scale trickling biofilter (TBF) system in natural environment for the treatment of domestic wastewater. Environmental Technology. 2018;39(10):1295-306.

pISSN 1859-1388
eISSN 2615-9678

11. Ngan NNT, Tuan LV, Lieu PK, Hieu DV, Y HTN, Thuong LTH, et al. Hydrogen peroxide as an extra oxygen source for activated sludge. Vietnam Journal of Science and Technology. 2015;53(3A): 97–102.

12. Tuan LV, Tung TQ, Giang LTH, Thuy HTT, Nguyen NTT, Loc DTT. Performance of adding H2O2 in activated sludge process for treatment of wastewater containing refractory organic compounds. Hue University Journal of Science: Natural Science. 2016;117(3):219-225.

13. Tuan LV, Toan HX, Nguyen NTT, Loc DTT. Performance of H_2O_2-aerated biofilter in treatment of wastewater containing humic acid. Vietnam Journal of Science and Technology. 2016;54(2A): 149-155.

14. Standard Methods for the Examination of Water and Wastewater (23rd Edition). Washington DC: American Public Health Association; 2017

15. Ministry of Natural Resources and Environment. QCVN 14:2008/BTNMT – National Technical Regulation on Domestic Wastewater. Hanoi: Ministry of Natural Resources and Environment; 2008.

16. Arregui L, Liébana R, Calvo P, Pérez-Uz B, Salvadó H, Serrano S. Bioindication in activated sludge wastewater treatment plants. Handbook of Wastewater Treatment: Biological Methods, Technology and Environmental Impact: Nova Science Publishers, Inc.; 2013. p. 277-91.