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On-site anaerobic treatment of medium-strength wastewater under different hydraulic retention times

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Abstract

Decentralized anaerobic wastewater treatment technologies have attracted growing attention because of their low energy requirements, simple operation, and suitability for developing countries. This study evaluated and compared the treatment performance of an anaerobic baffled reactor (ABR) and anaerobic filter (AF) treating medium-strength wastewater under hydraulic retention times (HRTs) of 12 h and 24 h. Laboratory-scale reactors were operated under continuous-flow conditions using domestic wastewater. Both systems were operated under natural sludge growth conditions and monitored through start-up and steady-state stages. Reactor performance was assessed based on pH, total suspended solids (TSS), volatile suspended solids, biochemical oxygen demand, chemical oxygen demand (COD), alkalinity, and volatile fatty acids. The results showed that increasing HRT improved treatment performance in both reactors. During steady-state operation, ABR achieved COD removal efficiencies of 39.34% and 50.14% at HRTs of 12 h and 24 h, respectively, while AF achieved higher COD removals of 55.74% and 73.56% under the same conditions. Similarly, TSS removal efficiencies increased from 76.45% to 78.57% in ABR and from 84.06% to 88.45% in AF when HRT was increased from 12 h to 24 h. Compartmental analysis showed progressive pollutant removal in both reactors, while AF consistently performed better due to enhanced biomass retention and attached microbial growth. Additional adsorption experiments demonstrated that sponge media contributed substantially to particle retention and turbidity removal, achieving approximately 90% turbidity reduction after 24 h of contact time. Biodegradation analysis further indicated that organic removal followed first-order kinetics with a degradation constant of 0.02 h^{-1}. In conclusion, AF operated at 24 h HRT demonstrated the highest treatment efficiency and was identified as the optimum configuration for medium-strength wastewater treatment. The findings highlight the potential of attached-growth anaerobic systems as effective and sustainable alternatives for decentralized wastewater management.

Keywords: Anaerobic baffled reactor; Anaerobic filter; Hydraulic retention time; Medium-strength wastewater; Organic removal; Wastewater treatment

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1. Introduction

The increasing generation of wastewater resulting from population growth, rapid urbanization, and industrial expansion has become a major environmental challenge worldwide. Discharging untreated or inadequately treated wastewater degrades receiving water bodies and poses serious risks to the environment and public health.[1,2] In developing countries, wastewater management remains particularly challenging due to limited infrastructure, insufficient financial resources, and inadequate treatment facilities. In Cambodia, wastewater treatment coverage remains relatively low despite increasing wastewater generation from domestic and commercial activities. Approximately 1,000,000 m^3 of wastewater are generated daily from around 3,000 small enterprises, while only a small proportion receives adequate treatment before discharging into natural water bodies.[3] Consequently, the development of efficient, affordable, and sustainable wastewater treatment technologies has become increasingly important for improving water quality and protecting public health.

Wastewater contains a complex mixture of suspended solids, biodegradable organic matter, nutrients, pathogens, and various dissolved contaminants that can adversely affect aquatic ecosystems if discharged without treatment. High concentrations of organic pollutants increase oxygen consumption in receiving waters, deteriorating water quality and causing ecological imbalance.[4] The characterization of wastewater typically involves parameters such as pH, total suspended solids (TSS), volatile suspended solids (VSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), alkalinity, and volatile fatty acids (VFAs), which are important indicators for assessing treatment performance and designing suitable treatment processes.[5,6] The increasing need to reduce pollutant discharge has driven the development of numerous wastewater treatment technologies employing physical, chemical, and biological processes.

Conventional wastewater treatment systems are generally categorized as centralized or decentralized systems. Centralized treatment facilities collect and treat large volumes of wastewater through extensive sewer networks and treatment plants. Although these systems are effective for densely populated urban areas, they require substantial capital investment, energy consumption, and operational expertise.[7] In contrast, decentralized wastewater treatment systems treat wastewater close to the point of generation. They are often considered more suitable for rural communities and developing regions because of their lower infrastructure requirements and operational costs.[8,9] The implementation of decentralized systems can significantly reduce the costs associated with wastewater collection and conveyance while providing flexible and scalable treatment solutions for communities with limited resources.

Among available treatment technologies, biological processes are widely applied because they can remove biodegradable organic matter efficiently. Biological treatment systems utilize microorganisms to degrade pollutants and convert organic compounds into more stable products.[2] Anaerobic digestion has attracted considerable attention as an environmentally sustainable biological treatment process because it requires less energy, generates less excess sludge, and has the potential to produce biogas as a renewable energy source.[10] The anaerobic digestion process consists of four major stages, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, during which complex organic compounds are sequentially converted into methane and carbon dioxide by different groups of microorganisms.[11,12] The efficiency and stability of anaerobic systems are strongly influenced by environmental conditions such as pH, alkalinity, hydraulic retention time (HRT), organic loading rate, and microbial activity.[13,14]

An anaerobic baffled reactor (ABR) is one of the most widely studied decentralized anaerobic treatment technologies. The reactor consists of multiple compartments separated by vertical baffles that direct wastewater through a series of upflow sludge blanket zones, thereby enhancing contact between wastewater and active biomass.[15] This configuration improves organic matter degradation and biomass retention while reducing sludge washout from the system.[2] Because of its simple design, low operational requirements, and relatively low construction cost, ABR has been considered suitable for wastewater treatment applications in developing countries.[2] Another promising anaerobic technology is the anaerobic filter (AF), which utilizes fixed media to support biofilm development and microbial attachment. In AF systems, wastewater flows through a packed medium where pollutants are removed through biological degradation and physical retention mechanisms.[2,16] The support media provide a large surface area for microbial growth, allowing high biomass retention and stable treatment performance even under variable loading conditions. In addition to biological degradation, pollutant removal may also occur through adsorption and filtration processes associated with the packing media.[16]

Despite the advantages of both technologies, direct comparison between ABR and AF systems remains limited. Previous studies have typically evaluated these reactors independently under different wastewater characteristics, reactor configurations, operating conditions, and

environmental settings. Consequently, it remains difficult to determine whether the observed differences in treatment performance stem from reactor design or variations in experimental conditions. Furthermore, limited information is available about the influence of HRT on the relative performance of ABR and AF systems operated under identical conditions. Thus, further investigation is needed to identify the most effective anaerobic treatment configuration for medium-strength wastewater treatment. This study aims to evaluate and compare the treatment performance of ABR and AF systems treating medium-strength wastewater under HRTs of 12 h and 24 h. The study further investigated the influence of natural sludge development on reactor performance, evaluated organic degradation kinetics, and assessed the contribution of sponge media to pollutant removal. The findings are expected to provide useful information for optimizing and applying decentralized anaerobic wastewater treatment technologies in developing countries, particularly as sustainable and low-cost wastewater management solutions, as indicated in the case study of Cambodia for an on-site wastewater management system.[17]

2. Materials and methods

This study evaluated the performance of ABR and AF for treating medium-strength domestic wastewater. Laboratory-scale reactors were operated under continuous-flow conditions using wastewater collected from the sewer system. Reactor performance at HRTs of 12 h and 24 h was determined. Influent and effluent samples were periodically collected and analyzed to evaluate treatment performance under different operating conditions.

2.1. Experimental setup

Two laboratory-scale reactors constructed from acrylic materials, as shown in Figure 1, were used in this study. The ABR consisted of 8 compartments separated by vertical baffles with a working volume of 71 L (121 cm × 25 cm × 30 cm). The AF consisted of 5 compartments with a working volume of 52 L (95 cm × 25 cm × 30 cm). Sponge media were installed in the AF as support materials for biomass attachment. Both reactors were operated at HRTs of 12 h and 24 h. The corresponding flow rates were adjusted based on the required HRT and monitored daily throughout the experimental period to ensure stable operation.

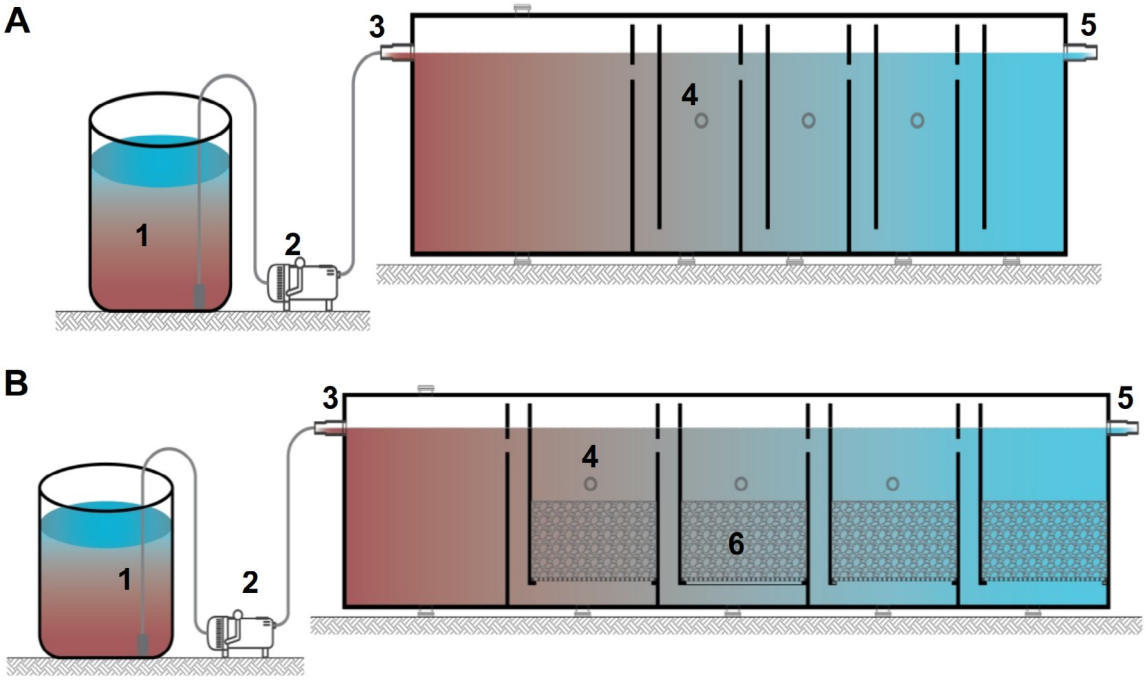


Figure 1. Experimental setup of (A) ABR and (B) AF. 1: Feed tank, 2: Motor, 3: Influent, 4: Sampling port, 5: Effluent, 6: Filter media. Figure created by the authors with Adobe Illustrator.
Abbreviations: ABR: Anaerobic baffled reactor; AF: Anaerobic filter.

2.2. Experimental procedure

Domestic wastewater was continuously collected and supplied directly to the treatment units through feed tanks. Both reactors were operated under continuous-flow conditions and natural sludge growth conditions without adding external seed sludge. During the 12-week start-up phase, wastewater was continuously fed into the reactors to promote biomass development and acclimatization of anaerobic microorganisms. Throughout this period, influent and effluent wastewater quality were monitored weekly to evaluate reactor development and treatment stability. Particular attention was given to pH, alkalinity, VFAs, COD, and BOD, which were used as indicators of anaerobic digestion performance and reactor stabilization.

After the start-up phase, the reactors achieved stable operating conditions and entered the performance evaluation stage. Stable operation was established when treatment performance showed relatively small fluctuations and the system maintained favorable anaerobic digestion conditions. To maintain suitable operating conditions during this stage, sodium bicarbonate was added when necessary to regulate influent pH and provide sufficient alkalinity for anaerobic microbial activity. Performance evaluation was subsequently conducted under HRTs of 12 h and 24 h for both reactor configurations. Reactor performance under steady-state conditions was monitored for eight consecutive weeks. Influent and effluent samples were collected periodically to determine treatment efficiencies, and additional samples were obtained from individual compartments to evaluate pollutant removal along the treatment pathway and compare the treatment behavior of ABR and AF. The experimental data obtained during the steady-state period were used to assess the effects of HRT on reactor performance and to compare the treatment efficiencies of ABR and AF. The evaluation focused on the removal of suspended solids and organic pollutants, as well as reactor stability under natural sludge growth conditions.

2.3. Wastewater quality analysis

Influent and effluent wastewater samples were analyzed to evaluate reactor performance throughout the experimental period. The monitored parameters included pH, TSS, VSS, TN, TP, alkalinity, VFAs, COD, and BOD. pH was measured using a multiparameter meter, Horiba Laqua WQ-300 (Japan). Other parameters were analyzed following the *Standard Methods for the Examination of Water and Wastewater*.[18] It should be noted that the five-day BOD test was used for BOD value measurement, while COD was measured using the closed reflux colorimetric process. Moreover, alkalinity and VFAs were analyzed using titration-based methods. To evaluate anaerobic digestion performance, the VFA-to-alkalinity ratio was calculated and used as an indicator of process stability. Reactor performance was assessed based on pollutant removal efficiency, which was calculated as in **Equation 1**:

$$\text{Removal efficiency (\%)} = \frac{(C_i - C_e) \times 100}{C_i} \quad (1)$$

where C_i and C_e represent influent and effluent concentrations, respectively.

2.4. Data analysis

All experimental data were processed using Microsoft Excel 2019 (United States). Descriptive statistical analyses were performed to determine mean values and standard deviations for the measured parameters. Treatment performance under different reactor configurations and HRT conditions was evaluated using pollutant removal efficiencies. Comparative analyses were conducted between ABR and AF as well as between HRTs of 12 h and 24 h. In addition, compartmental performance was evaluated to examine pollutant removal profiles along the reactors. The resulting data were used to assess reactor stability and identify the operating condition with the highest treatment performance.

3. Results and discussion

3.1. Influent wastewater characteristics

The characteristics of influent wastewater are presented in Table 1. Note that the parameter values reported in this section were obtained during the steady-state monitoring period, whereas the start-up conditions are reported separately in Section 3.2. The wastewater exhibited considerable fluctuations during the experimental period, reflecting variations in daily domestic activities and wastewater generation patterns. The mean influent pH was 7.67 ± 0.29, while average TSS and VSS concentrations were 130.38 ± 40.05 mg/L and 51.21 ± 34.36 mg/L, respectively. The average COD and BOD concentrations were 871.24 ± 153.30 mg/L and 275.88 ± 87.44 mg/L, respectively. These concentrations exceeded the permissible discharge standard, indicating the need for treatment before environmental discharge. In addition to organic pollutants, the wastewater contained measurable concentrations of TN and TP, indicating nutrients that could support microbial growth during biological treatment. The variability in influent quality was expected because wastewater was supplied directly from the sewer network without equalization or pretreatment. Such fluctuations are commonly observed in decentralized wastewater treatment systems receiving domestic wastewater.

Table 1. Influent wastewater characteristics

Parameters	Unit	Value (± SD)
pH	–	7.67 ± 0.29
TSS	mg/L	130.38 ± 40.05
VSS	mg/L	51.21 ± 34.36
Alkalinity	mg/L[a]	576.70 ± 112.90
VFA	mg/L[a]	125.82 ± 38.86
COD	mg/L	871.24 ± 153.30
BOD	mg/L	275.88 ± 87.44
TN	mg/L	2.80 ± 0.98
TP	mg/L	2.74 ± 4.46

Note: [a] indicates that the parameter was measured in mg/L as $CaCO_3$. Abbreviations: BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; SD: Standard deviation; TN: Total nitrogen; TP: Total phosphorus; TSS: Total suspended solids; VFA: Volatile fatty acids; VSS: Volatile suspended solids.

3.2. Start-up stage

Both reactors were operated under natural sludge growth conditions during the start-up period. Continuous wastewater feeding was maintained for 12 weeks to promote biomass development and acclimatization of anaerobic microorganisms. During this period, reactor stability was evaluated through pH, TSS, VSS, TN, TP, alkalinity, VFAs, COD, and BOD monitoring. The average influent pH was 6.71 ± 1.15, while the average effluent pH ranged from 6.41 to 6.56 for all operating conditions. Although the influent pH occasionally decreased to 4.55 due to fluctuations in wastewater composition, no significant adverse effect on reactor operation was observed. As reported by Musa and Idrus,[19] optimal anaerobic digestion activity requires a range of pH for microbial growth. The measured pH in this study remained within a suitable range for anaerobic microbial activity and sludge development.

Removal efficiencies and parameter variations during the start-up phase are shown in Figure 2. High TSS removal was achieved in all reactors, with average removal efficiencies exceeding 80%. Similarly, VSS removal remained within the range of 70%–80%. These results indicate that solid–liquid separation occurred effectively even during the early phase of reactor operation. Moreover, nutrient concentrations gradually decreased during operation, suggesting nutrient uptake associated with biomass growth and microbial activity. The reduction of TN and TP indicates that a portion of the nutrients were utilized for cell synthesis during the sludge development process. As described by Tchobanoglous *et al.*[20] the composition of 100 g microbial cell biomass ($C_{12}H_{87}O_{23}N_{12}P$) requires 12.2 g of nitrogen and 2.3 g of phosphorus, which includes major inorganic nutrients (nitrogen, sulfur, phosphorus, potassium, magnesium, calcium, iron, sodium, and chloride) and minor nutrients (zinc, manganese, molybdenum, selenium, cobalt, copper, and nickel). Although these anaerobic reactors were effective at removing organic matter and suspended solids,[21] limited nutrient treatment performance was observed.[22-24] TN and TP were therefore not analyzed in the subsequent sections. The evolution of alkalinity and VFAs is shown in Figure 2C. During start-up, alkalinity concentrations decreased while VFAs accumulated within the reactors. This behavior is characteristic of the acidogenic phase of anaerobic digestion, where organic matter is converted into intermediate acids faster than methanogens can consume them.[25] Consequently, the VFA-to-alkalinity ratio remained relatively high, indicating that the reactors had not yet achieved complete stabilization.

COD and BOD removal efficiencies during start-up are presented in Figure 2D. Although organic matter removal was observed, COD removal remained below 50% under all operating conditions, and BOD removal exhibited considerable fluctuations throughout the monitoring period. These results indicate that the reactors were still under microbial acclimatization and had not yet achieved stable methanogenic activity, as described by Bhuvaneswari *et al.*[26] The combination of high VFA accumulation, relatively low alkalinity, and fluctuating COD removal suggests that the reactors were predominantly operating under acidogenic conditions. After approximately 12 weeks of operation, the systems gradually transitioned toward stable anaerobic digestion conditions, indicating successful biomass establishment and reactor maturation.

3.3. Steady-state stage

Following the start-up period, both reactors gradually achieved stable operating conditions after approximately 12 weeks of continuous operation. Reactor stabilization was verified by reduced performance fluctuations and the establishment of optimal anaerobic digestion conditions. Influent pH of approximately 7–8 and alkalinity of 600–700 mg/L as $CaCO_3$ were maintained. Under these conditions, the VFA-to-alkalinity ratio remained below 0.25, indicating stable methanogenic activity within the reactors.[27]

3.3.1. Effect of hydraulic retention times on anaerobic baffled reactor performance

pH variation during stable ABR operation is presented in Figure 3A. The average influent pH was maintained at 7.67 ± 0.29, while average effluent pH values were 6.93 ± 0.19 and 6.89 ± 0.23 at HRTs of 12 h and 24 h, respectively. Minor pH reductions were observed during several monitoring periods, which were associated with organic acid

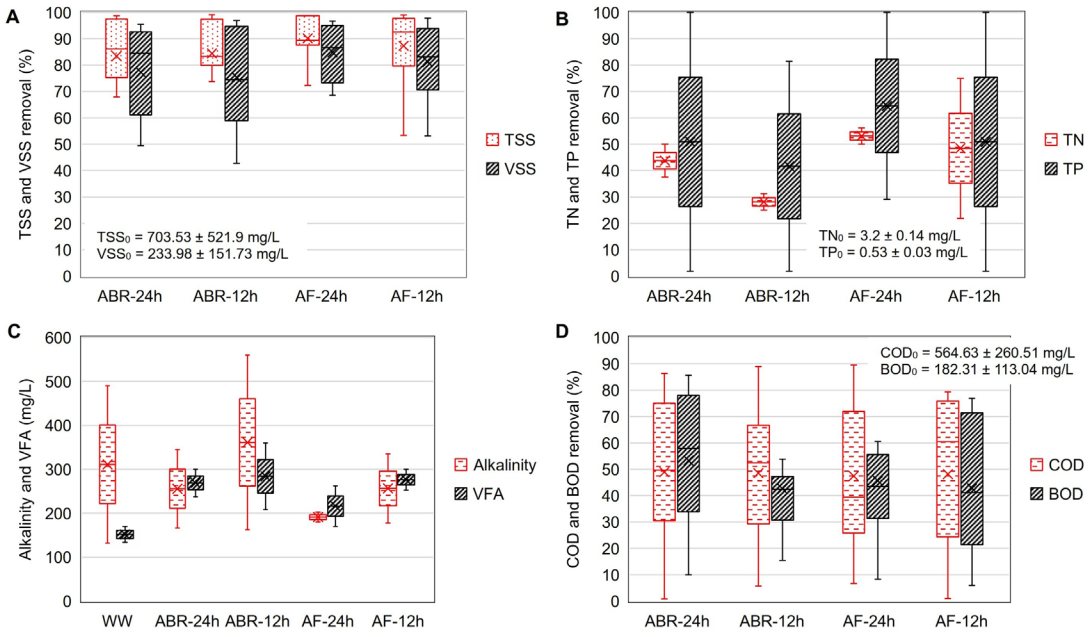


Figure 2. Removal efficiency and variation of: (A) TSS and VSS, (B) TN and TP, (C) alkalinity and VFA, and (D) COD and BOD during the start-up stage. Abbreviations: ABR: Anaerobic baffled reactor; AF: Anaerobic filter; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; TN: Total nitrogen; TP: Total phosphorus; TSS: Total suspended solids; VFA: Volatile fatty acids; VSS: Volatile suspended solids; WW: Wastewater.

production during anaerobic degradation. Nevertheless, the pH remained within the optimal range for anaerobic microbial activity and did not adversely affect reactor performance. Similar observations have been reported for anaerobic systems operating under stable digestion conditions, where pH values between 6.5 and 7.6 support efficient microbial activity.[28] The removal efficiencies of TSS and VSS are shown in Figure 3B. The average influent TSS and VSS concentrations were 130.38 ± 40.05 mg/L and 51.21 ± 34.36 mg/L, respectively. Under stable operation, TSS removal efficiencies reached 76.45% and 78.57% at HRTs of 12 h and 24 h, respectively. Similarly, VSS removal efficiencies increased from 62.76% at 12 h to 67.97% at 24 h. The improved performance observed at longer HRT can be attributed to increased settling time and enhanced contact between wastewater and active biomass, resulting in more effective solid retention and degradation.

Moreover, the variations in alkalinity and VFAs, along with the removal efficiencies of COD and BOD, are shown in Figure 3C and 3D**.** The alkalinity concentrations remained relatively stable throughout the monitoring period, indicating sufficient buffering capacity within the reactors. Meanwhile, VFAs remained substantially lower than alkalinity concentrations, resulting in a VFA-to-alkalinity ratio below the critical threshold for process inhibition. These results demonstrate that methanogenic activity was successfully established after the start-up period, maintaining stable reactor performance.[29,30] In terms of COD removal, increasing the HRT from 12 h to 24 h improved COD removal from 39.34% to 50.14%. A similar trend was observed for BOD removal. The improved performance at longer HRT suggests that increased contact time enhanced microbial degradation of organic matter and promoted more complete anaerobic digestion. Recent studies have also demonstrated that HRT significantly affects both COD and BOD removal in ABR systems.[31,32] Overall, the results demonstrate that HRT influenced ABR performance. The 24 h HRT consistently achieved higher removal efficiencies than the 12 h HRT for most monitored parameters, indicating that longer retention time favored pollutant degradation and solid stabilization within the reactor.

3.3.2. Effect of hydraulic retention times on anaerobic filter performance

Variation in pH in the AF under stable operating conditions is shown in Figure 4A. Similar to ABR, influent pH was maintained at approximately 7.67 ± 0.29. The average effluent pH was 6.66 ± 0.25 and 6.86 ± 0.29 at HRTs of 12 h and 24 h, respectively. Although pH decreased slightly during several monitoring periods, the values remained within the acceptable range for anaerobic digestion and

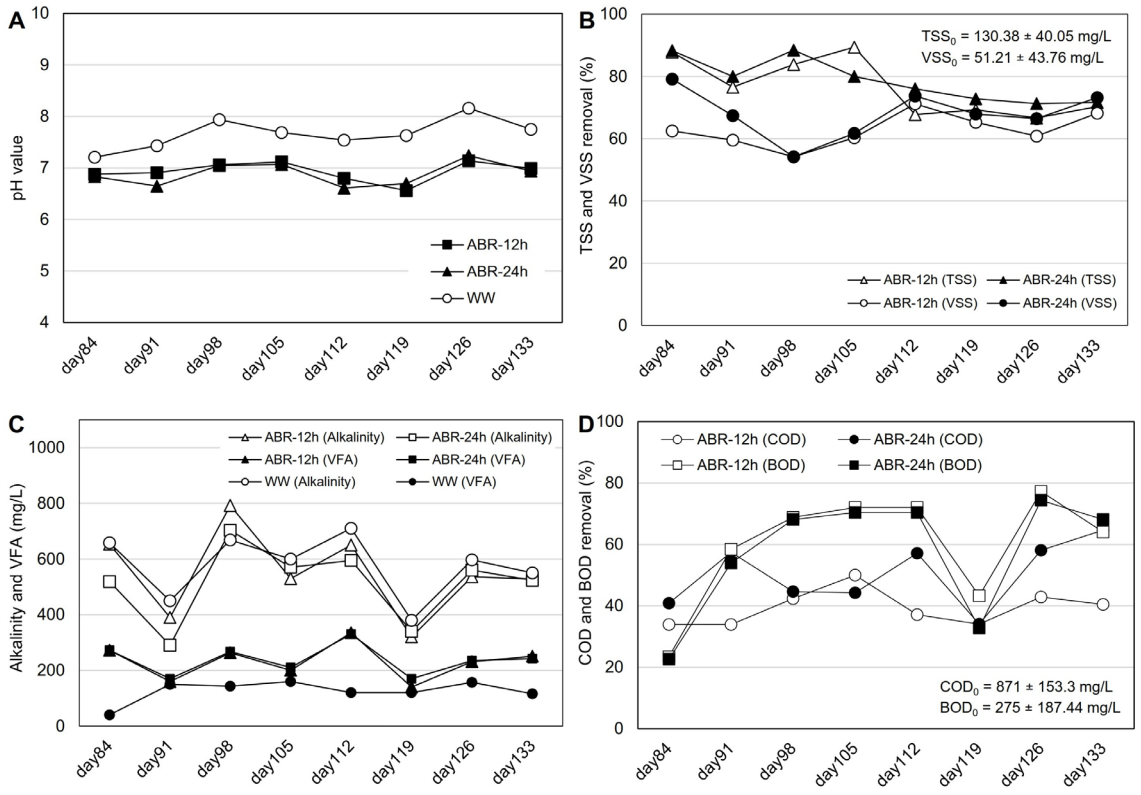


Figure 3. Variation in (A) aquatic pH value, (B) TSS and VSS removal efficiencies, (C) alkalinity and VFA concentrations, and (D) COD and BOD removal efficiencies during steady-state ABR operation.
Abbreviations: ABR: Anaerobic baffled reactor; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; TSS: Total suspended solids; VFA: Volatile fatty acids; VSS: Volatile suspended solids; WW: Wastewater.

did not affect reactor stability. Figure 4B presents the removal efficiencies of TSS and VSS. AF achieved superior solid removal compared with ABR under both HRT conditions. Average TSS removal efficiencies reached 84.06% and 88.45% at HRTs of 12 h and 24 h, respectively, while VSS removal efficiencies were 77.44% and 83.16% at 12 h HRT and 24 h HRT, respectively. The enhanced solid removal performance can be attributed to the presence of sponge media, which promoted particle retention and provided additional surfaces for microbial attachment.

Alkalinity and VFA profiles during stable AF operation are shown in Figure 4C. Alkalinity concentrations remained between approximately 300 and 600 mg/L as $CaCO_3$, while VFAs generally remained below 300 mg/L as $CaCO_3$ throughout the monitoring period. This profile is similar to a previous study,[29] in which alkalinity in the range of 650 to 850 mg/L and VFA in the range of 50 to 300 mg/L were recorded as the optimal ranges for maintaining utmost anaerobic stability. The relatively low VFA accumulation and stable alkalinity concentrations indicate that the AF maintained optimal conditions for methanogenesis and reactor stability. The COD and BOD removal efficiencies are shown in Figure 4D. AF achieved substantially higher organic matter removal than ABR under both HRT conditions. Average COD removal efficiencies were 55.74% and 73.56% at HRTs of 12 h and 24 h, respectively. Similarly, BOD removal efficiencies increased from 62.07% to 64.11% when HRT was increased from 12 h to 24 h. The substantial increase in COD removal at 24 h HRT indicates that retention time played an important role in promoting biological degradation and improving treatment efficiency, which is consistent with previous findings.[31,33] The superior performance of AF compared with ABR is likely related to the presence of sponge media, which enhanced biomass retention and provided favorable conditions for biofilm development. The increased microbial population associated with attached growth systems contributed to improved organic matter degradation and solid removal.[33-35] Recent studies using sponge or other porous carrier media in anaerobic reactors have demonstrated that attached-growth media can improve biomass retention and organic matter

removal.[33,36] Gopalakrishnan *et al.*,[36] for example, reported approximately 66% COD removal using a porous biofilm carrier in an anaerobic fixed-film reactor at 14 h HRT.

3.3.3. Organic removal mechanism

The mechanisms responsible for pollutant removal in the reactors were further investigated through biodegradation and adsorption experiments, as presented in Figure 5. The biodegradation experiment was conducted using wastewater with an initial COD concentration of approximately 713 mg/L and an anaerobic sludge concentration of 1.82 g/L. During the first four h of operation, COD removal was negligible (0.14%), indicating limited biological activity at short contact times (see Figure 5A). However, COD removal gradually increased to 5.66%, 16.13%, 24.17%, and 32.73% at contact times of 6, 14, 20, and 24 h, respectively. The degradation behavior followed first-order kinetics with R^2 = 0.93 and a degradation constant, k, of 0.02 h^{-1}. This result suggests that biological degradation was the dominant mechanism contributing to organic matter removal during reactor operation.[37]

In addition to biodegradation, sponge media contributed significantly to pollutant removal through physical adsorption and particle retention. The adsorption experiment demonstrates that wastewater turbidity decreased from an initial value of 206.1 NTU to 41.9 NTU, exhibiting approximately 80% removal within only 2 h when sponge media were present, as illustrated in Figure 5B. Pollutant removal efficiency further increased to approximately 90% after 24 h of contact time. In comparison, systems without sponge media achieved only 75% removal after 2 h and approximately 80% removal after 24 h. These findings indicate that sponge media enhanced reactor performance not only by supporting microbial attachment but also by increasing the retention of suspended particles within the treatment system.

These findings align with recent evaluations of sponge-retrofitted anaerobic reactors by Ullah *et al.*,[33,34] demonstrating that pollutant elimination within porous polyurethane matrices is driven by synergistic pathways. Specifically, the extensive sponge surface area serves as an immediate sink for physical substrate adsorption, while its

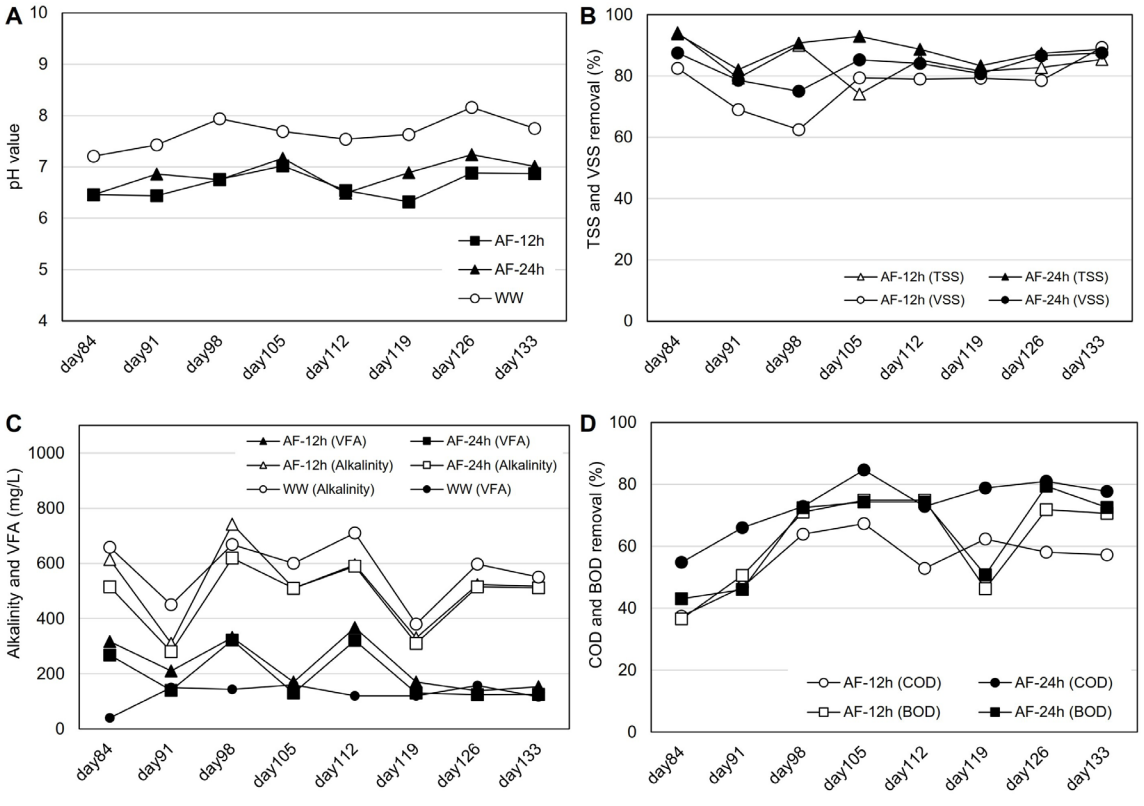


Figure 4. Removal efficiency and variation of: (A) aquatic pH value, (B) TSS and VSS, (C) alkalinity and VFA, and (D) COD and BOD under steady-state AF.

Abbreviations: AF: Anaerobic filter; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; TSS: Total suspended solids; VFA: Volatile fatty acids; VSS: Volatile suspended solids; WW: Wastewater.

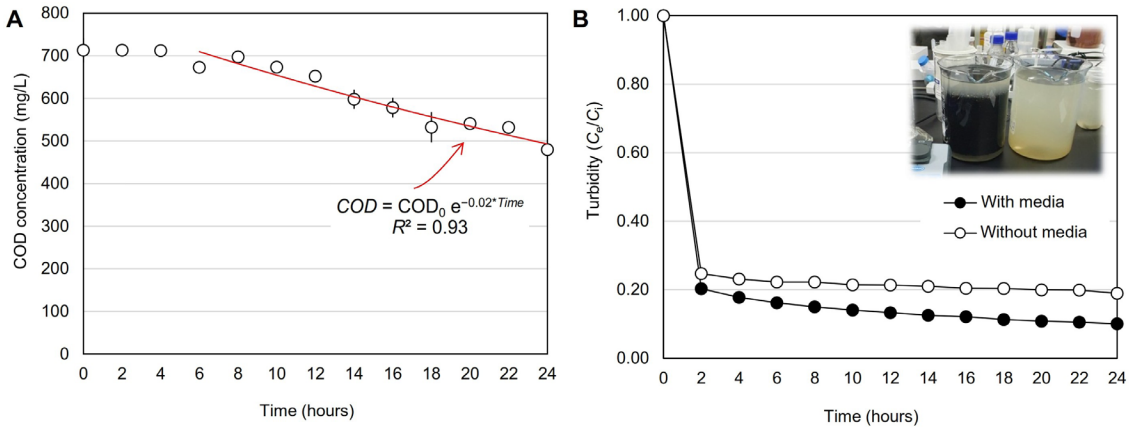


Figure 5. Pollutant removal experiment: (A) Organic degradation kinetics and (B) particle adsorption capacity of sponge media
Abbreviation: COD: Chemical oxygen demand.

interconnected macropores physically trap and intercept incoming suspended particles. Once retained, these captured organic solids undergo prolonged biological degradation via the densely populated attached biofilms, preventing biomass washout and maintaining stable treatment performance even under reduced HRTs. The combined effects of biodegradation and particle adsorption explain the superior performance of AF compared with ABR. Figure 6 illustrates the treatment mechanism of combined biodegradation and particle adsorption. The sponge media acted as both a filtration medium and a support matrix for attached microbial growth, thereby improving solids retention and enhancing organic matter degradation throughout the reactor.

3.4. Configuration and operation analysis

3.4.1. Compartmental analysis

COD removal performance along the reactor compartments at 12 h HRT is presented in Figure 7. In the ABR system, COD removal gradually increased from the first to the final compartment. The first compartment achieved an average COD removal of 23.24%, followed by 25.07%, 26.53%, 27.79%, 31.62%, 33.61%, 36.16%, and 38.63% in the second through eighth compartments, respectively. The gradual increase in removal efficiency indicates continuous organic degradation throughout the reactor, with each compartment contributing to pollutant reduction. The increasing COD removal efficiency along the reactor compartments indicates effective compartmentalization and continuous biodegradation of organic matter. Similar findings were reported by Ghaniyari-Benis *et al.*,[38] who demonstrated that anaerobic compartmentalized reactors promote microbial phase separation, with acidogenesis occurring in the front compartments and methanogenesis dominating in the latter compartments, leading to enhanced overall COD removal. However, AF exhibited higher removal efficiencies in all comparable compartments, as the first compartment achieved a COD removal of 31.08%, increasing to 36.06% and 42.19% in the second and third compartments, respectively. AF showed a COD removal efficiency approximately 7.8 percentage points higher than that of ABR in the first compartment and approximately 12.8 percentage points higher removal in subsequent compartments. This trend agrees with previous studies demonstrating that the incorporation of an AF enhances organic matter removal beyond that achieved by an ABR alone. Khan *et al.*[39] reported that AF COD removal increased approximately 6%–9% over ABR, when AF was incorporated as a post-treatment unit, highlighting the contribution of attached-growth biomass to wastewater treatment performance. Furthermore, Sousa *et al.*[40] highlighted that AF systems provide extensive surface area for microbial attachment and biofilm development, promoting higher biomass retention and more effective degradation of organic substrates. Therefore, the superior compartmental COD removal observed in AF in the present study is likely attributable to enhanced biofilm-mediated biodegradation and reduced biomass washout compared with the suspended-growth conditions prevailing in ABR.

The higher performance observed in AF is attributed to the sponge media, which provided a larger surface area for microbial attachment and enhanced biomass retention. The media also improved the retention of suspended particles, resulting in greater contact between pollutants and active microorganisms. Consequently, organic degradation occurred more efficiently in AF than in ABR throughout the treatment process. The compartmental

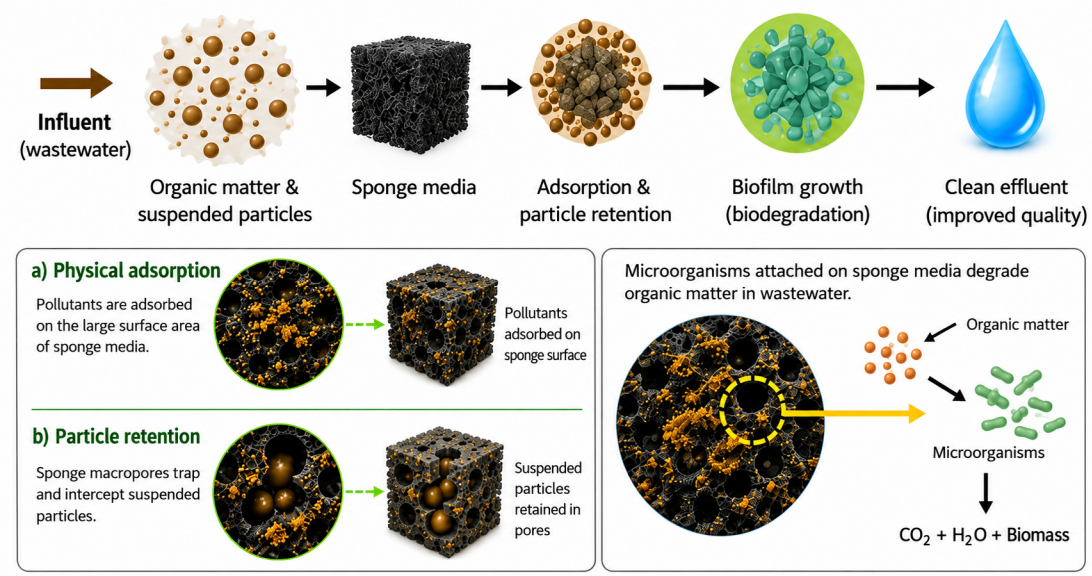


Figure 6. Proposed organic-matter removal mechanisms of the sponge medium in the AF. Figure created by the authors with ChatGPT.
Abbreviation: AF: Anaerobic filter.

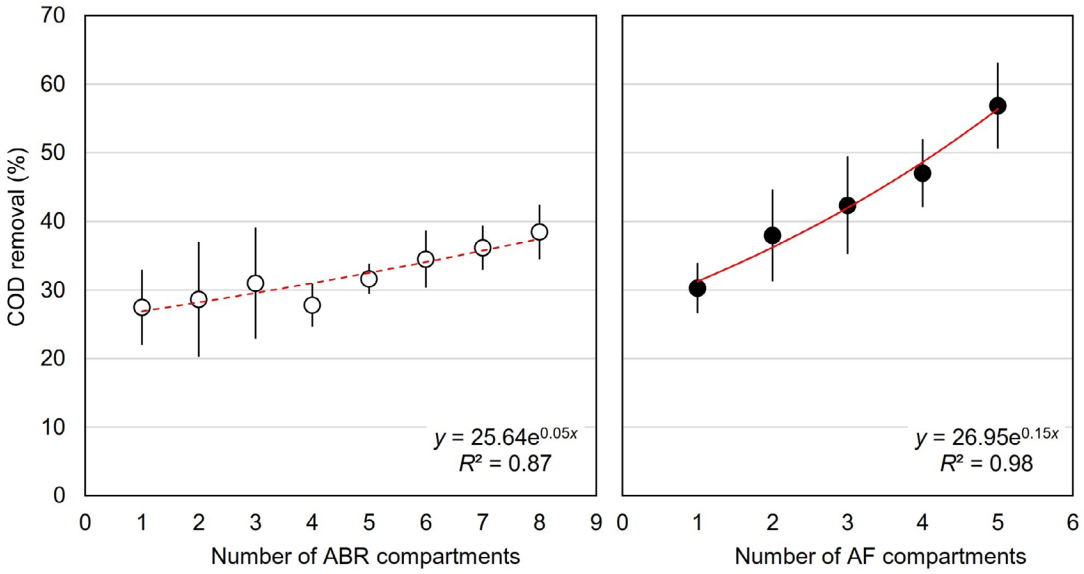


Figure 7. COD removal performance along reactor compartments
Abbreviations: ABR: Anaerobic baffled reactor; AF: Anaerobic filter; COD: Chemical oxygen demand.

analysis further demonstrates that pollutant removal was not confined to a single compartment but distributed progressively throughout the reactors. However, AF maintained consistently higher removal efficiencies at all locations, indicating that the incorporation of sponge media improved reactor effectiveness.

3.4.2. Hydraulic retention time optimization

As discussed, increasing HRT from 12 h to 24 h improved pollutant removal in both reactor configurations. In ABR, average COD removal increased from 39.34% to 50.14%, representing an increase of 10.80 percentage points. AF exhibited a higher increase, with COD removal improving

from 55.74% to 73.56%, corresponding to an increase of 17.82 percentage points. Longer HRTs also had a positive effect on TSS and VSS removal. In ABR, TSS removal increased from 76.45% to 78.57%, while VSS removal improved from 62.76% to 67.97%. AF achieved even higher performance, with TSS removal increasing from 84.06% to 88.45% and VSS removal increasing from 77.44% to 83.16% when HRT was extended from 12 h to 24 h. A similar trend has been reported in anaerobic treatment systems. Khan *et al.*[39] observed that COD removal in ABR decreased by 9% after reducing HRT from 14 h to 8 h, indicating that reduced retention time limited microbial degradation and negatively affected treatment efficiency. Similarly, Yang *et al.*[41] reported that COD removal efficiency in an ABR increased under longer HRT conditions, reaching approximately 79% at 24–36 h HRT, while performance declined at shorter HRTs due to increased hydraulic and organic loading, resulting in insufficient contact between wastewater and microbial biomass. The authors further highlighted that ABRs benefit from prolonged biomass retention and the spatial separation of acidogenesis and methanogenesis, which contributes to enhanced process stability and organic matter degradation.[41]

A comparison between reactor configuration and operating conditions is presented in Figure 8. Under both HRT conditions, AF consistently outperformed ABR for all major performance indicators. At 12 h HRT, AF achieved a COD removal efficiency 16.40 percentage points higher than that of ABR; at 24 h HRT, the difference was 23.42 percentage points. Similar trends were observed for TSS, VSS, and BOD removal. The superior performance of AF can be explained by the dual function of sponge media, as discussed in Section 3.3.3. In addition to serving as a support medium for attached microbial growth, the sponge also retained suspended particles and increased biomass concentration within the reactor. The combined mechanisms enhanced both physical retention and biological degradation, resulting in higher pollutant removal efficiencies than those achieved by ABR. The interaction between HRT and attached biomass is also illustrated by a recent anaerobic biocarrier study, in which HRT variations influenced organic removal while the biocarrier promoted attached biofilm growth.[42] Overall, AF operated at an HRT of 24 h demonstrated the highest treatment efficiency among all investigated conditions. This configuration achieved the greatest removal of COD, BOD, TSS, and VSS while maintaining stable anaerobic digestion conditions throughout the experimental period. Under the investigated conditions, AF at 24 h HRT demonstrated the highest treatment performance, achieving 73.56% COD removal, 88.45% TSS removal, and 83.16% VSS removal. However, extending HRT from 12 h to 24 h also increases the required reactor volume for a given wastewater flow.

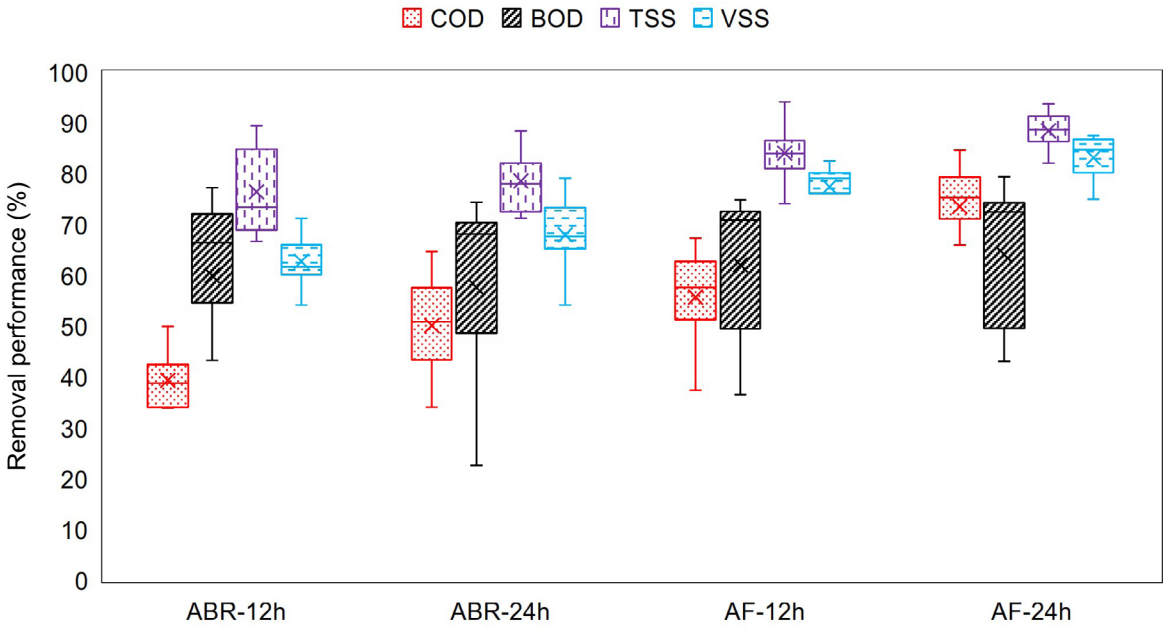


Figure 8. Comparative performance of ABR and AF under different HRTs

Abbreviations: ABR: Anaerobic baffled reactor; AF: Anaerobic filter; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; HRT: Hydraulic retention time; TSS: Total suspended solids; VSS: Volatile suspended solids.

More importantly, the residual COD after anaerobic treatment indicates that AF alone may not provide sufficient effluent quality where stringent discharge limits apply. Recent decentralized treatment studies have demonstrated the potential benefit of coupling anaerobic treatment with subsequent biological polishing processes to achieve higher final effluent quality.[43] Therefore, AF-24 h should be regarded as the highest-performing anaerobic configuration evaluated in this study rather than a complete standalone treatment system. For practical decentralized application, AF could be considered as a primary treatment or pretreatment unit followed by an appropriate polishing process, such as aerobic biological treatment, depending on the required effluent quality. Moreover, practical implementation should also consider reactor footprint, biogas and odor management, sludge accumulation, and subsequent sludge handling. These factors were not evaluated in the present laboratory-scale study.

4. Conclusion

This study evaluated and compared the treatment performance of ABR and AF treating medium-strength wastewater at HRTs of 12 h and 24 h. Both reactors were operated under natural sludge growth regimes to investigate their treatment efficiency and operational stability for decentralized wastewater treatment. The results demonstrate that reactor performance was strongly influenced by HRT. Increasing HRT from 12 h to 24 h improved pollutant removal efficiencies in both systems due to the extended contact time between wastewater and active biomass. Under steady-state conditions, ABR achieved average COD removal efficiencies of 39.34% and 50.14% at HRTs of 12 h and 24 h, respectively, whereas AF achieved higher COD removals of 55.74% and 73.56% under the same operating conditions. Similar trends were observed for BOD, TSS, and VSS removal.

Compartmental analysis revealed that pollutant removal occurred progressively along the treatment pathway in both reactors. However, AF consistently exhibited superior treatment performance due to the presence of sponge media, which enhanced biomass retention, promoted attached microbial growth, and improved particle retention. Additional adsorption experiments verified that sponge media contributed not only to biological degradation but also to the physical removal of suspended particles. However, the residual COD indicates that anaerobic treatment alone may not be sufficient where a stringent final effluent limit is required. In conclusion, AF operated at 24 h HRT exhibited the highest treatment performance among all investigated conditions and was identified as the optimum operating configuration for medium-strength wastewater treatment. It should be considered a promising anaerobic primary treatment or pretreatment step rather than a complete standalone treatment system. The findings demonstrate that attached-growth anaerobic systems can significantly improve treatment efficiency compared with conventional compartmentalized anaerobic reactors while maintaining the simplicity and low operational requirements required for decentralized wastewater treatment applications.

The findings of this study show the advantages of combining suspended-growth and attached-growth anaerobic treatment mechanisms. Therefore, future research should focus on developing integrated anaerobic treatment systems that combine the strengths of ABR and AF configurations and/or integrated anaerobic–aerobic treatment systems to further improve organic matter removal and reactor stability. Additional studies should investigate the optimization of reactor configuration, including compartment number and arrangement, media distribution, and reactor volume allocation, to enhance treatment efficiency while minimizing construction requirements. Future work should also evaluate the long-term operational performance of integrated anaerobic systems under varying wastewater characteristics and loading conditions to improve their practical applicability for decentralized wastewater treatment. Furthermore, nutrient removal, sludge production, microbial community dynamics, and resource recovery potential should be investigated to provide valuable information for advancing sustainable anaerobic wastewater treatment technologies and supporting their implementation in developing countries.

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Conflict of interest

The authors declare they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

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Availability of data

Data are available from the corresponding author upon reasonable request.

References

1. Abbassi B, Abuharb R, Ammary BY, Almanaseer N, Kinsley C. Modified septic tank: innovative onsite wastewater treatment system. *Water*. 2018;10(5):578.

   doi: 10.3390/w10050578

2. Musa MA, Idrus S. Physical and biological treatment technologies of slaughterhouse wastewater: a review. *Sustainability*. 2021;13(9):4656.

   doi: 10.3390/su13094656

3. Harrendorf N, EuroCham Cambodia. Partnership Ready Cambodia: Water Supply and Wastewater Treatment. Phnom Penh, Cambodia: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH; 2020. Accessed July 16, 2026. https://www.giz.de/de/downloads/GBN_Sector%20Brief_Kambodscha_Wasser_E_WEB.pdf

4. Akpor OB, Muchie M. Environmental and public health implications of wastewater quality. *Afr J Biotechnol*. 2011;10(13):2379-2387.

   doi: 10.5897/AJB10.1797

5. Pooja A. Physical, chemical and biological characteristics of water. Bathinda, Punjab, India: Central University of Punjab; 2017. Accessed July 16, 2026. https://www.researchgate.net/publication/322419790_Physical_Chemical_and_Biological_Characteristics_of_Water_e_Content_Module

6. Englande AJ Jr, Krenkel P, Shamas J. Wastewater treatment & water reclamation. In: *Reference Module in Earth Systems and Environmental Sciences*. Amsterdam, The Netherlands: Elsevier; 2015.

   doi: 10.1016/B978-0-12-409548-9.09508-7

7. De Anda J, López-López A, Villegas-García E, Valdivia-Aviña K. High-strength domestic wastewater treatment and reuse with onsite passive methods. *Water*. 2018;10(2):99.

   doi: 10.3390/w10020099

8. Massoud MA, Tarhini A, Nasr JA. Decentralized approaches to wastewater treatment and management: applicability in developing countries. *J Environ Manage*. 2009;90(1):652-659.

   doi: 10.1016/j.jenvman.2008.07.001

9. US Environmental Protection Agency. *Handbook for Managing Onsite and Clustered (Decentralized) Wastewater Treatment Systems: An Introduction to Management Tools and Information for Implementing EPA's Management Guidelines*. Cincinnati, OH, USA: National Service Center for Environmental Publications; 2005. EPA-832-B-05-001. Accessed July 13, 2026. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20017K2G.txt

10. Lin CY, Lay CH, Chen CC. High-strength wastewater treatment using anaerobic processes. In: Lee DJ, Jegatheesan V, Ngo HH, Hallenbeck PC, Pandey A, eds. *Current Developments in Biotechnology and Bioengineering: Biological Treatment of Industrial Effluents*. Amsterdam, The Netherlands: Elsevier; 2017:321-357.

    doi: 10.1016/B978-0-444-63665-2.00013-8

11. Achinas S, Achinas V, Euverink GJW. Microbiology and biochemistry of anaerobic digesters: an overview. In: *Bioreactors: Sustainable Design and Industrial Applications in Mitigation of GHG Emissions*. Amsterdam, The Netherlands: Elsevier; 2020:17-26.

    doi: 10.1016/B978-0-12-821264-6.00002-4

12. Wu D, Li L, Peng Y, *et al.* State indicators of anaerobic digestion: a critical review on process monitoring and diagnosis. *Renew Sustain Energy Rev*. 2021;148:111260.

    doi: 10.1016/j.rser.2021.111260

13. Akunna JC. Anaerobic treatment of brewery wastes. In: Hill AE, ed. *Brewing Microbiology: Managing Microbes, Ensuring Quality and Valorising Waste*. 2nd ed. Cambridge, UK: Woodhead Publishing; 2025:377-388.

    doi: 10.1016/B978-0-323-99606-8.00008-0

14. Sun H, Wu S, Dong R. Monitoring volatile fatty acids and carbonate alkalinity in anaerobic digestion: titration methodologies. *Chem Eng Technol*. 2016;39(4):599-610.

    doi: 10.1002/ceat.201500293

15. Ndibnuh PAS, David NY, Ilorme F. Conceptual design of a decentralized wastewater treatment system for the Bamenda Regional Hospital, Cameroon. *J Pollut*. 2018;1(2):1-11. https://hindi.hilarispublisher.com/abstract/conceptual-design-of-a-decentralized-wastewater-treatment-system-for-the-bamenda-regional-hospital-cameroon-28925.html

16. Borja R. Biogas production. In: Moo-Young M, ed.

Comprehensive Biotechnology. 2nd ed. Amsterdam, The Netherlands: Elsevier; 2011:785-798.

doi: 10.1016/B978-0-08-088504-9.00126-4

17. Global Green Growth Institute. *Current Sewerage Situation in Cambodia: Capacity Development Programme for the Provincial Water Supply and Sanitation Project*. Phnom Penh, Cambodia: Ministry of Public Works and Transport; 2025. Accessed July 13, 2026. https://gggi.org/report/current-sewerage-situation-in-cambodia-capacity-development-programme-for-the-provincial-water-supply-and-sanitation-project/

18. American Public Health Association. *Standard Methods for the Examination of Water and Wastewater*. 23rd ed. Washington, D.C., USA: American Public Health Association; 2017.

19. Musa MA, Idrus S. Effect of hydraulic retention time on the treatment of real cattle slaughterhouse wastewater and biogas production from HUASB reactor. *Water*. 2020;12(2):490.

doi: 10.3390/w12020490

20. Tchobanoglous G, Stensel HD, Burton FL. *Wastewater Engineering: Treatment and Reuse*. 4th ed. New York, NY, USA: McGraw-Hill; 2003.

21. Gutterer B, Panzerbieter T, Reckerzügel T, Sasse L. *Decentralised Wastewater Treatment Systems (DEWATS) and Sanitation in Developing Countries: A Practical Guide*. Loughborough, UK: WEDC, Loughborough University; 2009.

22. Collivignarelli C, Urbini G, Farneti A, Bassetti A, Barbaresi U. Anaerobic-aerobic treatment of municipal wastewaters with full-scale upflow anaerobic sludge blanket and attached biofilm reactors. *Water Sci Technol*. 1990;22(1-2):475-482.

doi: 10.2166/wst.1990.0171

23. Foxon K, Pillay S, Lalbahadur T, Rodda N, Holder F, Buckley C. The anaerobic baffled reactor (ABR): an appropriate technology for on-site sanitation. *Water SA*. 2004;30(5):44-50.

doi: 10.4314/wsa.v30i5.5165

24. Muchaonyerwa P, Oyawoye AA, Odindo AO. Nitrogen and phosphorus removal from anaerobic baffled reactor effluent using *Lemna minor* and fertiliser value of the biomass for ryegrass production. *Environ Monit Assess*. 2025;197(11):1188.

doi: 10.1007/s10661-025-14592-4

25. Ripley LE, Boyle WC, Converse JC. Improved alkalimetric monitoring for anaerobic digestion of high-strength wastes. *J Water Pollut Control Fed*. 1986;58(5):406-411. Accessed July 13, 2026. https://www.jstor.org/stable/25042933

26. Bhuvaneswari A, Asha B, Selvakumar D. Start up and enhancement granulation in an anaerobic baffled reactor for the treatment of textile wastewater. *SSRN*. Preprint posted online July 10, 2017. Accessed July 13, 2026. https://ssrn.com/abstract=2639037

27. Yenji SS, Munavalli GR, Koli MM. Field-scale anaerobic baffled reactor for domestic wastewater treatment: effect of dynamic operating conditions. *Water Pract Technol*. 2021;16(1):42-58.

doi: 10.2166/wpt.2020.103

28. Ciotola RJ, Martin JF, Tamkin A, *et al.* The influence of loading rate and variable temperatures on microbial communities in anaerobic digesters. *Energies*. 2014;7(2):785-803.

doi: 10.3390/en7020785

29. Bassuney DM, Ibrahim WA, Moustafa MAE. Performance of an anaerobic baffled reactor (ABR) treating high-strength food industrial wastewater with fluctuating pH. In: Proceedings of the International Conference on Advances in Civil, Structural and Environmental Engineering (ACSEE 2013). Institute of Research Engineers and Doctors; 2013:98-102.

doi: 10.3850/978-981-07-7965-8_38

30. Zhu Y, Yu D, Koornneef E, Parker WJ. Pilot-scale evaluation of cascade anaerobic digestion of mixed municipal wastewater treatment sludges. *Water Environ Res*. 2024;96(7):e11072.

doi: 10.1002/wer.11072

31. Al Kholif M, Subianto A, Sutrisno J. Effect of hydraulic retention time (HRT) in an anaerobic baffled reactor (ABR) on the reduction of BOD and COD in slaughterhouse industrial wastewater. *Adv Environ Technol*. 2025;11(1):1-12.

doi: 10.22104/aet.2024.6805.1860

32. Mahdi FK, Abu-Alhail S, Dawood AS. Performance of the anaerobic baffled reactor for primary treatment of rural domestic wastewater in Iraq. *Open Eng*. 2022;12(1):859-865.

doi: 10.1515/eng-2022-0346

33. Ullah N, Sheikh Z, Ahmad O, Khan SJ. Performance evaluation of sponge anaerobic baffled reactor for municipal wastewater treatment. *Sustainability*. 2024;16(21):9398.

doi: 10.3390/su16219398

34. Ullah N, Sheikh Z, Khan MS, Alotaibi SB, Saddam. Treatment of real municipal wastewater in a sponge anaerobic baffled reactor with cultivation-based microbial characterization. *Water Sci Technol*. 2026;93(9):1346-1362.

doi: 10.2166/wst.2026.271

35. Chan R, Chiemchaisri C, Chiemchaisri W. Application of membrane bioreactor with sponge media in aquaculture wastewater treatment. *J Fish Environ*. 2021;45(2):106-118. Accessed July 13, 2026. https://li01.tci-thaijo.org/index.php/JFE/article/view/247757

36. Gopalakrishnan S, Dipin Nath RS, Shende AD, Bhaskaran K. Needle-Felt Coir fibre: A natural substitute for synthetic media in anaerobic fixed film reactors for wastewater treatment. *J Environ Chem Eng*. 2024;12(2):112382.

doi: 10.1016/j.jece.2024.112382

37. Ghorbanian M. *Enhancement of Anaerobic Digestion of Actual Industrial Wastewaters: Reactor Stability and Kinetic Modeling*. Doctoral dissertation. University of Louisville; 2014.

doi: 10.18297/etd/494

38. Ghaniyari-Benis S, Borja R, Monemian SA, Goodarzi V. Anaerobic treatment of synthetic medium-strength wastewater using a multistage biofilm reactor. *Bioresour Technol*. 2009;100(5):1740-1745.

doi: 10.1016/j.biortech.2008.09.046

39. Khan A, Khan SJ, Miran W, Zaman WQ, Aslam A, Shahzad HMA. Feasibility study of anaerobic baffled reactor coupled with anaerobic filter followed by membrane filtration for wastewater treatment. *Membranes*. 2023;13(1):79.

doi: 10.3390/membranes13010079

40. Sousa SR, Rodrigues LS, Sampaio RR, Dutra JC, Silva IJ. Efficiency of the anaerobic baffled reactor followed by anaerobic filter in the removal of nutrients and pathogenic organisms in fish processing effluents. *Arq Bras Med Vet Zootec*. 2022;74(5):892-900.

doi: 10.1590/1678-4162-12504

41. Yang B, Xu H, Wang J, Yan D, Zhong Q, Yu H. Performance evaluation of anaerobic baffled reactor (ABR) for treating alkali-decrement wastewater of polyester fabrics at incremental organic loading rates. *Water Sci Technol*. 2018;77(9-10):2445-2453.

doi: 10.2166/wst.2018.194

42. Park J, Dash SR, How SW, Wu D, Kim J. Anaerobic fluidized bed membrane bioreactor with multichanneled biocarrier for carbon-neutral, decentralized greywater treatment. *ACS EST Eng*. 2024;4(10):2346-2357.

doi: 10.1021/acsestengg.4c00186

43. Raja W, Rohith GSN, Brar SK, Kumar P. Decentralized sewage treatment and energy recovery in high-rise buildings using anaerobic baffle reactor coupled with plant biofilter reactor: a focus on surfactant and phenol removal. *Sci Total Environ*. 2025;982:179661.

doi: 10.1016/j.scitotenv.2025.179661