

Improving the efficiency of livestock farm wastewater treatment with combined anaerobic reactor and anaerobic filter technology

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Abstract: Highly concentrated wastewater from local cattle farming requires treatment before being discharged into the environment. Anaerobic wastewater treatment is popularly employed, but the efficiency of removing high amounts of organic matter still has limitations. The objective of this study was to evaluate the efficiency of the combined anaerobic reactor. We investigated the effects of Chemical Oxygen Demand (COD) loading rate, hydraulic retention time (HRT), and greenhouse gas emissions. The volume of the total reactor is 1,050 liters. The retention times ranged from 0 to 28 hours, while COD loading rates were 0.39-1.17 kg-COD/m³-d. The results showed that the wastewater before treatment had a COD value of $2,253.5 \pm 683.1$ mg/L, Total Kjeldahl Nitrogen (TKN) 144.0 ± 31.5 mg/L, and Total Phosphorus (TP) 26.0 ± 5.5 mg/L. After treatment, the combined anaerobic reactor and anaerobic filter (AR/AF) system with 28 hours of retention time removed COD up to 68.15% and TKN up to 46.67%. The suitable COD loading rate was 0.39 kg-COD/m³-d, as the system eliminated COD up to 69.37% and TKN up to 39.47%. Compared to only AR, the AR/AF system was 79% more efficient and produced low greenhouse gas emissions, equivalent to 21.64 kg CO_{2e} per year.

Keywords: Anaerobic process, Cattle farm, Environmental management, Greenhouse gas, Wastewater treatment.

1. Introduction

The commercial beef cattle industry in Sakon Nakhon Province, Thailand, particularly Ponyangkham's private operation, is a significant regional economic sector. In 2019, the industry generated 763,074,000 Baht from 7,783 cattle. Currently, Ponyangkham Cooperative can produce 6,000-8,000 beef cattle annually; however, market demand is expected to reach 15,000-16,000 cattle per year. Despite its importance, especially for community economics, the industry faces challenges related to waste management, such as wastewater affecting the environment. Wastewater from beef farms typically contains high levels of organic matter, nutrients, and suspended solids. Several wastewater treatment methods are used for livestock farms, including anaerobic digestion systems, septic tanks, anaerobic filter systems, Up-flow Anaerobic Sludge Blanket (UASB) reactors, and fixed-film anaerobic systems [1, 2]. However, to increase the efficiency of the traditional wastewater treatment system and to treat wastewater quality according to legal standards, it is necessary to develop more efficient wastewater treatment methods. A new wastewater treatment technology called the combined AR/AF system has been developed and applied as a promising alternative in wastewater treatment systems. This combined wastewater treatment system operates on two main principles: (1) the separation of suspended solids contaminated with wastewater and (2) the enhancement of bacterial adhesion to the media to increase contact opportunities and efficient degradation of substances. This combined wastewater treatment process has been practically applied in the wastewater treatment of a swine farm and has shown good efficiency in reducing contaminants [3]. Based on the study by Boopathy and Tilche [4], the results show that this combined wastewater treatment system not only removed organic matter but also reduced COD by more than 70% with a COD-loading rate of 20 kg-COD/m³-day. In

other words, this system can treat wastewater and reduce high organic matter. Due to the increasing contact between the microorganisms and the organic compounds when the wastewater passes through the treatment process, this system can decrease organic concentrations and increase the efficiency of this AR/AF system. In addition to gaining wastewater treatment efficiency, the new system shortens wastewater retention period, improves wastewater treatment capacity, and can adjust the treatment capacity to variable wastewater amounts. Compared to other systems, anaerobic treatment systems demonstrate significant advantages. For instance, shortened biomass retention time results in the adjusted system and responds well to changing wastewater loads. Unlike the aerobic treatment systems, the anaerobic treatment systems also produce significantly less biomass and less sludge disposal [5, 6]. An anaerobic reactor plays an important role in wastewater treatment, particularly in effectively separating and reducing acidogenesis processes. Therefore, it both reduces the acid accumulation during the fermentation process and promotes the increase in the number and diversity of microorganisms within the system, especially the bacterial groups that are responsible for decomposing organic matter in anaerobic conditions. The system consists of two phases, which improve the stability of the treatment process in terms of efficiency and resilience to variable wastewater amounts [7-9]. According to the recommendations of the Pollution Control Department [10], the key considered parameters for designing an effective anaerobic filter system are wastewater retention time, bio-media layer depth, and center layer porosity. A previous study reported the potential of the system in various applications. For instance, a study on the treatment of slaughterhouse wastewater showed an optimal COD removal efficiency of 10.72 kg COD/m³-d by using an organic loading rate (OLR) and a wastewater HRT of 3 days [11]. Unlike a separate system, AR/AF technology can achieve higher efficiency in treating contaminants in wastewater since the novel system can utilize the strengths of each process. In other words, anaerobic digestion of organic matter combines with aerobic nutrient removal, which synergistically enhances each other. This research aimed to study the efficiency of combined AR and AF for wastewater treatment at Ponyangkham beef cattle farm in Sakon Nakhon Province, Thailand. This study focused on evaluating the relationship between OLR and HRT of wastewater in the system and estimating the greenhouse gas emissions generated from the treatment process.

2. Methods and Methods

2.1. The Wastewater Characteristics of Ponyangkham Beef Cattle Farm

The wastewater from the beef cattle farm was collected five times a week before it entered the treatment system for evaluation of the efficiency of the combined anaerobic reactor system. After collecting, the samples were filtered through a sieve to remove large coarse particles and then filtered through a 0.45-micron filter paper. Consequently, the sample is of consistent quality and suitable for laboratory analysis. The filtered wastewater samples were analyzed for key wastewater quality parameters, including COD, TKN, TP, and temperature, since these parameters were selected as the key indicators of system performance. Moreover, the study evaluated the effects of different OLR and COD concentrations on system performance under variable organic matter concentrations. In order to evaluate the stability of the system and treatment efficiency, the quality of the treated wastewater was recorded continuously for 2 months.

2.2. Experimental Design

The beef cattle farm wastewater treatment system consists of a three-chamber reactor with a final sedimentation tank, as shown in Figure 1. The total volume of the system is 1,050 liters, and the effective working volume of each chamber is 350 liters. The reactor design incorporates specific features for optimizing the anaerobic treatment process. The first chamber acts as the primary anaerobic reactor and provides primary biological treatment to the wastewater. The second and third chambers are equipped with special plastic media shelves with 100-centimeter height. The media selected for these chambers consisted of a 90 mm diameter Plastic media type Pall Ring, so the specific surface area is 105 square meters per cubic meter with a 95% free space. This design promotes effective bacterial adhesion,

while the fluctuating wastewater flow does not affect the system efficiency. In order to control the flow rate of wastewater into the system, the pump was submerged in the wastewater for feeding into the first chamber. The wastewater then flowed to the next chamber by gravity through a plug flow system, which ensures optimum and consistent contact time between the wastewater and biomass throughout the treatment process. To examine the efficiency of the treatment system, wastewater was sampled after passing through the anaerobic reactor (the first chamber) and after passing through the aerobic filter reactor (the third chamber). Therefore, we can accurately assess the efficacy of treatment at each stage. The equipment for sample collection was as follows: (1) clean and sterilized 1–2-liter bottles, (2) gloves and personal protective equipment, (3) labels with the date, time, and location of sample collection, and (4) an ice bucket for maintaining sample temperature during transport. Wastewater was collected at the exit of the primary anaerobic reactor (the first chamber), and then the wastewater flowed to the second chamber, which had plastic media. Before collection, wastewater was released from the system for 2–3 minutes, so the wastewater represented the real condition of the system. Sampling should be done during normal system operation, and approximately 2 liters should be collected in a prepared bottle. Do not violently agitate or shake the samples. For sampling collection after the Aerobic Filter Reactor (the third chamber), the second sampling point is the exit of the third chamber, and before the wastewater entered sedimentation tank at the final step. Wastewater collection had to not excessively agitate the system since the third chamber had plastic media to promote microorganism attachments. In other words, strong agitation caused the sample contamination due to the biomass released from the media. Like the first sampling point, wastewater was released from the system for 2–3 minutes. In order to compare treatment efficacy, sample collections at both sites were performed simultaneously or at approximately the same time. After collection, samples were analyzed within 24 hours and kept at 4°C with ice during transport and storage.

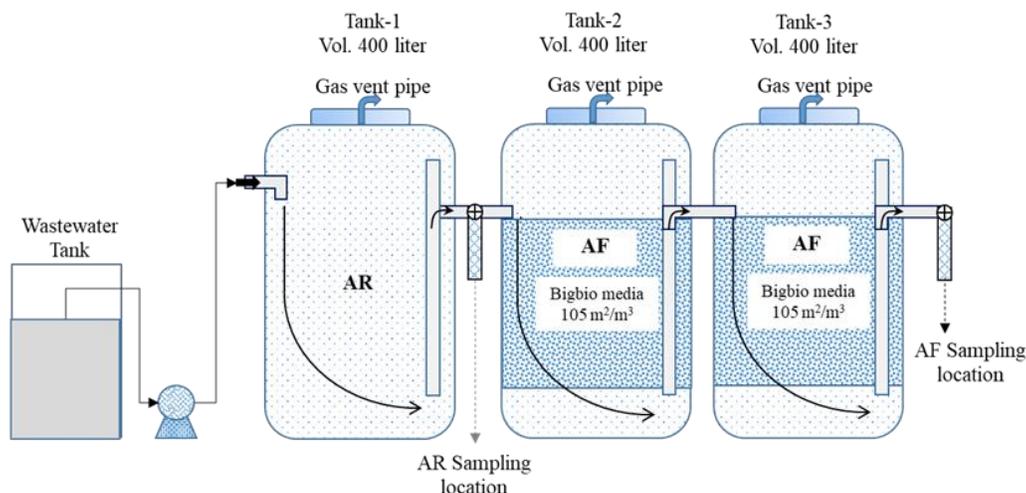


Figure 1.
Schematic of a combined anaerobic reactor.

2.3. Methods of Analysis

In this study, water quality parameters were analyzed according to the APHA (American Public Health Association) standard methods. The following parameters were determined: COD according to APHA 5220D (Closed Reflux Colorimetric Method), TKN according to APHA 4500-Norg (Kjeldahl Method), and TP according to APHA 4500-P E (Ascorbic Acid Method). The pH measurements were performed using an electrolyte pH meter calibrated with standard buffer solutions according to the APHA 4500-H⁺ standard. In order to ensure the reliability and accuracy of the data, all analyses were

performed on multiple sample sets. The sampling protocol followed standard APHA 1060 (Collection and Preservation of Samples) procedures to obtain representative samples from various collection points within the farm wastewater system. Means and standard deviations were reported. In this study, multiple measurements were employed to obtain reliable overall compositional characteristics of wastewater.

3. Results

3.1. The Wastewater Characteristics of Ponyangkham Beef Cattle Farm

This study analyzed the quality of wastewater originating from the beef cattle farm. The research area was 17°05'05.0"N 104°13'45.6" E (latitude 17.084716, longitude 104.229344). The total population was 30 cattle, which consisted of 10 fattened beef cattle and 20 beef cattle. Daily wastewater production from feed production for 20 beef cattle is 1,000 liters. Ten wastewater samples were collected every day for laboratory analysis. The results of the analysis of the quality of wastewater from the beef cattle farm (n=10) are shown in Table 1. Means of COD, TKN, TP, wastewater temperature, and pH value were $2,253.5 \pm 683.1$ mg/L (Range 1,258-3,249 mg/L), 144.0 ± 31.5 mg/L (range 98-190 mg/L), 26.0 ± 5.5 mg/L (range 18-34 mg/L), $27.0 \pm 0.7^\circ\text{C}$ (range 26-28°C), and 7.54 ± 0.29 (range 7.12-7.96), respectively.

Table 1.

Characteristics of wastewater (before the treatment) from Ponyangkham farm, Sakon Nakhon Province.

| Parameters | Mean | Sample | Standard deviation |
|------------------|-----------|--------|--------------------|
| COD (mg/L) | 1258-3249 | 10 | 683.1 |
| TKN (mg/L) | 98-190 | 10 | 31.5 |
| TP (mg/L) | 18-34 | 10 | 5.5 |
| pH | 7.12-7.96 | 10 | 0.7 |
| Temperature (°C) | 26-28 | 10 | 0.29 |

3.2. Effect of Retention Time on the Efficiency of the AR System

In this study, we investigated only the effect of HRT on the COD concentration reduction efficiency in an AR system. We set 0, 9, 20, and 28 hours as the retention times, 350 liters as the working space of the anaerobic reactor, and 0.78 kg-COD/m³-d as the COD loading rate. The results demonstrate that COD concentrations in wastewater decreased significantly with increasing retention time. COD concentrations for retention times of 0, 9, 20, and 28 hours were 3,254.33, 2,708.33, 2,137.67, and 1,746.00 mg/L, respectively (Figure 2). When the retention time expanded to 9, 20, and 28 hours, the increasing COD removal percentages were 16.64%, 34.21%, and 46.26%, respectively. As the retention time increased, COD removal efficiency also improved. Like COD removal, TKN concentrations reduced with increasing retention time. TKN concentrations for the 0, 9, 20, and 28-hour retention times were 190.00, 158.67, 129.67, and 117.67 mg/L, respectively. Similarly, the increasing percentages of TKN removal for the 9, 20, and 28-hour retention times were 16.49, 31.75, and 38.07%, respectively. These results support previous findings that expanding retention time is related to promoting TKN removal capacity.

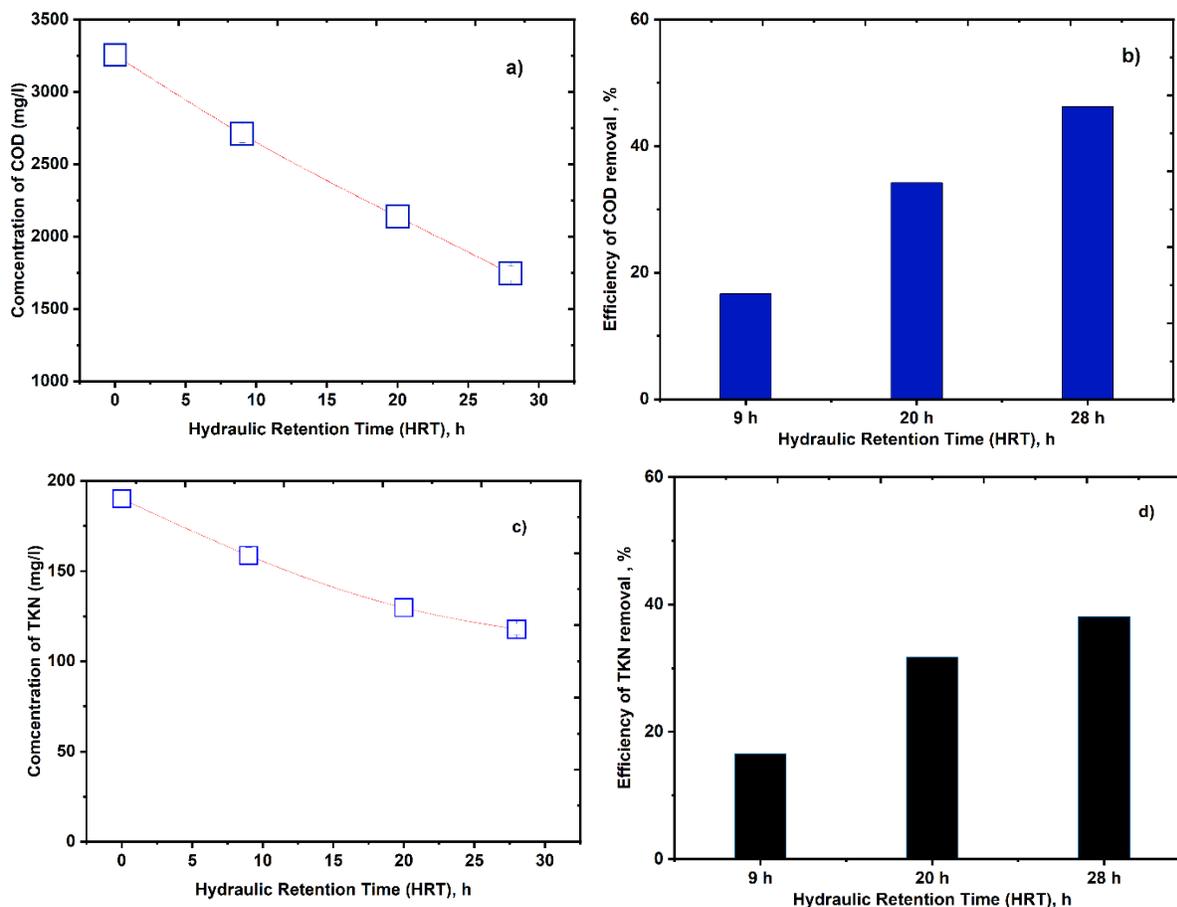


Figure 2.

The effect of hydraulic retention time (HRT) of AR on COD and TKN concentrations: a) reduced COD concentrations, b) the percentages of COD removal, c) reduced TKN concentrations, and d) the percentages of TKN removal.

3.3. Effect of COD Loading Rate on the Efficiency of the AR System

In this study, we investigated only the effect of COD loading rate on the reduction efficiency of COD and TKN concentrations in the AR system. We set 20 hours as the retention time with a 350-liter reactor. The results using COD-loading rates of 0, 0.39, 0.78, and 1.17 kg-COD/m³-day are shown in Figure 3. COD concentrations after passing through the anaerobic reactor were 3,254.33, 1,696.33, 2,137.67, and 2,466.00 mg/L, respectively. The elevating percentages of COD removal were 47.87, 34.31, and 24.22, respectively. These results indicate that increasing the COD loading rate inversely correlated with the COD removal efficiency. Similar to COD removal efficiency, COD loading rate inversely correlated with TKN removal efficiency. TKN concentrations after passing through the anaerobic reactor were 190.00, 136.00, 149.67, and 156.00 mg/L, respectively. In other words, the percentages of TKN removal were 28.42, 21.23, and 17.89, respectively. In conclusion, the increasing COD loading rate resulted in decreasing TKN removal efficiency. According to the analysis of only the anaerobic reactor, the results show that a COD loading rate of 0.39 kg-COD/m³-d resulted in the highest COD removal efficiency (47.87%). On the other hand, when the COD loading rate increased, the COD removal efficiency continuously decreased since excessive contaminants possibly entered the anaerobic reactor.

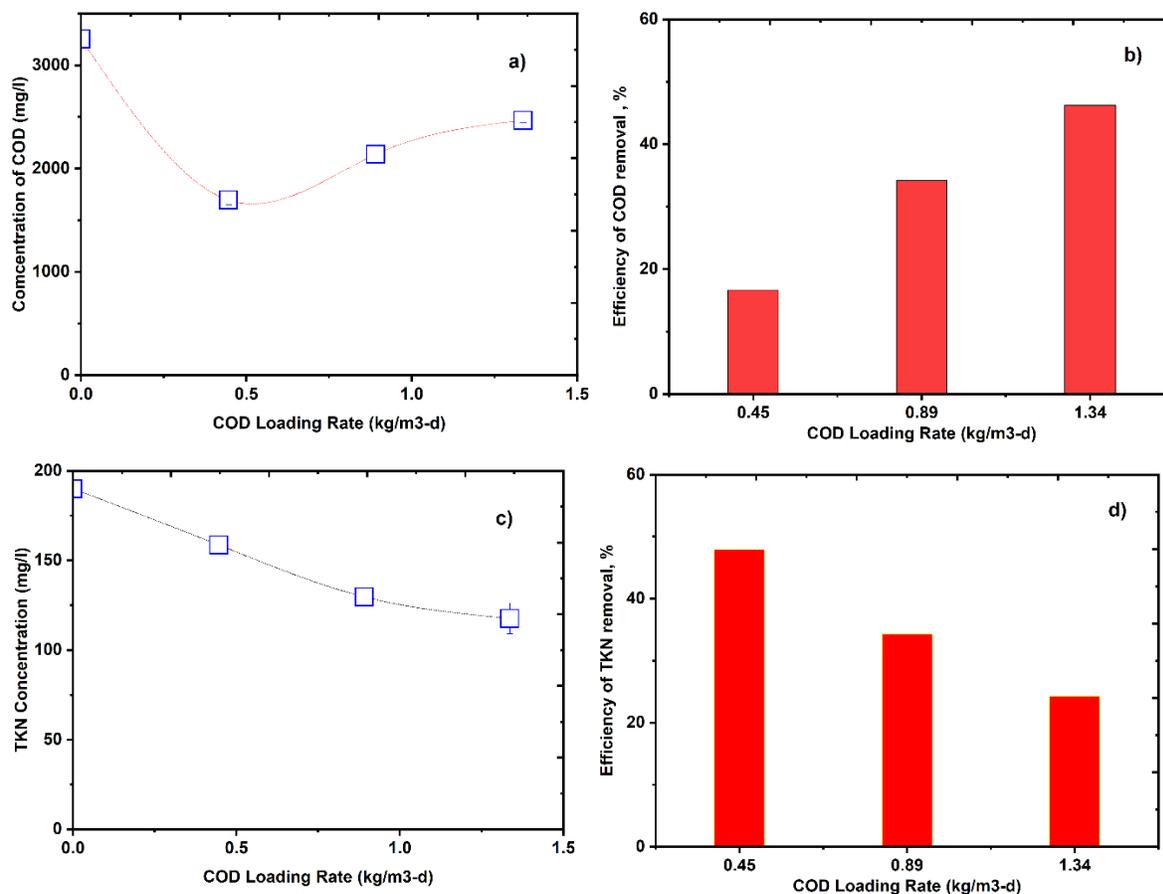


Figure 3.

The effect of COD loading rate (kg-COD/m³-day) of AR on COD and TKN concentrations: a) COD reduction concentrations, b) the percentages of COD removal, c) TKN reduction concentrations, and d) the percentages of TKN removal.

3.4. Effect of Retention Period on the Efficiency of the Combined AR/AF System

In this study, we investigated the effect of HRT on the performance of a combined AR/AF system using a 1,050 L reactor with retention times of 0, 9, 20, and 28 hours and a constant COD loading rate of 0.78 kg-COD/m³-d. The results show that the COD removal efficiency of the AR/AF system with 0, 9, 20, and 28-hour retention times was 3,254.33, 2,267.00, 1,261.67, and 1,036.00 mg/L, respectively (Figure 4). In other words, the percentages of COD removal increased significantly. The percentages of COD removal with 9, 20, and 28-hour retention times were 30.34, 61.23, and 68.15, respectively. The results demonstrate that the AR/AF system significantly outperforms the only AR system. For TKN removal efficiency, TKN concentrations at 0-, 9-, 20-, and 28-hour retention times were 190.00, 137.33, 120.00, and 101.33 mg/L, respectively. The percentages of TKN removal at 9-, 20-, and 28-hour retention times were 27.72, 36.84, and 46.6, respectively. In summary, increasing retention time improved nitrogen removal efficiency. Compared to only the AR reactor, the combined anaerobic reactor and anaerobic filter (AR/AF) system showed significantly better performance. The percentages of COD removal for the combined AR/AF system and only the AR reactor at 20-hour retention time were 61.23 and 34.21, respectively. It can be concluded that increasing surface areas for microbial adhesion in the AF improves COD removal.

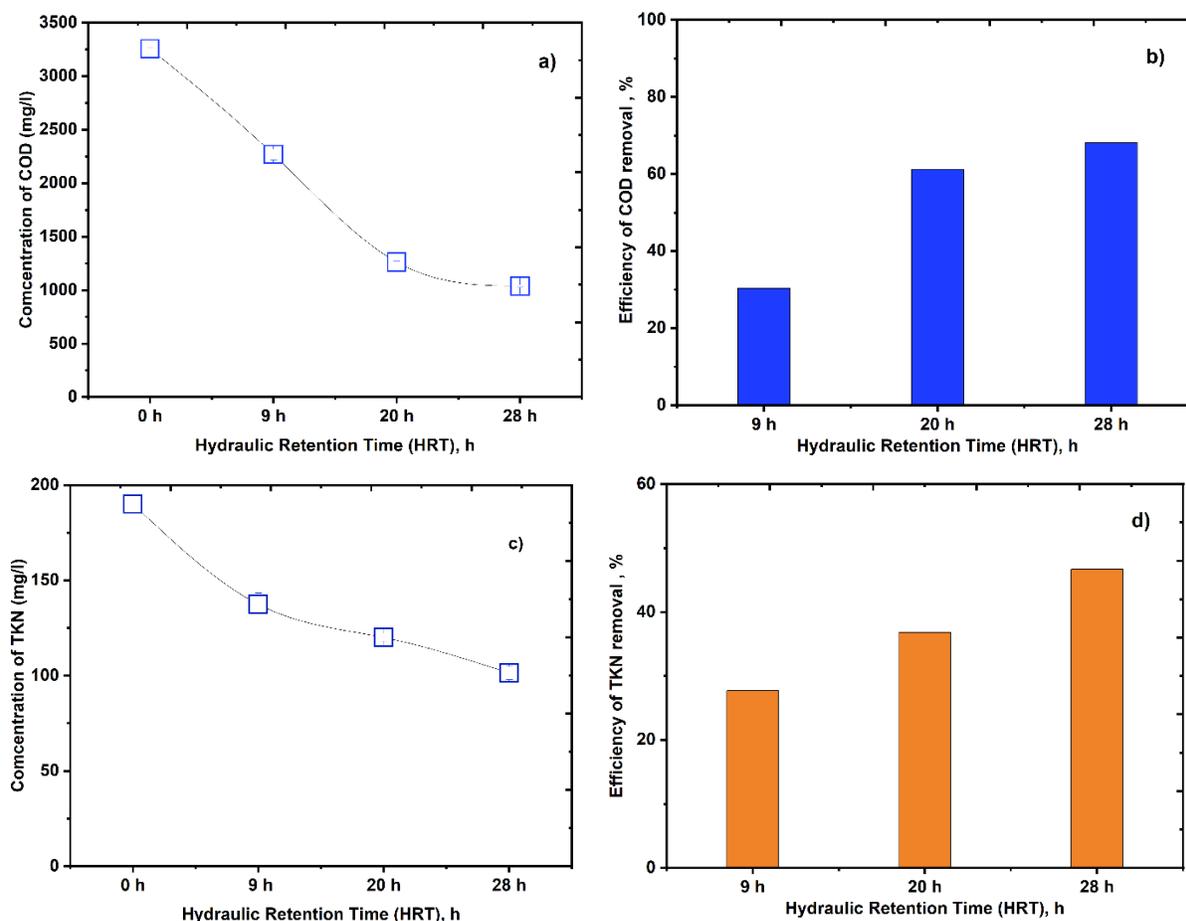


Figure 4.

The effect of hydraulic retention time of AR/AF on COD and TKN concentrations in the AR/AF system. a) COD concentration reduction, b) the percentages of COD removal, c) TKN concentration reduction, and d) the percentages of TKN removal.

3.5. Effect of COD Loading Rate on the Efficiency of Combined AR/AF System

In this study, we explored the effect of COD loading rate on the performance of a combined AR/AF system with a constant retention time of 20 hours and a 1,050-liter reactor. To evaluate wastewater treatment efficiency, COD loading rates were 0.39, 0.78, and 1.17 kg-COD/m³-d. The results indicate that COD loading rates significantly affected COD removal efficiency in the AR/AF system. When COD loading rates were 0.39, 0.78, and 1.17 kg-COD/m³-d, COD concentrations after passing through the combined anaerobic reactor and anaerobic filter (AR/AF) system were 996.67, 1,261.00, and 1,461.00 mg/L, respectively, while the percentages of COD removal were 69.37, 61.23, and 55.11, respectively. These results clearly show that the COD loading rate inversely correlates with the COD removal efficiency. In other words, increasing COD loading rates resulted in decreasing COD removal efficiency. The study also examined the relationship between COD loading rate and TKN removal efficiency. The loading rates with the AR/AF system at 0.39, 0.78, and 1.17 kg-COD/m³-d eliminated 39.47, 28.25, and 24.39% of TKN, respectively. Similar to COD removal, increasing COD loading truly caused a reduction in TKN removal. The results demonstrate that a COD loading rate of 0.39 kg-COD/m³-d promoted the highest removal efficiency of both COD and TKN. In other words, the AR/AF system at low COD loading rates yields better results. Additionally, the performance of the combined AR/AF system was significantly better than that of only the AR system. Based on the results,

when the COD loading rate was set at 0.78 kg-COD/m³-d, the percentages of COD removal for the AR system and the combined AR/AF system were 34.31 and 61.23, respectively.

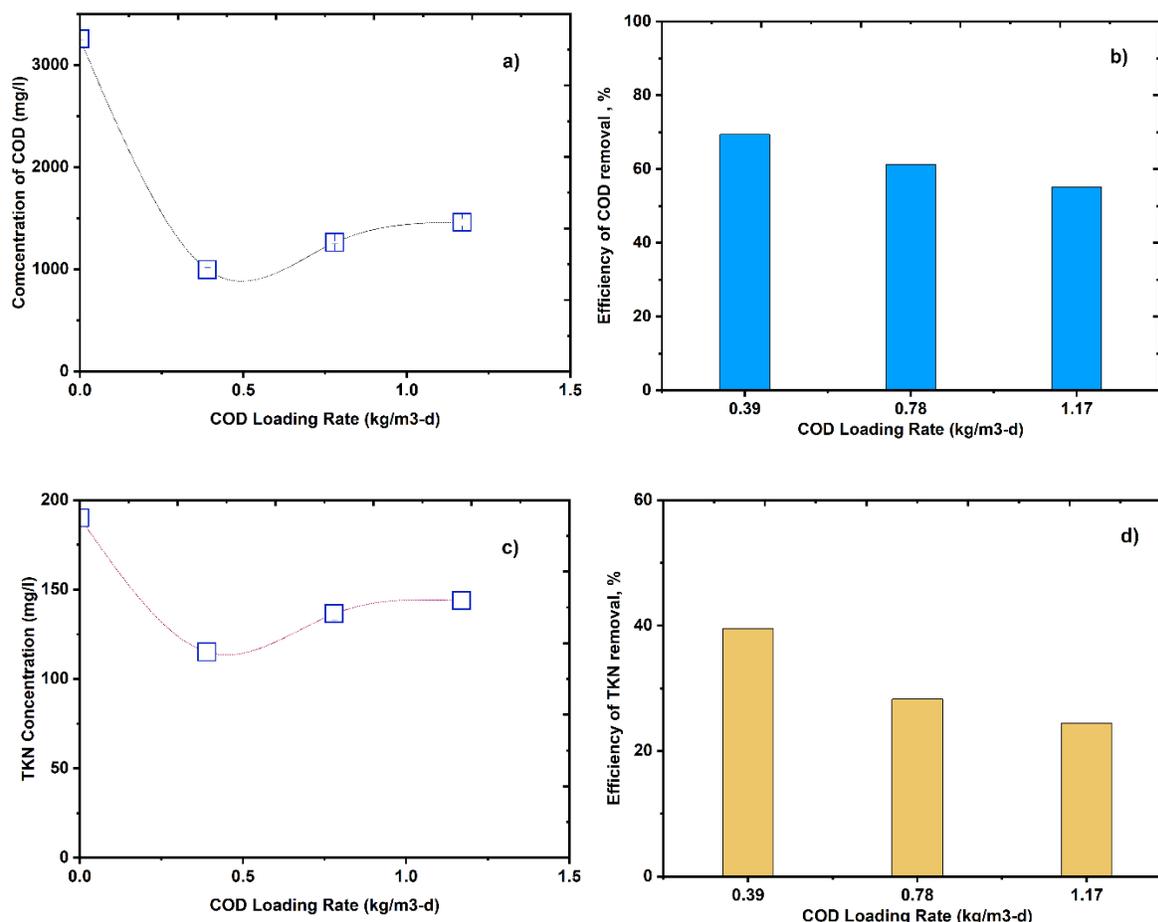


Figure 5. The effect of COD loading rate (kg/m³-day) on COD and TKN concentrations in AR/AF process: a) COD concentration reduction, b) the percentages of COD removal, c) TKN concentration reduction, and d) the percentages of TKN removal.

3.6. Assessment of Greenhouse Gas Emissions from Wastewater Treatment System

Equation 1, which is accurate and rapid, was employed since it calculated the total greenhouse gas emissions directly, as this generated gas from the wastewater treatment affects the environment [12]. This equation considers the main greenhouse gas emissions from anaerobic treatment processes: methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O). Also, the equation converts to CO₂ equivalent (CO₂e) units to compare the total impacts.

$$P_{\text{onsite}} = [(E_{\text{CO}_2} + (E_{\text{CH}_4} \times \text{GWP}_{\text{CH}_4}) + (E_{\text{N}_2\text{O}} \times \text{GWP}_{\text{N}_2\text{O}})] \quad (1)$$

$$E_{\text{CO}_2} = \text{EF}_{\text{CO}_2} \times M_{\text{BOD}}; E_{\text{CH}_4} = \text{EF}_{\text{CH}_4} \times M_{\text{BOD}}; E_{\text{N}_2\text{O}} = \text{EF}_{\text{N}_2\text{O}} \times M_{\text{TN}}$$

$$M_{\text{BOD}} = (\Delta\text{BOD} \times Q) \times 10^{-3}; M_{\text{TN}} = (\Delta\text{TN} \times Q) \times 10^{-3}$$

Where GWP is the global warming potential term (kgCO₂e/kg); E_{CO₂} is the carbon dioxide quantity (kg/d); E_{CH₄} is the methane quantity (kg/d); E_{N₂O} is the nitrous oxide quantity (kg/d); Q is the flow rate (m³/d); ΔBOD is the BOD reduction (mg/l); ΔTN is the total nitrogen reduction (mg/l); M_{BOD} is the BOD volume (kgBOD); and M_{TN} is the total nitrogen volume (kgTN). Kyung et al. [12] proposed the

following emission factors (EF) for direct greenhouse gas emissions: $EF_{CO_2} = 23.61 \text{ kgCO}_2\text{e/kg BOD}$, $EF_{CH_4} = 0.146 \text{ kgCO}_2\text{e/kg BOD}$, and $EF_{N_2O} = 0.653 \text{ kgCO}_2\text{e/kg TN}$.

Table 2.

Characteristics and efficiency of the AR/AF system for treating wastewater at Ponyangkham beef cattle farm.

| WWTPs | Type | Capacity | Average BOD (mg/L) | | Average TN (mg/L) | |
|-------|---------------|-----------------------|--------------------|----------|-------------------|----------|
| | | (m ³ /day) | Influent | Effluent | Influent | Effluent |
| Cows | AR/AF Process | 1.0 | 2274.3 | 1022.7 | 190.0 | 40.0 |

We evaluated the combined AR/AF wastewater treatment system at Ponyangkham beef cattle farm, and the average wastewater treatment capacity of the system was 1.0 cubic meter per day. The average BOD and TN values of wastewater entering the system were 2,274.3 and 190.0 mg/L, respectively. Conversely, the BOD and TN values of wastewater after treatment were 1,022.7 and 40.0 mg/L, respectively. The results demonstrate that the system had approximately 55.0% BOD removal efficiency and 78.9% TN removal efficiency. Additionally, the assessment of greenhouse gas emissions from the AR/AF system revealed low emissions. The results show that this system emitted 0.060 kilograms of CO₂e per day, or 21.64 kilograms of CO₂e annually.

4. Conclusions

The results in this study demonstrate the efficiency of the combined AR/AF system for wastewater treatment at Ponyangkham beef cattle farm, Thailand. Wastewater treatment efficiency was associated with retention time. Unlike only the AR reactor, the highest percentages of COD and TKN removal of the combined AR/AF were 68.15% and 46.67%, respectively. In contrast, the contaminant removal efficiency of the system decreased when COD loading rates increased. For example, the percentages of COD removal efficiency were 69.37, 61.23, and 55.11%, respectively, while the percentages of TKN removal efficiency were 39.47, 28.25, and 24.39, respectively, when the COD loading rate increased from 0.39, 0.78, to 1.17 kg-COD/m³-d. This system also treated 1,000 liters of wastewater per day with greenhouse gas emissions of only 0.060 kgCO₂e per day or 21.64 kgCO₂e per year, which was equivalent to 0.060 gCO₂e per liter of wastewater treated. In contrast to other wastewater treatment systems, the combined anaerobic reactor and anaerobic filter (AR/AF) system demonstrated a low environmental impact. The optimum conditions for maximizing treatment efficiency required 20–28 hours as the retention time and 0.39–0.78 kg-COD/m³-d as the organic loading rates. The AR/AF system is therefore a potential alternative for wastewater treatment from small livestock farms in Thailand.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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