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A review of modified and hybrid anaerobic baffled reactors for industrial wastewater treatment

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Abstract

This review discusses high-strength wastewater treatment using anaerobic baffled reactors (ABRs) and modified ABRs. The research findings and applications of ABRs in treating various types of high strength wastewater generated from food companies, livestock, and industries were summarized and reported. Measurement parameters affecting the performance of ABRs are briefly discussed. The state-of-the-art laboratory studies are compiled and critically reviewed. Critical challenges and suggestions for future investigation are also addressed.

Keywords: Anaerobic baffled reactor; Industrial food wastewater; Livestock wastewater; High-strength wastewater; Anaerobic digestion

1. Introduction

Biological remediation processes have many merits such as environmentally friendliness, low operational cost (Mulkerrins et al., 2004), and simple management (Arvin et al., 2019). Generally, biological treatment methods are divided into aerobic and anaerobic treatments. Anaerobic treatment outweighs aerobic treatment especially for its lower capital and operation costs, energy consumption, simple design and operation, and the effectiveness in converting organic matter to biogas (Elreedy et al., 2016; Farhadian et al., 2008). Anaerobic digestion can degrade chemical oxygen demand (COD), inactivate pathogenic microorganisms, and recover energy and nutrients (Yee et al., 2019). The four major processes in anaerobic digestion are hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Fig. A.1) (Ju et al., 2015). During hydrolysis, complex organic feedstock is hydrolyzed into simple organic components such as glucose and amino acids. Hydrolyzed organic components are converted to volatile fatty acids (VFAs) and alcohols in the acidogenesis stage. Propionic and butyric acids are further converted to acetic acid and CO_2/H_2 during acetogenesis and finally converted to CH_4 and CO_2 by methanogens (Madigan et al., 1997; Malina et al., 2017). Methane generated during COD removal can be recovered and converted into energy (Mendoza et al., 2009). 1 m^3 of biogas with 75% methane is able to generate 1.4 kW h of electricity, and it can be used in dual fuel generators or street lighting (Arceivala and Asolekar, 2006). In addition, an analysis of net energy gains proved that a modified anaerobic baffled reactor (ABR) operated at ambient temperature could generate 3.68 kJ of energy per gram of removed COD (Xu et al., 2017).

ABR was pioneered by McCarty and coworkers (Bachmann et al., 1983, 1985). It is a multi-staged bioreactor with a high biomass retention time due to the forced flow of wastewater through various compartments. Hydrolytic and organic acid-producing bacteria are isolated from methanogens with multiple compartments separated by a series of vertical baffles, through which wastewater moves upward and downward between the partitions along the reactor (Gulhane et al., 2017; Plumb et al., 2001). One of its great merits lies in its ability to

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separate the processes longitudinally, making the reactor an easy-controlled, low-cost, and multiple-stage system. The simple design with no moving part or mechanical mixing reduces its construction cost (Ozdemir et al., 2013). Kuşçu and Sponza (2006) reported that ABR is able to separate acidogenesis and methanogenesis longitudinally down the reactor to prepare the most desirable conditions for development of various groups of bacteria. ABRs are more adaptable to hydraulic and organic shock loading and show a high efficiency in COD removal (Zhang et al., 2011). It has been reported that sludge washout is less likely to occur in an ABR compared to an up-flow anaerobic sludge blanket (UASB) reactor with a single compartment (Hahn and Figueroa, 2015). Therefore, ABRs are suitable for remediation of different high-strength industrial effluents containing toxic and xenobiotic compounds (Majumder and Gupta, 2007; Zhang et al., 2011). ABR is a suitable sanitation technology that can easily be constructed above ground or underground (Bwapwa, 2012).

However, several studies have claimed some instabilities of ABRs at low hydraulic residence times (HRTs), and excess sludge cannot be solved using traditional ABRs (Chang et al., 2020). Hence, some modifications have been introduced to enhance the performance of traditional ABRs. Baffles can be installed vertically with a slanted edge angle of 45° in ABR (1) to create an up-comer and down-comer medium (Faisal and Unno, 2001; Li et al., 2021), (2) to aid closer contact of wastewater with active biomass in ABRs (Ahmad et al., 2021), and (3) to reduce the sludge that is brought up by produced biogas (Sayedin et al., 2018). Fig. A.2 shows the differences between conventional and modified ABRs. This review focuses on high-strength wastewater treatment using conventional and modified ABRs and potential improvements associated with pre- and/or post-treatments (Fig. 1).

2. High-strength wastewater

The strength of wastewater is characterized by biological oxygen demand (BOD), total suspended solids (TSS), COD, and fat, oils, and grease (FOG). High-strength wastewater contains high concentrations of organic matter and other pollutants, causing a high organic load even at a low influent flow rate (Pirsaheb et al., 2015). High organic content restricts aerobic remediation systems due to prohibitive aeration costs. Therefore, it is recommended to treat high-strength wastewater anaerobically to produce low surplus sludge (Hamza et al., 2016). Normally, high-strength wastewater is generated from food industries, livestock manure, landfills, and other industries (Lin et al., 2017; Trzcinski et al., 2011). These organic wastewaters have a great potential to be converted to methane-rich biogas and further transformed into thermal and electrical energy to reduce energy consumption in wastewater treatment plants or within the industry itself (Cheng et al., 2021).

2.1. Industrial wastewater

Some relevant studies on treatment of industrial food wastewater by ABRs or modified ABRs are listed in Table A.1. Most of these studies have been carried out at mesophilic

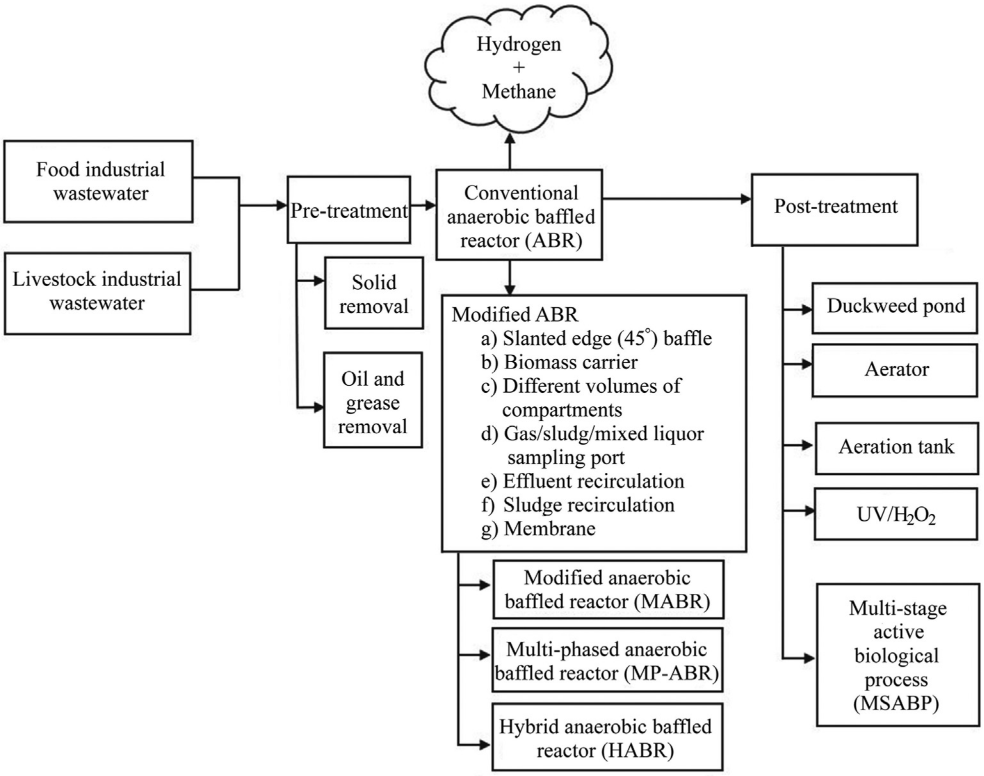

Fig. 1. Summary of ABR studies including possible pre- and post-treatments.

temperatures in ABRs with 4−8 compartments. There is a lack of data on thermophilic ABRs and comparison between mesophilic and thermophilic ABRs. As shown in Table A.1, COD removal percentages were within the range of 70% to higher than 90% at HRTs ranging from a few days to 30 d, and feedstock with COD over 100 g/L was successfully treated in ABRs. There is no clear indication that a recycle of effluent is beneficial in all situations but may be required for feedstock with low buffering capacity to avoid drastic pH drops.

According to the work by Sayedin et al. (2018), 66% of COD was removed in the first compartment when corn thin stillage was treated in an ABR; the COD removal efficiency declined to 26%, 4%, and 3% in the following compartments with an organic loading rate (OLR) of 1.0 kg/(m^3·d) of COD. No significant change occurred in the third and fourth compartments when OLRs of 1.5 kg/(m^3·d) and 2.0 kg/(m^3·d) were applied, but the COD removal increased by 3% in the fourth chamber at OLRs of 3.0−3.5 kg/(m^3·d). Hybrid ABRs were able to withstand higher OLRs, but methane gas production was adversely affected by OLRs. The methane percentage reduced from 71% to 54% when OLR increased from 1.0 kg/(m^3·d) to 3.5 kg/(m^3·d) as acidogenesis overtook methanogenesis. In the same study, the sulphate removal efficiency was investigated under different OLRs. The result showed that more than 90% of sulphate was removed within an OLR range of 1.5−3.5 kg/(m^3·d) of COD. 37%−59% of phosphorus removal can be achieved in ABRs (Sayedin et al., 2018), which is consistent with the removal rate of 68% achieved using a high-rate anaerobic fluidized bed reactor (AFBR) (Andalib et al., 2012).

In tapioca wastewater treated by ABR, the COD removal increased from 14% to 29% when HRT decreased from 24 h to 6 h and finally dropped to 22% when HRT was 3 h (Chang and Lin, 2004). pH in the fourth compartment decreased from 5.18 to 4.90 when HRT decreased from 24 h to 18 h, but it increased again to 5.72 when HRT was further reduced from 18 h to 3 h. The acid fermentation led to VFA accumulation, and then pH drop (Chang and Lin, 2004). These studies have indicated that operating a conventional ABR at a low HRT (less than 10 h) is generally not sustainable.

When Napier Grass liquor was treated, a fixed OLR (0.5 kg/(m^3·d) of COD) was set during the start-up period (14 d), and it gradually increased from 1.0 kg/(m^3·d) to 8.0 kg/(m^3·d) (Suaisom et al., 2019). After reactor failure at an OLR of 8.0 kg/(m^3·d) of COD, trace elements were added to ABR under a semi-continuous feeding scheme. The grass liquor was fed six times per day under successive OLRs of 2.0 kg/(m^3·d), 3.0 kg/(m^3·d), 4.0 kg/(m^3·d), and 6.0 kg/(m^3·d). It was found that 8.0 kg/(m^3·d) of COD was not suitable for biogas production as imbalance between acid and methane production occurred. This was due to the increased influent flow because the reduced HRT led to methanogens inhibition or washout. The optimum OLR to retain the microbial mass was 4.0 kg/(m^3·d) of COD. The methane gas yield at OLRs of 1.0−4.0 kg/(m^3·d) was 0.28 Nm^3/kg of COD on average and drastically declined at an OLR of 8.0 kg/(m^3·d). The methane yield was higher under the continuous feeding scheme at an OLR of 4.0 kg/(m^3·d) of COD compared to the feeding scheme of once a day. A low VFA concentration enhanced methane yield under high OLRs. The recirculation rate ranging from 0.5 to 2.0 did not affect VFA and alkalinity but reduced COD removal and methane yield probably because the increased mixing intensity led to sludge washout (Suaisom et al., 2019).

Another ABR was equipped with a series of 120° baffles with peaks facing each other to treat beer wastewater (Li et al., 2016b), and it enhanced the mixing of the entire reaction system. Gas production in each compartment increased with OLR because the high degree of fluidization of the granules prevented the formation of channels through the bed.

Li et al. (2016a) operated a modified laboratory-scale ABR with four chambers for more than 110 d to treat brown sugar liquid. There were up- and down-flow zones installed in each chamber with a volume ratio of 4.6:1. The operation was divided into four stages, and the influent COD was fixed at 4 g/L in each stage. HRT was gradually reduced from 2.0 d to 1.7 d, 1.3 d, and 1.0 d on the 37th, 63rd, and 84th days, respectively. In stage 1 with an HRT of 2.0 d, acetate concentration was higher than propionate and butyrate in each chamber but decreased along the chambers. Fermentation products were reduced when HRT was decreased from stage 2 to stage 3 but increased again in stage 4 with an HRT of 1.0 d. In stages 2 and 3, the production of propionate was higher than acetate and butyrate. H_2 was detected in the first chamber, and its yield increased when HRT was decreased from 2.0 d to 1.0 d. Up to 15.7 L/d of CH_4 was produced in the first compartment during stage 3, and CH_4 production was higher in the second compartment in stage 4. COD removal was the highest in the first compartment in stage 3 (66.1%).

A special design of moveable baffles was used in a multi-phased anaerobic baffled reactor (MP-ABR), and it was different from other studies (Ahamed et al., 2015). The volumes of the first three compartments and the last compartment were 10.7 L and 21.4 L, respectively. A mixer rotated at a speed of 100−150 r/min to reduce dead zones and short circuiting. The down-flow sections were enlarged to enhance the solid flow. Initial OLR was kept low at 0.5−1.0 kg/(m^3·d) of COD. HRTs were 6 d, 6 d, 6 d, and 12 d for the four compartments, respectively. pH dropped from 7.5 to 3.5 in the first chamber when COD increased in the first compartment on days 0−30, and the same situation occurred in the second and third compartments before pH eventually reached a steady point. 87.6% of total organic carbon (TOC) and 92.7% of VFA were removed on average. However, the rapid accumulation of VFA in compartment 3 led to instabilities because of the rapid growth of acid-producing bacteria that inhibited syntrophic bacteria and methanogens. As a result, accumulation of reduced intermediates occurred. This was also due to the insufficient HRT in compartment 3 and the fact that acetoclastic methanogens did not have sufficient time to grow. It was finally mitigated by recycling the sludge (1 L/d) to the third compartment on days 85−100. However, it triggered the increment of loading in the fourth compartment, and the biomass concentration was reduced. Hence, it discontinued and the retention time of the third compartment should be extended by 50% by increasing the volume of the third compartment to 16.05 L. After the amendment, COD removal was the highest in the first compartment, and VFA removal was the highest in the second compartment. Both of them declined along the compartments, which could be attributed to the degradation of long-chain fatty acids into short-chain VFAs. Total COD and soluble COD removals were 85.3% and 94.5%, respectively. On average, 89.65% of VFAs were removed, and the removal efficiency was higher in the first period due to the higher HRT and consumption of acetate by acetoclastic methanogens. Methanogenesis aided COD removal, and the highest removal efficiency was in the last compartment (90%). Biogas production stabilized around 4.8 L/d in the second period with 50%−60% of methane in the biogas.

Studies that have attempted to model or optimize ABRs are rare. Only one study used a software to design an experiment in order to optimize the treatment of baker's yeast wastewater (Pirsaheb et al., 2015). Accordingly, modifications were made to increase the height and number of compartments, and effluent recycles were used to adjust up-flow velocity (v_{up}). The start-up stage (three months) was operated, followed by a steady-state period. An HRT of 4 d and a recycle ratio of 22:1 with an up-flow velocity of 2 m/h were applied in the first stage. After that, HRTs of 2−6 d and v_{up} of 2−4 m/h were selected based on the experiment designed by the design expert system. The highest COD removal efficiency was 94.3%, slightly lower than the predicted value of 95.1% at an HRT of 6 d and the lowest v_{up} of 2 m/h. COD removal was adversely affected by the increased v_{up} (or high OLR). Colour removal increased significantly with v_{up} at HRTs of 2−4 d and slightly declined at an HRT of 6 d. Colour removal was the highest (43.0%) at an HRT of 4 d and v_{up} of 4 m/h but did not meet the environmental discharge standard. The low colour removal efficiency was due to the non-biodegradability of melanoidins (Movahedyan et al., 2007). v_{up} did not significantly affect VFA removal. VFA removal was the highest at an HRT of 6 d and v_{up} of 4 m/h. The effluent pH increased with HRT at the lowest v_{up}, but the effluent pH declined at the highest v_{up} when HRT was 6 d. Increased v_{up} enhanced methane production at an HRT of 2 d (Pirsaheb et al., 2015).

In Gulhane et al. (2017), an ABR was seeded with inoculum for a week before daily feedings of vegetable waste at an OLR of 0.5 g/(L·d) of volatile solids (VS) and an HRT of 20 d. The purpose of the experiment was to study bacterial diversity in the four compartments of ABR after a stabilized state of operation was achieved and to investigate the effect of effluent recycling on bacterial diversity. In this experiment, three operating conditions (OC) were adopted: no effluent recirculation (OC I), 25% of effluent recirculation (OC II), and 100% of effluent recirculation (OC III) in compartment 4. During OC I, accumulation of VFAs (3.46 g/L) was the highest in the first compartment. The highest utilisation was in the second compartment (83%−85%), and then it declined in the third and fourth compartments. Although the concentration of VFA was lower in the first compartment in OC I, similar trends appeared in OC II and OC III, which was caused by the presence of vegetable slurry from recycled effluent. Previous studies have shown that most of VFAs were detected in the second compartment, indicating the occurrence of acidogenesis. This was totally different from current findings because VFAs were utilised at a maximum rate in the second compartment and converted to CH_4 and CO_2, and a longer residence time of substrate in the first chamber promoted the growth of hydrolytic and fermentative bacteria (Ahamed et al., 2015). 85% of acetic acid was reduced in the first compartment because the effluent recirculation provided a buffering capacity for a favorable pH. The overall COD removal in OC II and OC III (91%−95%) was greater than that in OC I (85%−88%) because the effluent recirculation provided suitable conditions for complete decomposition of substrate. This finding was consistent with Zuo et al. (2013) who found that the recirculation of effluent from the methanogenic reactor to the acidogenic reactor enhanced COD removal (Gulhane et al., 2017). Certain bacterial population vanished in all compartments in OC III. The bacterial loss gradually along the reactor contradicted the growth of new communities during OC I, indicating that the effectiveness of ABRs in various conditions (Gulhane et al., 2017). A mass balance analysis revealed the distribution of carbon during the process: CH_4 (49% in gas phase) > CO_2 (34.4% in gas phase) > carbon in effluent (6.2%) > CH_4 (3.7% in dissolved phase) > biomass (3.4%). Only 3.3% of the input carbon could not be accounted for in the four-chambered baffled reactor. These results indicated that the content of dissolved methane was negligible. This finding agreed with Chorukova and Simeonov (2015) who found that the dissolved methane component could be neglected without affecting the mass balance analysis owing to the low solubility of methane in water.

Zwain et al. (2013) constructed a modified ABR (MABR) to treat paper-mill wastewater. The start-up time was shortened by developing an active methanogens biomass with a high digesting capacity. The MABR consisted of five chambers, and each chamber was separated by a modified vertical baffle. From day 1 to day 9, the reactor was operated in a batch mode and fed with 1000 mg/L of COD. During continuous feeding (days 10−30), the MABR was fed at an organic loading rate of 0.2 g/(L·d) of COD and an HRT of 5 d pH dropped from 7.3 to 6.2 due to the accumulation of VFAs and dissolved H_2, but the VFA concentration decreased along the compartments toward the rear of the reactor. The removal efficiencies of COD, BOD, TSS, total solids (TS), and volatile suspended solids (VSS) were 71.1%, 70.7%, 50.0%, 45.5%, 48.0%, and 45.0%, respectively.

Hydrogen production in ABRs has rarely been reported in previous studies. Ju et al. (2015) used a 200-L ABR to study the hydrogen gas generated from the decomposition of wheat starch. During start-up, OLR was increased gradually from 0.6 kg/(m^3·d) to 3.2 kg/(m^3·d), and the feed strength was fixed at 3.6 g/L of COD. A fraction of the feed was fed to each compartment to speed up the start-up. Generally, CO_2 yield was greater than H_2. Due to the inhibition of methanogens, the concentration of CH_4 declined from 25% to 9% during start-up, and H_2 concentration was 60% in the first compartment and then declined to 22% in the third compartment in 72 d after start-up. In contrast, CH_4 concentration increased from 2% to 31%, and CO_2 concentration slightly increased from 38% to 47%. Chen et al. (2008) evaluated hydrogen production and COD removal from tapioca wastewater using an ABR. Initially, the ABR was purged with nitrogen for 1 h to create anaerobic conditions and was fed with tapioca wastewater at an OLR of 16.15 g/(L·d) of COD. HRT was then reduced gradually from 24 h to 18 h, 12 h, 6 h, and 3 h. H_2 content was 16% and gradually increased to 29% when HRT was decreased to 12 h, and it further dropped to 12% when HRT was decreased to 3 h. Although a high HRT could promote the activity of hydrogen producing bacteria, it could restrict the gas production (Chen et al., 2008). Methane gas was produced at an HRT of 12 h, and the yield increased by 0.63%−3.70% when HRT was decreased to 6 h and 3 h (Thanwised et al., 2012). This indicated that methanogenic bacteria started to survive and adapted themselves at low HRTs because over- and under-flow of the liquid mitigated bacterial washout, thereby retaining active biological solids (Thanwised et al., 2012; Vossoughi et al., 2003). Normally, methanogenic bacteria do not survive at a low pH, but certain acid-tolerant methanogens can acclimatize to an acidic pH of 4.4 (Horn et al., 2003). An HRT of 6 h was the optimum condition for the operation of ABRs (Thanwised et al., 2012). Hydrogen production in ABRs has been shown to be feasible, but the production is not stable and hard to control because hydrogenotrophic methanogens eventually become active and convert hydrogen and CO_2 to methane. More research should be carried out to selectively inhibit hydrogenotrophic methanogens to optimize hydrogen production. Li et al. (2007) studied hydrogen production from diluted molasses. A remarkable hydrogen percentage between 50% and 60% in the headspace was achieved after 25 d of operation and maintained for 30 d. Compared to the complete stirring tank reactor, higher rates of substrate conversion and hydrogen production can be achieved due to the stability of the system and microbial activity. These studies have shown that hydrogen production can be achieved in ABRs at HRTs from 3 h to 15 h, but it is hard to control. This is because methane can be produced at HRTs as low as 10 h when right conditions (i.e., pH and granules) are met.

2.2. *Livestock wastewater*

Livestock is defined as the domesticated animals reared with the purpose to manufacture commodities (Lee and Shoda, 2008). Livestock wastewater contain high strengths of COD, BOD, colour, nitrogen, phosphorus, suspended solids (Lee and Shoda, 2008), heavy metals, xenobiotics, and pathogens, and its discharge rate into the water body has been rising (Hu et al., 2017). Although wastewater from large-scale livestock farms has been remediated to meet the corresponding discharge standards, the low levels of chemical components contained in large quantities of treated wastewater may still be excessive when discharged into the water body (Zhang et al., 2014). Wastewater from slaughterhouses contains high levels of FOG, BOD (151−200 g/L), COD (385 g/L), total nitrogen (TN), pathogenic and non-pathogenic viruses, bacteria, and parasite eggs (Bull et al., 1982; de Haan et al., 1996; Tritt and Schuchardt, 1992). Recent investigations on livestock wastewater treatment by ABRs or modified ABRs are listed in Table A.2.

Cao and Mehrvar (2011) studied an ABR combined with ultraviolet (UV)/H_2O_2 to treat slaughterhouse wastewater. The flow rate ranged from 6.2 mL/min to 27.6 mL/min, corresponding to HRTs of 3.8 d, 2.2 d, 1.7 d, and 0.9 d in the ABR and HRTs of 3.6 h, 2.2 h, 1.7 h, and 0.8 h in the UV photoreactor. The TOC loading rate was 0.2−1.1 g/(L·d), and the influent concentration ranged from 671.0 mg/L to 973.3 mg/L. The flow rate of hydrogen peroxide was 0.6 mL/min. The concentration of dissolved oxygen ranged from 0.5 mg/L to 1.6 mg/L (Cao and Mehrvar, 2011). TOC removal occurred in the first two compartments. Its removal efficiency in the second chamber was 87.8% at an HRT of 3.8 d. Prolonged HRTs enhanced TOC removal. 42.9%, 78.3%, 86.2%, and 87.8% of TOC were eliminated in the second compartment as HRTs increased from 0.9 d to 3.8 d. The highest final TOC removal efficiency was 89.9% at an HRT of 3.8 d. UV/H_2O_2 enhanced TOC removal by an extra 50.8% at an HRT of 3.8 d in the ABR. COD and five-day BOD (BOD_5) removals were effective in the first two chambers, and the removal rates declined with the decrease in the flow rate. At an HRT of 3.8 d, the maximum COD and BOD_5 removal rates were 97.7% and 96.6%, respectively. UV/H_2O_2 alone was able to remove 83.7% and 84.3% of COD and BOD_5 at an HRT of 2.5 h, respectively. The combination of ABR and UV/H_2O_2 were unable to remove TN.

A 60-L ABR with eight chambers was used to treat fishmeal wastewater (Putra et al., 2020). Chambers 1 and 2 functioned as an oil and grease (O&G) trap with partial acidification and hydrolysis, while other biochemical activities were carried out in chambers 3 and 4. The operation was carried out for 200 d with an OLR of 7 kg/(m^3·d). The recirculation ratio in compartment 5 was adjusted to 1:10 (Putra et al., 2020). 98% of total COD and 94% of soluble COD were eliminated after 200 d. 98% of TSS and VSS were removed, and 95.2% of total protein was removed. O&G was completely eliminated. The effluent recycled into the fifth compartment aided the steady condition of the ABR because high organic-degrading microorganisms were able to degrade the remaining solid compounds in the sixth to eighth compartments. The presence of the byproduct ammonium nitrogen in the anaerobic process is still an issue that needs to be addressed in further studies before full-scale treatment can be implemented.

A hybrid anaerobic baffled reactor (HABR) combined with the multi-stage active biological process (MSABP) was used to treat dairy wastewater at an HRT of 24 h. Biomass carriers were located in the upper chamber of each compartment of the HABR to allow microorganisms to form biofilms and improve wastewater treatment (Lin et al., 2012; Qi et al., 2019). The MSABP was designed to remove ammonia nitrogen, which is one the main drawback of conventional ABRs (Pirsaheb et al., 2019). The experiment was designed using the response surface methodology (RSM) based on Box−Behnken design (Chang et al., 2020). From the results of RSM, temperature (A) had the greatest impact on COD and NH_4^+ removals, followed by HRT (B) and pH (C). The cross products of AB and AC showed significant impacts on COD and NH_4^+ removals. Optimum parameters were temperature of 33°C, HRT of 24 h, and pH of 7.35, and the theoretical results of COD and NH_4^+ removals were 99.89% and 97.83%, respectively. The experimental results matched the predicted values, proving that the optimization results were reliable.

There is a lack of experiments to investigate the effect of temperature on the performance of ABRs. Chang et al. (2020) reported that the rise of temperature from 25°C to 30°C could reduce the effluent concentrations of COD and NH_4^+ below 10 mg/L and 2 mg/L, respectively, and 30°C was the optimum temperature to eliminate COD in dairy wastewater. Chang et al. (2020) investigated the impact of various pH values (6.5, 7.5, and 8.5) on the growth of microorganisms. It was shown that nitrifying bacteria were unable to survive when pH was 8.5, thereby reducing the performance of the reactor (Chang et al., 2020). In an ABR operated at high OLRs of 7 kg/($m^3 \cdot$d) and 8 kg/($m^3 \cdot$d) of COD and at HRTs of 20 d and 24 h, maximum COD removal rates of 98.5% in fishmeal wastewater and 98.6% in dairy wastewater were achieved (Putra et al., 2020; Chang et al., 2020). These studies indicated that OLRs in the range of 5−10 kg/($m^3 \cdot$d) are generally suitable in ABRs after acclimatization, but suitable HRTs fall within a wide range of 1−30 d, which should be determined on a case-by-case basis. Comparison of different reactors showed that ABR exhibited a higher COD removal rate in fishmeal wastewater than UASB, AFBR, the up-flow anaerobic filter, and the central anaerobic digester (Putra et al., 2020), highlighting the robustness of ABRs. Another novelty of the study of Putra et al. (2020) is the provision for O&G separation occurring in compartments 1 and 2, which is crucial for partial acidification and hydrolysis and subsequent biochemical processes (mostly carried out by *Syntrophobacter* sp. and *Methanosaeta* sp.) occurring in compartments 3 and 4. Methanogenesis also occurred in compartments 5−8 along with settling and further polishing (Putra et al., 2020). Overall, the combination of ABRs with other water remediation methods could enhance the removal of contaminants in wastewater, but the presence of UV could not remove TN (Cao and Mehrvar, 2011). Hence, TN removal is still a problem that need to be solved in industrial wastewater.

3. Enhancement of performance of ABRs

Several pre- and post-treatments can be used to mitigate the problems encountered by ABRs. For example, solid removal as pre-treatment is normally practiced in full-scale wastewater treatment plants. Physical settling is used to separate the solids from thin stillage wastewater on industrial scales, and the separated solids were further used as animal feed (Sayedin et al., 2018). Alternatively, the volume of the first compartment can be increased, and it must withstand high solid contents if mixing is provided (Boopathy and Tilche, 1991).

On the other hand, post-treatment can be used to remove residual COD and TSS and reduce the concentrations of nutrients and pathogens (Conley et al., 1991). For instance, a stabilization pond can be used as natural post-treatment. It was reported that NH_4^+ is hard to remove in anaerobic biological processes, and only small amounts can be removed through bacterial metabolism (Chang et al., 2020). Algal and plant systems may be used to eliminate mainstream nitrogen and phosphorus because algae and plants take up nitrogen and phosphorus to grow and can be harvested as biomass (Park et al., 2011). However, there is a lack of studies on the treatment of ABR effluents using these systems. Duckweed ponds as modified stabilization ponds can be used to remove NH_3 from wastewater because ammonia can be converted to plant protein in a duckweed pond. Then, the harvested duckweed may be used as fish or animal feed (Skillicorn et al., 1993). The effectiveness of duckweed ponds was reported to be better than alternative methods (Smith and Moelyowati, 2001). Up to 73% of nitrogen and 65% of phosphate were removed, but their final concentrations still exceeded the discharge limits defined by local regulations (Nasr et al., 2009). However, these natural systems can be feasible under suitable climate, land availability, and less stringent discharge limits (Hahn and Figueroa, 2015).

It was reported that the effluents from more than 100 UASBs in India did not meet the discharge quality standard. Hence, post-treatment is often required after ABRs (Owaes et al., 2020). The removal efficacy of surface aeration and activated sludge in treating UASB effluents was able to meet the wastewater discharge standards. They had high ranks of removal efficiencies just after the down-flow hanging sponge. Owaes et al. (2020) conducted an experiment using the aerobic granular biomass (AGB) in post-treatment of UASB effluents. It was found that COD removal efficiency was above 90% during the aerobic reaction, but the maximum removal was only 64% in UASB. Phosphorus removals were higher than 74% and 43% in UASB and AGB, respectively. The highest TN removal in AGB was 99%. In contrast, 78% of TN was removed in UASB. This indicated that AGB is feasible for post-treatment of anaerobic effluents. The demerit of AGBs is that AGBs require a longer time to form granules. Although there are data regarding the micro-aeration post-treatment of UASB effluents, more investigations are needed on micro-aeration post-treatment of ABRs. Overall, ABRs have been successfully combined with other remediation methods. Most combinations were able to improve the efficiency of the reactor, but these were sometimes not sufficient to meet standard effluent regulations.

The problem of adaptation of various microorganisms in the reactor could be mitigated with the presence of biofilm. The thickness of biofilm affects the concentration of dissolved oxygen. Therefore, it could be divided into oxygen-rich and oxygen-depleted regions. During steady operation of the hybrid aerating membrane-anaerobic baffled reactor

(HMABR), aerobic heterotrophic bacteria in the inner of the biofilm and anaerobic denitrifiers in the outer of biofilm elaborate their own strengths to remove COD significantly. Nitrite accumulated in the inner of the biofilm is partially oxidized to nitrate and converted to nitrogen gas in the outer of biofilm via the denitrification process. The incomplete denitrification process produced some NO_3^- and NO_2^-, thereby inhibiting the methanogenic process (Klüber and Conrad, 1998). The methanogenic process resumed only when the concentration of nitrate in the influent of the compartment decreased (Hu et al., 2009). However, there are still some obstacles preventing the implementation of this system, such as the C/N ratio in the wastewater affecting organic carbon and nitrogen removals and the thickness of the biofilm that should be properly monitored and controlled to avoid diffusion limitation of solutes and gases across the biofilm. Dissolved methane is another problem faced by ABRs. It should be removed from ABR effluents in order to reach the maximum energy yield (Smith et al., 2015). Biological oxidation in downstream processes could reduce dissolved methane. However, this is energy wasting, and some methane will still escape into the atmosphere (Hahn and Figueroa, 2015).

4. Molecular biology tools to monitor ABR performance

Biological activity in wastewater treatment is conventionally evaluated by the specific consumption rate of substrates. However, less attention has been paid to the number of specific bacterial cells within the microbial community in a reactor. Characterisation of bacterial populations in an engineering system like biofilm or activated sludge has been introduced because conventional culture-dependent techniques prohibit the number and localisation of specific bacterial cells due to the cultivation bias (Saiki et al., 2002).

The analyses for studies of microbial community include polymerase chain reaction (PCR), denaturing gradient gel electrophoresis (DGGE), fluorescence in situ hybridization (FISH), and quantitative real-time PCR (q-PCR). Lin et al. (2012) used DGGE to analyse the change in the structure of the archaea community in a five-compartment ABR before and after nitrobenzene (NB) acclimation to figure out the dominant community. The number of archaea species in the ABR declined after NB degradation, but the dominant community of each compartment remained the same, including *Methanothrix soehngenii, Methanosarcina* sp., *Methanosaeta concilii*, *Methanobacterium beijingense* 8−2, uncultured *Archaeon* TA04, and uncultured *Methanobacterium* sp.

FISH with specific oligonucleotide probes has been used to identify the target cells in environmental samples (Pavlekovic et al., 2009). FISH has been used to analyse granular sludge (brewery wastewater) (Saiki et al., 2002), phenolic wastewater (Kubota et al., 2021) from full-scale UASBs, mixed-type three-phase fluidized bed bioreactors (Aoi et al., 2000), and submerged rotating disk reactors (Okabe et al., 1999). The application of FISH to HMABR showed that the spatial profiles of ammonia-oxidizing bacteria, nitrite-oxidizing bacteria, aerobic heterotrophic bacteria, and denitrifying bacteria were achieved by biofilm stratification (Hu et al., 2009). These techniques can provide comprehensive information to understand the distribution and growth of microorganisms.

q-PCR technology is the most sensitive and precise method to generate reliable quantification of any target sequences in a sample in a short time (Burgos et al., 2002; Klein, 2002). It was applied to an ABR treating high-strength sweet potato starch wastewater at mesophilic and ambient temperatures (Xu et al., 2017). The ABR operation was divided into four phases with respect to the influent COD level, operating temperature, and COD removal performance: phase I (set-up phase, days 1−24), phase II (operation phase at high temperature, days 25−58), phase III (operation phase at moderate temperature, days 59−137), and phase IV (operation phase at low temperature, days 138−172). The methanogen population was determined by quantifying the gene encoding the alpha subunit of methyl-coenzyme M reductase (*mcr*A). The results showed that the largest number of methanogens (5.29×10^8 copies of *mcr*A per milliliter of sludge) were found in phase III, and $1.2 \times 10^8 \pm 2.1 \times 10^7$ and $2.12 \times 10^8 \pm 1.3 \times 10^7$ were found in phases I and II, respectively. The number of methanogens declined to $1.60 \times 10^8 \pm 1.4 \times 10^8$ in phase IV, which might be caused by the low temperature (10°C). It was also reported that acetoclastic methanogens, such as *Methanosaeta*, was the major archaeal species in each compartment in phases I and II (Xu et al., 2017).

5. Conclusions

This review summarizes the performance of ABRs in treating high-strength wastewater from different sectors. For treatment of industrial wastewater, the highest COD removal rate was 97% (corn thin stillage), and the lowest 29.3% (tapioca wastewater). Nearly 100% of COD was removed in treatment of livestock wastewater, and 97.8% of NH_4^+ was removed from dairy wastewater.

Most ABRs were investigated at laboratory scale, and some compounds cannot be removed from ABRs. Hence, more investigations are needed to promote the removal of these substances from wastewater. Modifications on baffles and compartment sizes to modify velocities, stirrers, biofilm, membrane, and physicochemical or natural post-treatments are the methods to increase the efficiency and stability of ABRs.

For industrial wastewater, the effects of HRT, recirculation ratio, solid retention time (SRT), and temperature should be investigated further. The interaction between the factors affecting the performance of the reactor should be investigated using computational fluid dynamic simulations. In addition, more investigations should be carried out to solve the problems of poor TN removal, low methane yield, and balance of pH in the reactor to ensure methanogenic digestion. Lastly, the waste generated from the conversion process should be studied to target zero discharge of excess sludge and achieve green energy production. Most experiments have been carried out in laboratories, and SRT and excess sludge withdrawal have been often omitted. Ammonia removal and dissolved methane in the effluent remain an issue. More studies should be conducted at pilot and full scale to encourage the commercialization of ABRs or modified ABRs.

Declaration of competing interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wse.2022.06.004.

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