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Effect of hydraulic retention time (HRT) in an anaerobic baffled reactor (ABR) on the reduction of BOD and COD in slaughterhouse industrial wastewater

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ABSTRACT

The slaughterhouse industry generates large volumes of wastewater with high pollutant levels, such as biological oxygen demand (BOD) and chemical oxygen demand (COD). This study investigates using anaerobic baffled reactor (ABR) technology with predetermined hydraulic retention time (HRT) to treat slaughterhouse wastewater containing BOD and COD. The study was carried out in the ABR reactor with a volume of 20,000 cm^3 of wastewater on a laboratory scale. The study employed two HRTs: a 2-hour HRT (2h), wastewater was monitored at intervals of 2h for 10h, and a 6-hour HRT (6h), wastewater was monitored at 6h intervals over 30h. Undiluted (RPH-ud) and diluted (RPH-d) slaughterhouse wastewater were used. In the context of ABR technology, the HRT of the 2h and 6h applications demonstrated a strong correlation in reducing BOD_5 and COD levels in slaughterhouse wastewater. The correlation values between the two variables were within the range of 0.95 to 1.0. The most efficient values for the BOD_5 and COD parameters were attained at an HRT of 6h. For BOD_5, RPH-ud achieved a peak efficiency of 62.31%, while RPH-d reached 87.37%. Regarding COD, both RPH-ud and RPH-d exhibited their highest efficiencies with values of 66.98% and 92.69 %, respectively.

1. Introduction

The expansion of human population, industrialization, excessive consumption, waste production, and global climate change have caused a rapid decline in environmental quality [1-2]. The slaughterhouse industry has grown from small-scale to large-scale establishments and has played a significant role in this degradation. The industry produces both liquid and solid waste from cleaning animal cages, removing blood, and disposing of the rumen, intestinal contents, animal feces, and fat. Liquid waste from slaughterhouses contains contaminants such as biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and high levels of coliform bacteria, oil, and grease. When this liquid waste is discharged into water bodies, it poses a significant

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threat to aquatic ecosystems, endangering aquatic biota and leading to pollution, which reduces water quality [3-4].

The meat processing industry is a significant consumer of freshwater, accounting for nearly 25% of industrial usage. This water is primarily used for processing meat, cleaning, and maintaining sanitation standards [5]. The wastewater these operations produce contains high levels of primary pollutants, including oil and grease, carbohydrates, proteins, and lignin [6]. In contrast to urban domestic wastewater, which has moderate characteristics, slaughterhouse wastewater has significantly higher pollutant levels, such as being 3.9 times higher for total organic carbon (TOC), 6.3 times higher for BOD_5, 9.8 times higher for COD, 10.7 times higher for TN, 5.5 times higher for TSS, and 7.1 times higher for TP [5]. Conventional wastewater treatment methods are insufficient for handling these high pollutant loads, necessitating the adoption of advanced technologies to treat and mitigate pollution effectively [7-8].

The slaughterhouse industry generates substantial volumes of wastewater that can be effectively treated using various technologies. Biological treatments offer numerous advantages among the available alternatives, including high efficiency and low energy consumption [9]. However, aerobic wastewater treatment presents challenges due to its high energy demands and excess sludge production [10]. Conversely, anaerobic wastewater treatment reduces organic loads and generates biogas [11]. Multiple anaerobic systems are available for wastewater treatment, including the up-flow anaerobic sludge blanket reactor (UASB). The optimization of organic loading and hydraulic retention time (HRT) can be carried out by a lab-scale UASB reactor [12], an anaerobic continuously stirred reactor (ACSR), and an anaerobic baffled reactor (ABR). The ABR is the preferred choice for wastewater treatment due to its extended biomass retention time, excellent resistance to organic loads, and unique capacity to partially dissociate the anaerobic catabolism steps [13].

The ABR method has received significant attention for treating slaughterhouse wastewater. Studies have shown that the method, combined with techniques like UV/H_2O_2, can reduce COD, TSS, and TN in wastewater. With high levels of organic matter in slaughterhouse wastewater, it is crucial to implement extensive treatment processes [14]. ABR systems have emerged as a practical alternative to conventional anaerobic wastewater treatment techniques. The system comprises anaerobic reactors with compartments separated by barriers facilitating wastewater flow [13]. The sequential arrangement of these compartments within the ABR system enables prolonged interactions between wastewater and active biomass [15]. This design promotes the natural hydrolysis, acetogenesis, and methanogenesis separation across successive reactor compartments, ultimately enhancing methane production [16].

Previous studies on treating synthetic slaughterhouse wastewater using a combination of ABR and UV/H_2O_2 resulted in high COD and BOD_5 removal efficiencies of 97.7% and 96.6%, respectively, after a 5-day operation period [14]. However, a laboratory-scale ABR system that processed actual slaughterhouse wastewater for 152 days achieved only 70% COD and 33% solid removal at temperatures ranging from 15 to 23°C. When the temperature was increased to 40°C, the COD and solid removal increased to 90% and 44%, respectively, with daily biogas production reaching 122 mL/day [17].

This study introduces an innovative application of ABR technology for the treatment of slaughterhouse wastewater, focusing on optimizing HRT to enhance pollutant removal. Unlike previous research, which primarily dealt with synthetic wastewater or aerobic treatments, this study targets actual slaughterhouse effluent rich in organic matter, including blood, fats, and proteins. It investigates the impact of shorter HRTs (2-hour and 6-hour) on the reduction of BOD_5 and COD. Earlier studies have emphasized longer HRTs for optimal contaminant removal, often leading to increased energy consumption [14,18]. Meanwhile, this study demonstrates that a 6-hour (h) HRT can achieve pollutant removal rates comparable to or surpassing those of longer HRTs, offering a more energy-efficient and cost-effective treatment solution. The study also evaluates ABR performance with both undiluted (RPH-ud) and diluted (RPH-d) wastewater, finding that a 6h HRT resulted in up to

87.37% BOD_5 and 92.69% COD removal. Furthermore, the study identifies a strong correlation (0.95 to 1.0) between HRT and BOD_5/COD reduction, underscoring the ABR system's capability to simultaneously mitigate multiple pollutants, a dimension not extensively explored in prior research. Additionally, the study addresses the common issue of sludge accumulation by implementing preventive measures during pre-treatment, ensuring consistent reactor performance without the need for intensive sludge management, thus distinguishing it from traditional ABR operations.

This study emphasizes the innovation of employing shorter HRTs in lab-scale ABR technology and presents a practical and efficient solution for slaughterhouse wastewater treatment. It introduces a novel approach to wastewater treatment that significantly reduces energy consumption and costs while maintaining high pollutant removal efficiency. The findings indicate that optimized ABR technology offers a sustainable method for managing the high pollutant loads found in slaughterhouse effluents. Future research could explore the integration of ABR with other treatment processes or scaling up the system for broader industrial applications, potentially setting new standards for the industry.

2. Materials and methods

2.1. Experiment set-up

The ABR system was meticulously designed on a laboratory scale to effectively treat slaughterhouse industrial wastewater in the Kedurus area, Surabaya City, while adhering to predefined parameters. This study identified BOD_5 and COD as pivotal parameters for assessing slaughterhouse wastewater since they are widely recognized indicators of its pollutant characteristics. While BOD_5 and COD do not represent the sole contaminants in slaughterhouse wastewater, their presence often leads to adverse environmental impacts and a decline in overall environmental quality.

This study was divided into two categories to better categorize wastewater quality: undiluted (RPH-ud) and diluted (RPH-d). These categories were based on the relatively high BOD_5 and COD characteristics commonly observed in slaughterhouse wastewater. On the other hand, slaughterhouse wastewater was categorized to evaluate the ABR performance of BOD_5 and COD removal, considering a specific HRT. To accomplish this, a dilution process was carried out based on the initial COD concentration. This process employs diluted wastewater to attain a concentration of half the initial COD value. Specifically, RPH-ud exhibited a COD level of 11,563.05 mg/L, while RPH-d had a COD pollutant level equivalent to 50% of that observed in RPH-ud. Notably, the COD value obtained in this study significantly exceeded those reported in previous research, such as the study by Yousefi et al. [18], where COD values ranged between 2000 and 10,000 mg/L. Previous investigations into industrial wastewater from chicken slaughterhouses have also indicated lower concentrations. For instance, Al Kholif and Ratnawati [19] reported initial concentrations of 1,648 mg/L for BOD and 2,573 mg/L for COD in RPA wastewater.

The ABR system's performance for various wastewater qualities was evaluated by analyzing the differences in contaminant levels between RPH-ud and RPH-d. This evaluation is crucial in concluding the study and paves the way for the potential application of ABR technology on a pilot or larger scale. Additionally, this study incorporated the concept of HRT, which involves examining the duration of wastewater retention within the ABR system. In this study, HRT refers to the hydraulic retention time, which is the average time a fluid element spends in the reactor. Two distinct HRTs were implemented, namely HRT-2h and HRT-6h, referring to retention times of 2h and 6h, respectively. For HRT-2h, sample collection was performed at intervals of 2h (2, 4, 6, 8, and 10h), and for HRT-6h, sample collection was carried out at intervals of 6h (6, 12, 18, 24, and 30h). The sample collection intervals were used to monitor the process at regular stages.

2.2. ABR reactor design and operation

The ABR reactor features acrylic construction with dimensions of 50 cm in length, 30 cm in width, and 30 cm in height, resulting in a total volume of 45,000 cm^3. Within this structure, the reactor could hold approximately 20,000 cm^3 of wastewater (Figure 1). The ABR operates using a batch system, with specific HRTs consisting of 2h and 6h. The reactor design includes vertical baffles arranged in series at particular intervals to segment the reactor into chambers, promoting uniform chamber sizes. The influent and effluent systems are facilitated through pipe holes using silicon hoses, whereas a gas conduit positioned at the uppermost portion of the reactor discharges the gases. Additionally, influent silicon pipes strategically placed at the top of each compartment enable the uninterrupted flow of wastewater from one compartment to another, thereby optimizing the treatment process.

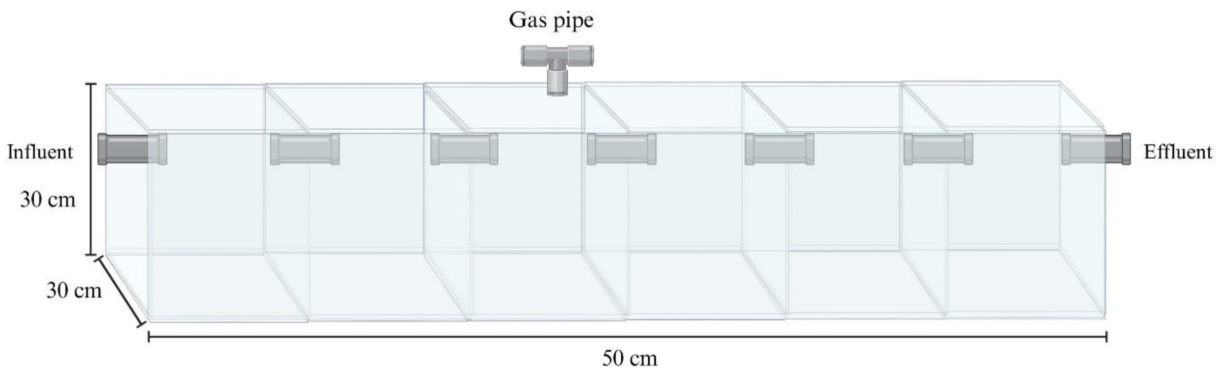

Fig. 1. Illustration of the side view of the ABR reactor

In general, the operation and treatment of wastewater in ABR reactors are based on the production of sludge and the presence of sludge layers in various chambers of the reactor. Therefore, this investigation implemented several preventative measures in the ABR to avert sludge accumulation, including (1) The collection of fresh wastewater in plastic tanks before its release into the environment and (2) The wastewater from the slaughterhouse was allowed to settle in a plastic drum for a period of three weeks before its introduction into the ABR reactor, ensuring that the sludge settled at the bottom of the drum. The wastewater was then carefully transferred to the ABR to minimize the transport of sludge. Consequently, the reactor experienced minimal sludge accumulation, eliminating the need to measure the sludge height and mixed-liquor suspended solid (MLSS) amount. This process also influenced other pollutant parameters, exhibiting values below the predefined quality standards and rendering further observation unnecessary.

2.3. Data collection and analysis methods

This study was conducted at the Environmental Engineering Laboratory of the Universitas PGRI Adi Buana Surabaya. Initial analysis of the wastewater samples was performed at the Environmental Service Laboratory, Surabaya City, to determine the initial characteristics of the wastewater using the standard values outlined in the Minister of Environment regulation number 2 of 2006 (Table 1). Results were assessed using the procedures outlined in Indonesia National Standard SNI-6989.72:2009 [20]. Laboratory analysis of the initial samples from the abattoir wastewater revealed high levels of BOD_5 and COD, measuring 5,942.23 mg/L and 11,563.05 mg/L, respectively. Eqs. 1 and 2 were used to gauge the effectiveness of reducing pollutants such as BOD_5 and COD [21-23].

$$\text{Removal (mg/L)} = C_0 - C \quad (1)$$

$$\text{Removal efficiency (\%)}\varepsilon = \frac{C_0 - C}{C_0} \times 100 \quad (2)$$

where ε is the efficiency, C_0 is the initial concentration, and C is the final concentration.

Table 1 shows that BOD_5 and COD concentrations were significantly high and exceeded the predetermined quality standards. However, the remaining parameters complied with the established regulations for slaughterhouse wastewater. The lower values of these parameters, except BOD_5 and COD, were attributed to the utilization of fresh wastewater stored in plastic drums for a week before processing in the ABR. In contrast, the elevated levels of BOD_5 and COD were primarily due to the organic constituents present in the wastewater, such as blood, protein, feces, and fat.

Table 1. Concentration of the slaughterhouse wastewater [24].

Parameter	Initial concentration (mg/L)	Quality standards* (mg/L)
pH	6.9	6 - 9
TSS	107	300
BOD_5	5,942.23	150
COD	11,563.05	400
Total ammonia	17	25
Oil and fats	20	25

3. Results and discussion

3.1. Effect of HRT on the BOD_5 and COD removal in ABR

The alteration of HRT brought about considerable changes in the removal of BOD_5 and COD pollutants. These parameters are of great significance for evaluating the presence of organic impurities in wastewater. An extended HRT duration offers microorganisms an increased chance to decompose or oxidize the organic substances present in the wastewater, resulting in more effective elimination of both BOD_5 and COD. The influence of HRT on removing BOD_5 and COD is depicted visually in Figure 2. Generally, anaerobic treatment systems demonstrate lower removal efficiency values for BOD_5 and COD than aerobic systems [25-26]. However, the effectiveness of removal is largely contingent on the initial characteristics of the treated wastewater.

The relationship between HRT-2h and HRT-6h in the removal of BOD_5 and COD was marked by highly significant correlation coefficients, ranging from 0.95 to 1.0. These values indicated a strong and consistent connection between the variables, emphasizing the impact of HRT on the reduction of BOD_5 and COD. The high correlation suggests that the removal rates of BOD_5 and COD in the wastewater samples exhibited similar patterns. In other words, an increase in BOD_5 efficiency resulted in a corresponding increase in COD and vice versa. This robust correlation further suggests that both BOD_5 and COD are reliable indicators of organic pollution in RPH wastewater.

The study conducted by Yousefi et al. [18] demonstrated that the efficiency of COD removal in an ABR increased with HRT and organic loading rate (OLR). At an HRT of 18 h and OLRs of 4, 7, and 10 kg COD/m³/day, the COD removal efficiencies reached 78.13%, 83.29%, and 85.72%, respectively.

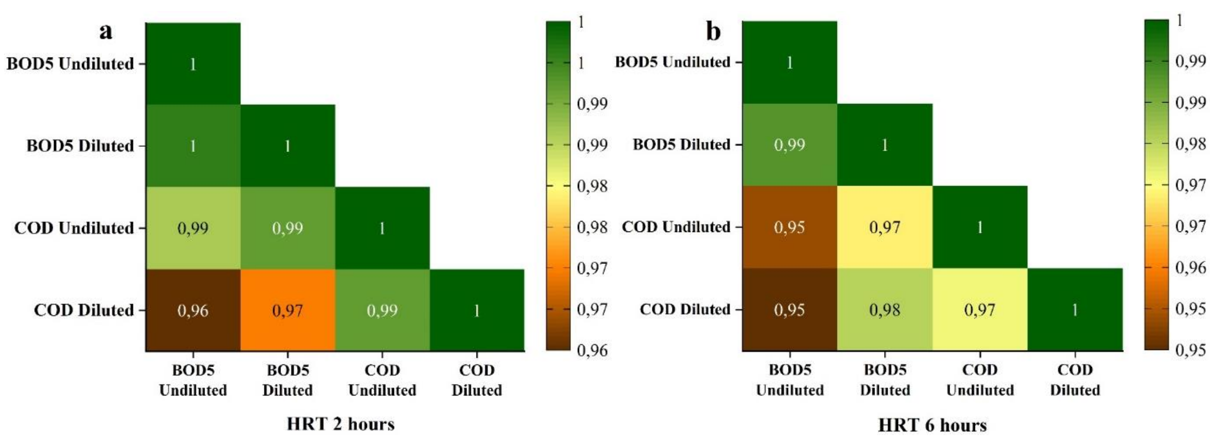

Fig. 2. Correlation between HRT on the BOD_5 and COD removal. (a) for HRT-2h and (b) for HRT-6h.

Another study focused on treating RPA wastewater using purple non-sulfur bacteria, which achieved impressive results. The bacteria successfully eliminated 85.3% or 147 mg/L of dissolved COD (sCOD). They lowered the total COD (tCOD) levels to 217 mg/L, BOD levels to 104 mg/L, total solids (TS) to 934 mg/L, suspended solids (SS) to 392 mg/L, and dissolved solids (DS) to 552 mg/L in the digester effluent after bacterial inoculation and incubation. These values are notably lower than those in influent digesters [27]. Moreover, previous research conducted by Al Kholif and Hermana [28] implemented an anaerobic biofilter reactor with a media hydraulic load of 0.006 m^3/m^2.day, achieving a remarkable COD removal rate of 96.32%. Overall, these studies highlight the efficacy of various approaches in wastewater treatment, demonstrating the potential to achieve significant reductions in BOD_5 and COD levels through different techniques. Wastewater with exceptionally high pollutant concentrations may be more effectively treated using anaerobic systems due to their superior capacity for removing organic matter. Conversely, aerobic systems processing wastewater with high initial pollutant concentrations may yield less favorable removal efficiency outcomes [29].

3.2. BOD_5 removal efficiency

The slaughterhouse industry generates liquid waste during the cleaning of animal carcasses. This wastewater, which appears oily and slightly thick, is characterized by blood, animal feces, and stomach contents. Initial sample analysis revealed that slaughterhouse wastewater is highly biodegradable, making it suitable for biological treatment using ABR technology. To evaluate the effectiveness of the ABR system in removing pollutants from slaughterhouse wastewater, the efficiency of various wastewater parameters, such as BOD_5 and COD, was assessed. Additionally, slaughterhouse wastewater contains contaminants such as NT, TP, and turbidity, contributing to its dark color [30]. The primary cause of BOD_5 degradation is the activity of decomposing microorganisms that break down organic matter in wastewater.

Applying the ABR system with HRT-2h and HRT-6h in treating slaughterhouse wastewater resulted in a continuous decrease in pollutant levels throughout the study (Figure 3). The most notable reduction in the BOD_5 parameter was observed for both RPH-ud and RPH-d in HRT-2h for operating time 10h and HRT 6h for operating time 30h. RPH-d exhibited higher efficiency among the two wastewaters due to its lower pollutant load. Specifically, the highest reduction in BOD_5 was achieved at HRT-2h, reaching 997.69 mg/L for RPH-ud and 182.66 mg/L for RPH-d. For HRT-6h, the decrease in BOD_5 was slightly more pronounced, with values reaching 937.26 mg/L for RPH-ud and 128.19 mg/L for RPH-d. Although HRT-6h demonstrated significant results in reducing BOD_5, the findings were not significantly different from those obtained with HRT-2h. Therefore, it could be concluded that both HRT-2h and HRT-6h effectively removed BOD_5 pollutants when integrated into the ABR system.

Figure 3 demonstrates the outstanding efficiency of the slaughterhouse in removing BOD_5. As the wastewater remained in the ABR for a longer period, the removal efficiency for both HRT variables, HRT-2h and HRT-6h, continued to increase. For HRT-2h, RPH-ud achieved the highest efficiency value of 60.65%, while RPH-d reached 80.00%. Similarly, at HRT-6h, RPH-ud had the highest efficiency of 62.31%, and RPH-d attained 87.37%. Interestingly, there was no significant difference in the removal efficiency of BOD_5 between HRT-2h and HRT-6h for RPH-ud. However, this difference was observed in the case of RPH-d's removal efficiency of BOD_5. The lower concentration of wastewater achieved at HRT-6h due to the dilution process enabled higher pollutant removal efficiency. Additionally, the decomposing microorganisms responsible for breaking down organic substances exhibited enhanced contaminant removal performance. The prolonged HRT of wastewater within the ABR significantly influenced the removal of BOD_5 pollutants. Furthermore, the implementation of ABR, an aerobic treatment method, proved effective in eliminating BOD_5 pollutants originating from RPH industrial wastewater. Similarly, an anaerobic biofilter system with a hydraulic load of 0.0015 m^3/m^2. day was applied to process chicken slaughterhouse industrial wastewater, which also yielded positive results in reducing BOD_5 quotations and COD levels. After processing in the anaerobic biofilter system, the efficiency of decreasing both BOD_5 and COD pollutant loads reached 96% [31].

3.3. COD removal efficiency

Efficiently removing COD is crucial in wastewater treatment as it is necessary to reduce organic matter to meet effluent standards. Including HRT in the ABR reactor can effectively minimize COD pollutants in slaughterhouse industrial wastewater. Numerous studies have demonstrated the ability of suspended microorganisms in ABR reactors to reduce COD pollutants. The ABR system achieved impressive results in reducing COD contaminants, with significant reductions observed at 10 and 30 h for HRT-2h and HRT-6h, respectively, as shown in Figure 4. However, there was no significant difference in COD reduction between HRT-2h and HRT-6h for RPH-ud. In contrast, a notable difference was observed in the case of RPH-d, with HRT-6h showing a higher decrease of 160.64 mg/L compared to HRT-2h, which reached 264.04 mg/L. The improved COD pollutant removal efficiency of RPH-d could be attributed to the reduced concentration of wastewater following the dilution process.

A study conducted in Serbia evaluated the quality of effluent wastewater from 41 slaughterhouses. Among these, 17 facilities exhibited high levels of COD, 12 displayed higher BOD levels, six had a high TSS content, and five exceeded the permissible limit for fats, oil, and grease (FOG) concentrations. This study employed standards from reputable sources such as the World Bank Group, the European Community Council, and the Republic of Serbia. It is crucial to recognize that directly discharging untreated slaughterhouse wastewater with high effluent concentrations into the environment can lead to anaerobic conditions and increased sludge deposition [32].

Efforts have been made in recent years to develop slaughterhouse wastewater treatment methods using FOG within anaerobic systems, often at concentrations ranging from 1-10%. When the FOG concentration was optimized at 5-10%, a biodegradability rate of 66-70% for tCOD removal and biomethane production rates of 562 and 777 mL CH_4 g-1 sCOD were achieved. However, as the FOG concentration increased to 10%, the following values were observed: tCOD (31.2 g/L), COD (28.6 g/L), TS (3.1 g/L), total volatile solids (TVS) (19.6 g/L), and volatile fatty acids (VFA) (12.6 g/L). In comparison, slaughterhouse and FOG wastes resulted in lower tCOD values of 8.9 and 14.9 g/L, respectively, and COD values of 2.03 and 2.4 g/L. Additionally, higher yields were observed for TS allowance of 143 g/L, TVS of 125 g/L, and VFA of 0.5 g/L [33].

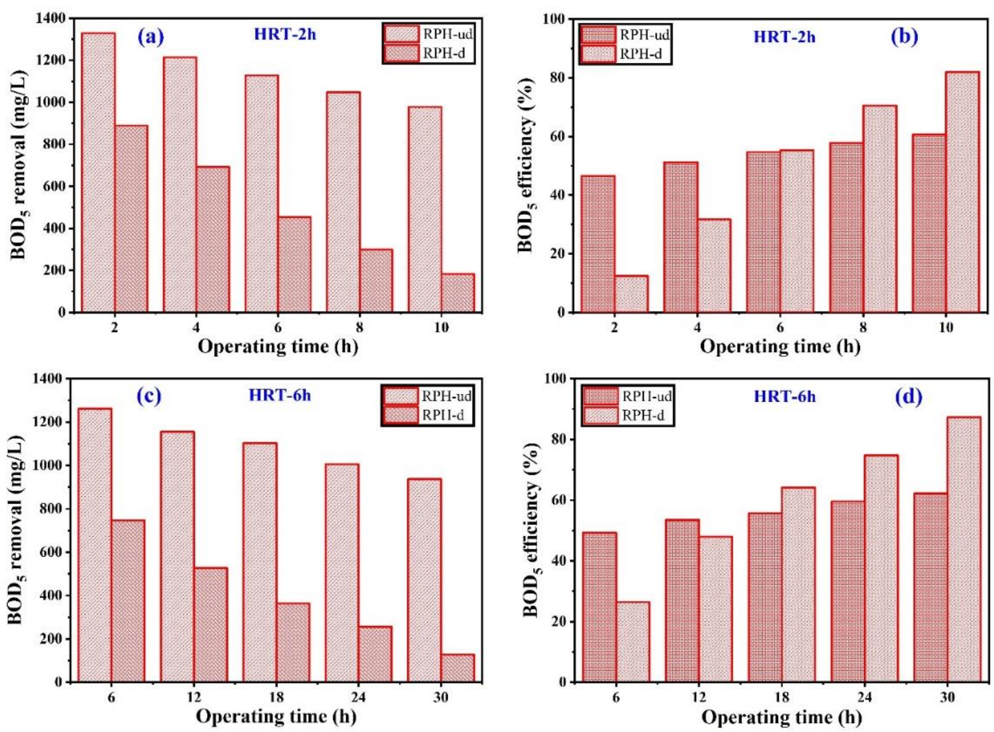

Fig. 3. illustrates the removal (mg/L) and efficiency (%) of BOD_5. (a) BOD_5 removal, (b) the removal efficiency of BOD_5 at HRT 2-h, (c) BOD_5 removal, and (d) the removal efficiency of BOD_5 at HRT 6-h.

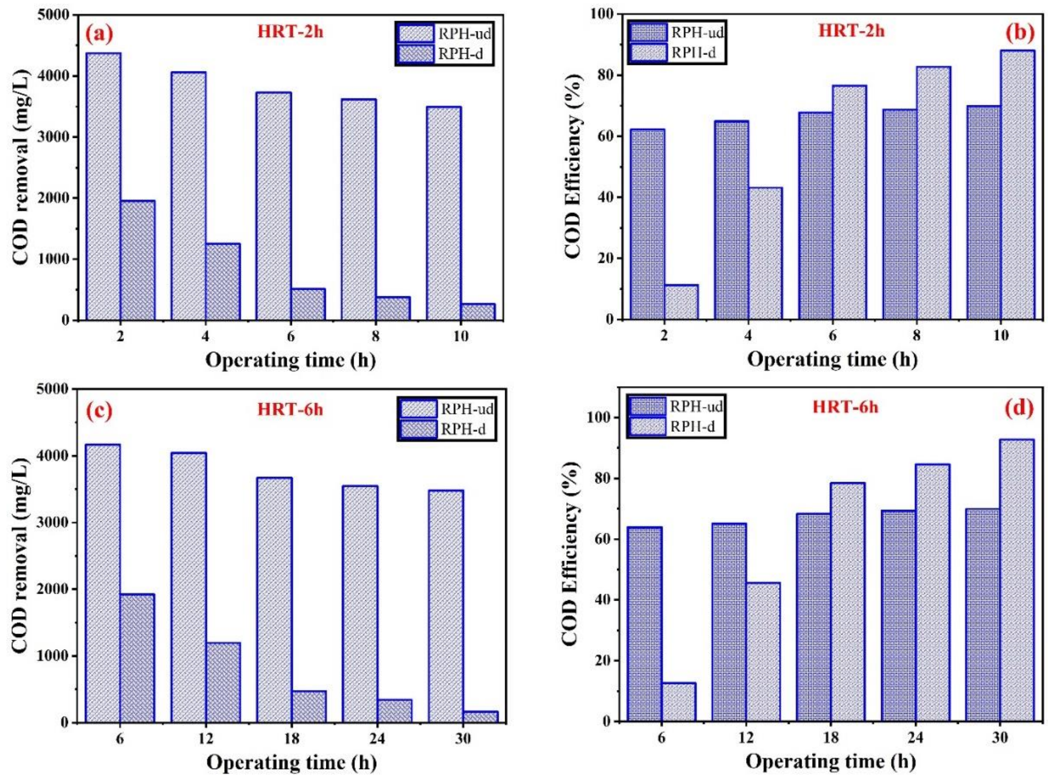

Fig. 4. illustrates the removal (mg/L) and efficiency (%) of COD. (a) COD removal, (b) the removal efficiency of COD at HRT 2-h, (c) COD removal, and (d) the removal efficiency of COD at HRT 6-h.

The highest removal efficiency of COD was observed in the RPH-d system, with values of 87.99% for an HRT of 2h and 92.69% for an HRT of 6h. However, the COD removal efficiency in the RPH-ud system remained stable, averaging 66.98%. Although the efficiency of RPH-ud was lower than that of RPH-d, a COD removal rate of over 60% could still be considered successful for removing COD contaminants using an ABR system. This is particularly noteworthy given the relatively high initial concentration of COD being treated by the ABR system. Previous studies have shown that increasing the OLR and HRT impacts the quality of the effluent significantly, with COD being a critical parameter in evaluating reactor performance [34]. For instance, in an anaerobic filter (ABR-AF) system, an HRT of 12h resulted in COD removal rates ranging from 78% to 81% [35]. Other studies have reported maximum COD removal efficiencies of 78.13%, 83.29%, and 85.72% for the ABR process at OLRs of 4, 7, and 10 kg/m^3/day, respectively, with an HRT of 18h [18]. ABR reactors operated for 8 and 152 days demonstrated remarkable total COD removal efficiencies of up to 90% [17,36]. The ABR process with an HRT of 24h demonstrated impressive average removal efficiencies for various parameters. Specifically, the process achieved 71% removal efficiency for BOD, 75% for COD, 79% for TSS, 23% for total Kjeldahl nitrogen (TKN), 30.3% for TP, and a coliform log reduction value (LRV) of 5.8 Log [37]. Another study found that operating the ABR reactor with an HRT of 18h and an OLR of 7 and 10 kg COD/m^3/day resulted in even higher removal efficiencies, with values of 83.29% and 85.79%, respectively [18]. These findings highlight the potential of the ABR process to improve wastewater treatment.

4. Conclusions

The application of laboratory-scale ABR technology with HRT-2h and HRT-6h showed remarkable effectiveness in removing BOD and COD pollutants from RPH wastewater. The critical role of HRT in the ABR reactor is evident in achieving efficient removal of BOD_5 and COD, as indicated by the strong correlation between HRT and pollutant removal in slaughterhouse industrial wastewater, with values ranging from 0.95 to 1.0. Notably, HRT-6h demonstrated exceptional efficiency in BOD_5 and COD removal, achieving the highest removal efficiencies of 87.37% and 92.69%, respectively, corresponding to concentration decreases of 128.19 mg/L and 160.64 mg/L. These results emphasize the effectiveness of ABR technology in addressing pollutant removal in the slaughterhouse industry, even when dealing with relatively high initial pollutant concentrations. Although ABR technology has proven its capability in this regard, it is advisable to explore the integration of additional technologies or combinations to enhance overall treatment efficiency further. This approach could alleviate the burden of ABR performance and provide a more robust solution for wastewater treatment in slaughterhouse facilities.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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