Environmental Science and Pollution Research (2021) 28:35–55
https://doi.org/10.1007/s11356-020-10921-x

REVIEW ARTICLE

Anaerobic treatment of slaughterhouse wastewater: a review

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Received: 5 May 2020 / Accepted: 17 September 2020 / Published online: 8 October 2020

Abstract

This article presents a review of anaerobic treatment technologies to treat slaughterhouse wastewater including its advantages and disadvantages. Physico-chemical characteristics and biochemical methane potential (BMP) of slaughterhouse wastewater are addressed. Various anaerobic treatment technologies are presented with the related operating parameters, viz., hydraulic retention time (HRT), organic loading rate (OLR), upflow velocity (V_{up}), and biogas yield vis-a-vis treatment efficiency in terms of chemical oxygen demand (COD). In addition, various factors that affect the anaerobic treatment of slaughterhouse wastewater such as high oil & grease (O & G) concentration in influent, inhibitors, volatile fatty acids (VFAs), and the loading rate are also addressed. The literature review indicated that the slaughterhouse wastewater can be treated effectively by employing any anaerobic treatment technologies at OLRs up to 5 kg COD/m^3.d with more than 80% COD removal efficiency without experiencing operational problems. Anaerobic hybrid reactors (AHRs) were found the most effective among various reviewed technologies because of their ability to operate at higher OLRs (8 to 20 kg COD/m^3.d) and lower HRTs (8 to 12 hrs).

Keywords Biochemical methane potential · Physico-chemical characteristics · Hydraulic retention time · Organic loading rate · Biogas yield · Inhibitors

Nomenclature

ABR	Anaerobic baffled reactor
AF	Anaerobic filter
AFBBR	Anaerobic fluidized bed biofilm reactor
AHR	Anaerobic hybrid reactor
AnMBR	Anaerobic membrane bioreactor
AnSBR	Anaerobic sequential batch reactor
BMP	Biochemical methane potential
BOD	Biochemical methane potential
COD	Chemical oxygen demand
CPCB	Central Pollution Control Board
d	Day
FAO	Food & Agriculture Organization
FOG	Fats, oil, & grease
HACCP	Hazard analysis and critical control points
hrs	Hours
HRT	Hydraulic retention time
ISO	International Organization for Standardization
MLSS	Mixed liquor suspended solids
O & G	Oil & grease
OLR	Organic loading rate
RTD	Residence time distribution
SCOD	Soluble chemical oxygen demand
SRB	Sulfate-reducing bacteria
SRT	Solid retention time
TDS	Total dissolved solids
TKN	Total Kjedahl nitrogen
TMP	Transmembrane pressure
TS	Total solids
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket reactor
UN	United Nations
USEPA	United States Environmental Protection Agency
VFA	Volatile fatty acids
VS	Volatile solids
VSS	Volatile suspended
V_{up}	Upflow velocity

The authors confirm that the manuscript is not be submitted anywhere else for simultaneous consideration. The submitted work is original and not has been published elsewhere in any form or language (partially or in full).

Responsible Editor: Ta Yeong Wu

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Introduction

A slaughterhouse or abattoir is an industry where the butchering of animals is done for meat processing and derive other commercial products. Some of the commercial products include skin/hide for leather industry; dung for manure production; bones for poultry food, drugs, and cutlery; fats for tallow manufacturing and blood for blood meal production (European Commission 2005). Wastewater from slaughterhouses and meat industries are treated as industrial wastewater and categorized under agricultural and food industries (Seif and Moursy 2001). For the first time in 2004, USEPA developed "Effluent limitations guidelines and new source performance standards for the meat and poultry products point source category" owing to its growing concerns. (USEPA 2004). The slaughterhouse, meat manufacturing, and related industries have to follow stringent "Sanitary and Food Safety Norms" laid by International organizations such as ISO: 22000; Hazard analysis and critical control points (Asian productivity organization 2004). As a result, a large volume of water is used to maintain the cleanliness, sanitation in each of the slaughtering, and meat processing operations which ultimately generates wastewater (Gauteng Provincial Government, South Africa 2009). The physico-chemical characteristics of slaughterhouse wastewater vary from region to region and depend upon the size of a slaughterhouse, water consumption, recovery of useful by-products, etc. The wastewater from the slaughterhouse industry is of diverse nature since it contains blood, oil, fats, salts, suspended solids (partially, fully, or undigested cattle dung), which are introduced in wastewater from the various slaughtering operations (Salminen 2002; CPCB 2017). Generally, for wastewater with high organic strength, anaerobic treatment is the most preferred option to substantially reduce the organic loads on following aerobic treatment systems (EPA Ireland 2008). This research work aims at exploring the suitable and appropriate anaerobic treatment option, which is techno-economically sustainable and offers ease in operation and maintenance.

Characteristics of slaughterhouse wastewater

Knowledge of the physico-chemical characterization of slaughterhouse wastewater is essential to design and implement an effective and economical wastewater treatment facility. Various studies have been carried out by different researchers to understand the nature of slaughterhouse wastewaters. The summary of several studies from different slaughterhouses reported by researchers is summarized in Table 1. It is interesting to note that there is wide variation in the wastewater characteristics, even in similar types of slaughterhouse industries. This indicates that the characteristics of wastewater largely depend on site-specific and local operating conditions. Regardless of the substantial variation in the physico-chemical parameters from different slaughterhouses, this review would be helpful to readers in the selection of an appropriate treatment method.

Slaughterhouse wastewater is generally described as having high organic strength owing to the presence of blood and intestinal contents and is a combination of proteins, fats, and complex organic compounds (Maroneze et al. 2014; Padilla-Gasca et al. 2011). The temperature of slaughterhouse wastewater depends upon local weather conditions. However, there are some slaughtering operations, viz., rendering, intestine, and tripe cooking/washing, which generate wastewaters with comparatively higher temperatures of the order of 40 to 60° C. High water temperatures have the potential to exert considerable adverse effect on the biological activity and also pose difficulties especially in the flotation process due to emulsification and ultimately affects fat removal (Salminen 2002; Johns 1995)

Slaughterhouse effluent contains adequate alkalinity for the anaerobic digestion (Kundu et al. 2013). Raw blood contributes on average 6 kg of BOD/cattle with its organic load equivalent to 0.14 to 0.18 kg BOD_5/kg of live weight. Organic load contribution from each of the individual slaughtering processes is reported by FAO (2001). Blood is also high in nutrients, typically 2400 mg/L of nitrogen and 1500 mg/L phosphates (Muhirwa et al. 2010). Organic nitrogen is introduced from the dung of cattle and it possesses 80 ± 12 mg protein/g of the solid substrate (Vijayraghavan et al. 2012). Slaughterhouse effluents contain dissolved protein and polysaccharides, which are colloidal (Sanders 2001). Furthermore, inorganic compounds are also introduced into the effluent stream from detergents and disinfectants used for cleaning and washing activities (Bustillo-Lecompte and Mehrvar 2015). Studies carried out by Mousavi and Khodadoost 2019 have demonstrated that the presence of detergents in wastewater may negatively affect anaerobic digestion such as the reduction in COD removal efficiency and biogas yield. Wastewater from rendering, fleshing, intestine, and tripe washing processes contain fat, oil & grease (FOG), and a large amount of long-chain fatty acids (Miranda et al. 2005). Salts from the hide storage section impart total dissolved solids (TDS) load into the main effluent stream. Slaughterhouse wastewater also contains a highly diverse population of fecal coliform/pathogens (Farzadkia et al. 2016). Enterococci, clostridia, and somatic coliphages are some of the microorganisms identified from slaughterhouse wastewater (Ottoson 2014). Additionally, there are several physico-chemical parameters in the slaughterhouse industry's wastewater that can affect the working of anaerobic treatment. The effect of these physico-chemical parameters including high oil & grease concentration, VFA/alkalinity ratio, and inhibitors is discussed below.

Table 1 Summary of wastewater characteristics reported by various researchers in different slaughterhouses

Sr. No.	pH	TSS	TDS	COD	BOD	Oil & grease	TKN	Nitrate	Phosphate	Sulfate	Total coliform	Remarks	Reference
1	7.53	TS = 5748		17,019	10,836	254	–	–	65.4	1009	19 × 10^5	200 goats +200 cows per month	Chukwu et al. (2011)
2	6.69	863.6	1826.42	2144	1235	–	145	7.12	94.8	96.96	–	Water consumption 400 m^3/d, Effluent screened at a 1-mm sieve	Sarairah and Jamrah (2008)
3	6.98	TS = 6394		11,588	4635	1302	841	8.59	48.4	–	–	Raw effluent	Wu and Mittal (2012)
4	8	946	3353	1421	718	–	–	51	17	56.5	–	Samples collected from the abattoir area (cows, goats, sheep, and camels)	Akan et al. (2010)
5	7.7	1900	1992	4306	2733	300	1100	–	318	–	2 × 10^7	Samples collected from Municipal Slaughterhouse	Padilla-Gasca et al. (2011)
6	6.62 ± 0.01	1130 ± 20	2000 ± 18	2200 ± 52	1060 ± 25	–	250 ± 17^	500 ± 25	18 ± 1.4	–	–	Cattle/sheep	Al Smadi et al. (2019)
7	6.9 ± 0.8	22,300 ± 212	–	32,000 ± 112	17,158 ± 95	1024 ± 34	915 ± 18^^	–	–	–	–	Cattle	Ali Musa et al. (2019)
8	–	–	–	2337.43 ± 836.8			346.85 ± 112.75^	–	21.42 ± 4.5	–	–	–	Besharati et al. (2019)
9	7.1	–	–	4502	2350	–	154	–	–	–	–	Cattle	Husam and Nassar (2019)

*All parameters are in mg/L except pH and total coliform

**Total coliform is expressed in colony-forming unit (cfu)/100 mL

^Value represents NH_3;

^^Value represents TN

Higher oil & grease concentration

Miranda et al. (2005) studied the effect of high oil & grease (O & G) content on the treatment of slaughterhouse wastewater in the upflow anaerobic sludge blanket reactor (UASB) reactor. The authors concluded that O&G/COD ratio above 20% resulted in biomass washout, gradual reduction in system efficiency, and failure of the process. The reason for the failure of the UASB reactor was attributed to the accumulation of excess long-chain fatty acids and the formation of hydrophobic sludge granules due to the adsorption of O & G on granules.

VFA/alkalinity ratio

For an anaerobic process, it is very important to maintain a suitable volatile fatty acids (VFA)/alkalinity ratio to avoid acidification in the process and hence it should always be kept below 0.4. Torkian et al. (2003) found VFA/Alkalinity ratios between 0.25 and 0.32 to be feasible and Kwarciak-kozłowska et al. (2011) observed the ratio to vary between 0.22 and 0.27. Slaughterhouse wastewater has the property to produce alkalinity to counteract VFAs generated during anaerobic treatment. This can be attributed to the presence of high organic nitrogen content in slaughterhouse wastewater (TKN value of 841 mg/L by Wu and Mittal 2012; 1100 mg/L by Padilla-Gasca et al. 2011). Organic nitrogen is converted to ammonia through ammonification by a process called hydrolysis. Subsequently, ammonia reacts with carbon dioxide produced during anaerobic digestion to form ammonium bicarbonate which contributes to alkalinity in the reactor (Padilla-Gasca et al. 2011). Since the slaughterhouse wastewater possesses high concentrations of organic nitrogen, maintaining the VFA/Alkalinity ratio during anaerobic treatment is not a major challenge.

Inhibitors

In some cases, slaughterhouse wastewater is subjected to the coagulation-flocculation process as a primary treatment before feeding effluent to anaerobic reactors. In one of the studies by Al-Mutairi (2006), it was demonstrated that 100–200 mg/L alum induced slight toxicity level to slaughterhouse effluent. At the same time, alum concentrations of 300–1000 mg/L, slaughterhouse effluent exhibited substantial residual chronic toxicity. In one of the studies, Jackson-Moss and Duncan (1991) concluded that an influent concentration up to 2500 mg/L Al^{3+} could be sustained by acclimatized methanogens in an anaerobic digester but further increase in Al^{3+} concentration resulted in inhibition. Jackson-Moss and Duncan (1990) investigated the capability of methanogens to adjust to high levels of iron and concluded that iron concentration of up to 5650 mg/L had no effects on anaerobic digestion except a decrease in biogas production. Hence, it is imperative to maintain the aluminum and iron concentration in treated effluent after coagulation-flocculation within a desirable limit to avoid anaerobic treatment offsets.

Moreover, it is quite well known that the presence of sulfates is inhibitory to methanogenesis. The main reasons for this inhibitory effect are (i) microbial reduction of sulfate produces sulfide or free H_2S, and (ii) sulfate-reducing bacteria (SRB) compete with methanogens for electron donors (Schönheit et al. 1982). Slaughterhouse wastewater contains a considerable amount of sulfates. Some reported values are 1009 mg/L (Chukwu and Chidiebere 2011), 96.96 mg/L (Sarairah and Jamrah 2008), and 56.5 mg/L (Akan et al. 2010). Although the inhibitory effect of sulfate on methane-producing bacteria is 1200 mg/L sulfate (120 to 140 mg/L sulfide) (Choi and Rim 1991), the concentration of sulfates should also be given due consideration while designing anaerobic treatment system for slaughterhouse wastewater.

Biochemical methane potential of slaughterhouse wastewater

Biochemical methane potential (BMP) is a test to assess the biodegradability of the substrate or to evaluate the potential methane yield of a sample (Elbeshbishy et al. 2012). If the substrate concentration and composition are known, it is easy to compute methane yield theoretically, using the Buswell equation. However, the actual methane yield obtained in a reactor will always be less than the theoretical value as the theoretical methane yield does not take into consideration the quantity of organic matter utilized for asexual reproduction. Moreover, even if the substrate concentration and composition are known, the substrate may not always undergo complete biodegradation (Angelidaki and Sanders 2004). BMP values reported by various researchers are presented in Table 2.

As shown in Table 2, Manjunath et al. (2000) found that for raw slaughterhouse wastewater at 30 ± 1° C, BMP_5 was between 90 and 100 mL/g COD and BMP_{30} was between 190 and 200 mL/g COD. Maya-Altamira et al. (2008) reported maximum practical methane yield at 35° C as 350 ± 70 mL/g COD for raw slaughterhouse wastewater. It is important to note here that there is a significant variation in the BMP values reported by Manjunath et al. (2000) and Maya-Altamira et al. (2008), although both the studies were carried out using raw slaughterhouse wastewater. The probable reason could be the COD available for the test. As can be seen from Table 2, the COD concentration which acts as a substrate for bacteria in the case of Manjunath et al. (2000) is as low as 1100 mg/L and it is 2850 mg/L in the case of Maya-Altamira et al. (2008). Thus, the greater substrate

Table 2 Reported BMP values for slaughterhouse wastewater

BMP test	Type of wastewater	COD (mg/L)	Inoculum used	BMP value	Biodegradation	Reference
BMP_5 at 30 ± 1° C	Raw slaughterhouse wastewater	1100–7250	Defined media as per the serum bottle technique	50 to 75 mL/g COD	–	Manjunath et al. (2000)
BMP_{20} at 30 ± 1° C	Raw slaughterhouse wastewater			190 to 200 mL/g COD		
BMP_{max} at 35 ± 1° C (20 to 30 d)	Raw slaughterhouse wastewater	10,400 ± 1000 (four times dilution) Approx. 2850	Sludge from the full-scale anaerobic continuous stirred tank reactor	350 ± 70 mL/g COD	100%; maximum achieved practical methane yield in COD units/theoretically expected methane yield in COD units	Maya-Altamira et al. (2008)
BMP_{max} at 35° C	Raw Slaughterhouse wastewater	109,800*	Granular sludge from full-scale UASB reactor	74.8 mL/g COD	–	Mainardis et al. (2017)
BMP_{20} at 35 °C ± 2 °C	Yard water (manure and urine)	1200 mg VS/L	Sludge from the full-scale anaerobic digester	325 mL/g VS	100% (As per ISO 11734)	Bauer (2011)
BMP_{20} at 35 °C ± 2 °C	Blood	600 mg VS/L		733 mL/g VS	100% (As per ISO 11734)	

*Soluble COD

availability at the start of the test results in higher BMP values (Yoon et al. 2014). However, too high substrate concentration may lead to inhibition of anaerobic digestion due to the accumulation of intermediate/inhibitory compounds (Filer et al. 2019). This is evident from the high COD concentration and low BMP value reported by Mainardis et al. (2017). However, Mainardis et al. (2017) reported that the probable reason for lower BMP values could be due to poor adaptability of granular sludge to the substrate. Temperature also favors the rapid degradation of COD, since the bacterial activity is directly proportional to the temperature (Westerman 1996). The test was conducted at 35 ± 1° C by Maya-Altamira et al. (2008) as against 30 ± 1° C Manjunath et al. (2000). As far as the differences in the selection of inoculum are concerned, studies carried out so far on BMP agree that different inocula may lead to different readings due to certain reasons such as different microbial populations or initial time for adaptation to the substrate (Moreno-Andrade and Buitrón 2004). Bauer (2011) reported BMP_{20} at 35 °C ± 2 °C for yard water (wastewater from Lairage section containing manure and urine) as 325 mL/g VS and for blood, it was 733 mL/g VS. Anaerobic biodegradability was 100% in both the studies carried out by Maya-Altamira et al. (2008) and Bauer (2011) as shown in Table 2. This contradicts the views of Angelidaki and Sanders 2004. However, the methods used for calculating theoretical methane yield in these studies were not based on the Buswell equation. Maya-Altamira et al. (2008) calculated theoretical methane yield based on the organic fractions and not the atomic composition. Moreover, while calculating the practical methane yield, the sample was diluted four times (25%) resulting in an overestimation of practical methane yield and biodegradation fraction. On the other hand, Bauer (2011) used ISO 11734 (1995) method and presented the substrate concentration and BMP values in terms of volatile solids (VS). Bauer also stated that the biodegradability measurements were based on the dissolved organic and inorganic carbon and did not take into account the suspended organic solids. Thus, the results reported by him are not the actual representation of the biodegradation that had occurred. However, as far as dissolved organic carbon is concerned, biodegradation is 100%. On the other hand, Pozo et al. (2003) reported 80% anaerobic biodegradability of slaughterhouse wastewater having an initial COD concentration of 1500 mg/L based upon the total COD reduction during the test period. BOD/COD ratio is also an indicator of the biodegradability of organic content present in wastewater. The BOD/COD ratio of the studies presented in Table 1 varied from 0.4 to 0.63. These values (Dinçer 2020) fall within the reported range of biodegradability hence suggesting that slaughterhouse wastewater is easily biodegradable. Based on the discussion and reported BMP values, slaughterhouse wastewater appears to be amenable to anaerobic treatment.

Anaerobic treatment of slaughterhouse wastewater

Anaerobic treatment involves decomposition of organic matter by different microbial communities in the absence of oxygen. It also results in the production of biogas and a liquid or semisolid digestate which can be used as a fertilizer after dewatering (Abalde 2013; Abdelgadir et al. 2014). Coordinated activity of diverse groups of bacteria having different metabolic capabilities is essentially required to carry out the anaerobic decomposition of organic matter from wastewater (Zinder 1984). Anaerobic digestion can be regarded as interdependent, as well as a parallel sequence of biological reactions during which the product generated from certain specific bacteria serves as a substrate for the next group of bacteria (Christy et al. 2014).

Anaerobic treatment of slaughterhouse wastewater is the most preferred option because of its capacities to handle high-strength wastewater with minimal sludge production as compared with aerobic treatment technologies and potential resource recovery in the form of methane. Typical anaerobic processes to manage slaughterhouse wastewater are up-flow anaerobic sludge blanket (UASB), anaerobic baffled reactor (ABR), anaerobic filter (AF), anaerobic hybrid reactor (AHR), anaerobic fluidized bed biofilm reactor (AFBBR), anaerobic sequential batch reactor (AnSBR), and anaerobic membrane bioreactor (AnMBR).

The basic principle of organic pollutants removal from the wastewater using anaerobic treatment technologies is the same. But there exist considerable differences between different anaerobic treatment technologies in terms of hydraulic regime, bacterial growth, operational problems, and requirements of complementary facilities such as sedimentation, mixing, and membranes for solid-liquid separation. These similarities and differences are presented in Table 3 along with their advantages, disadvantages, and precautionary measures. Each of the technology to treat slaughterhouse wastewater is discussed in length in the subsequent section. Comparisons between the performance of anaerobic treatment technologies to treat slaughterhouse wastewater have also been presented in the article.

Upflow anaerobic sludge blanket reactor

Upflow anaerobic sludge blanket reactors (UASBs) can be operated at varying organic loads, i.e., 4 to 12 kg COD/m^3.d (days) and the biomass concentration in sludge blanket ranges from 30.0 to 80.0 g/L. Upflow velocity for keeping granules in suspension varies in the range of 0.6 to 0.9 m/hr. Internal mixing within the reactor is favored by the biogas generation, which also encourages granules to develop (Daud et al. 2018). UASBs are often provided with an external sedimentation tank with sludge return to prevent major loss of biomass (Metcalf and Eddy 2003).

Studies carried out by various researchers to treat slaughterhouse wastewater using UASB reactor are presented in Table 4. Manjunath et al. (2000) assessed the adequacy of the UASB reactor for the treatment of slaughterhouse wastewater. The authors reported the COD removal efficiency of 70% with final effluent COD concentration varying between 330 and 2200 mg/L at OLR of 3.5 kg COD/m^3.d and HRT of 10 hrs. Kwarciak-kozłowska et al. (2011) found that with an increase in OLR from 0.27 to 0.82 kg COD/m^3.d, COD removal efficiency decreased from 85 to 65%, and concluded that OLR of 0.55 kg COD/m^3.d at HRT of 3 d as the most preferable treatment approach amongst the various OLRs tried during the study. Very high methane content of 75% in biogas was found in this study. Sayed et al. (1987) found fairly moderate COD removal efficiency between 52 and 56% at OLR of 2.5 to 16 kg COD/m^3.d and recommended a maximum allowable COD load up to 11 kg COD/m^3.d. The study showed that at OLR of 6 to 6.2 kg COD/m^3.d, 65% of COD was converted to methane and with the increase in OLR beyond 11 kg COD/m^3.d, COD conversion rate to methane decreased. Veiga et al. (1997) achieved a fairly high COD removal efficiency of 90% at OLR of nearly 1 kg COD/m^3.d, but the HRT was of the order of 6.5 d. However, such a long HRT may unnecessarily increase the size of the reactor and initial capital cost including extensive land requirements. At an OLR of more than 5 kg COD/m^3.d, floatation occurred and active biomass was washed out from the reactor. On the other hand, Caixeta et al. (2002) found the COD removal efficiency of nearly 90% at OLR of 8.7 kg COD/m^3.d. The pH during the period of operation was in the range of 7.5 to 8.5. Torkian et al. (2003) obtained SCOD removal efficiency of 85% at higher OLR of 27 kg SCOD/m^3.d. The reactor performance declined at OLR greater than 27 kg SCOD/m^3.d, but the authors did not report any phenomenon of sludge flotation/biomass washout. Ali Musa et al. (2019) compared the performance of conventional UASB and the improved UASB with the provision of flat round PVC mesh at the top of the reactor to treat slaughterhouse wastewater. The authors found that the COD removal efficiency at OLR of 10 and 14 kg COD/m^3.d was 54 and 50% for conventional UASB and it was 95 and 73% for improved UASB. This was because the provision of mesh at the top helped to retain granular biomass in the improved UASB compared with conventional UASB. Saghir and Hajjar (2018) studied the effect of HRT on COD removal efficiencies while treating slaughterhouse wastewater with UASB and found 24 hrs as the optimum HRT. The authors pointed out that the COD removal efficiencies increase with the increase in HRT which in turn related to the upflow velocity within the reactor. Lower HRTs increase the upflow velocity and as a result, biomass tends to escape from the reactor. The upflow velocity during the study period was below 0.32 m/hr. Chollom et al. (2018) studied the effect of OLR and HRT while treating slaughterhouse wastewater in

Table 3 Similarities and differences between anaerobic treatment technologies

Anaerobic treatment technology	Hydraulic flow; electricity requirement; biological growth; clogging problems; sedimentation	Advantages	Disadvantages	Precautionary measures
UASB	Upflow; pumping; suspended; no; often provided	Microorganisms attach themselves to form granules having high settleablity, which form the core of the sludge blanket at the bottom and retain sludge within the reactor (Lettinga and Vinken 1980; Rajeshwari et al. 2000)	Operational limitations like delay in start-up and granule formation may occur since granules development is a function of pH, upflow velocity, and nutrients.	"V_{up}" needs to be maintained within the range of 0.6 to 0.9 m/hr to favor granule formation. During the start-up phase, sufficiently higher "V_{up}" should be maintained to wash out non-flocculant sludge (Metcalf and Eddy 2003)
ABR	Alternate upflow-downflow; pumping; suspended; no; no	ABR can act as a two-phase system since it separates acidogenesis and methanogenesis lengthwise down the reactor (Weiland and Rozzi 1991) It avoids the common problems of clogging and expansion of the sludge bed (Manariotis and Grigoropoulos 2002).	Start-up time is longer and volatile fatty acid' (VFA) accumulation within the reactor(Liu et al. 2020)	During the start-up phase, loading should be kept sufficiently low to allow slow-growing microorganisms to acclimatize with the surrounding environment. The recommended initial loading rate is approximately 1.2 kg COD/m^3.d (Henze and Harremoës 1983)
AF	Upflow/Downflow; pumping; fixed film; yes; no	Locally available media can be used such as volcanic rocks to reduce the media cost (Escalante-Estrada et al. 2019)	The cost of the media may be an additional expenditure. Possibility of short-circuiting caused by clogging and channeling.	While selecting a media a balance needs to be maintained between specific surface area and porosity.
AFBBR	Upflow; pumping and fluidization/-recirculation; fixed film on media and media in suspension; no; no	Fluidization also helps to encounter operational difficulties such as clogging of beds and pressure loss, which is normally the case in the anaerobic fixed filters (Fernández et al. 2008)	Increased energy consumption due to high effluent recirculation ratio; lack of uniform fluidization through liquid distributors; long start-up time etc. (Heijnen et al. 1989)	At longer HRTs, biomass grows largely in suspension and moderately in the biofilm, (Murray 1984; Salonen et al. 1983). At shorter HRTs, biomass is completely in the form of attached growth. (Heijnen 1984; Bull et al. 1984). Thus, thought should be given to HRT and upflow velocity while designing.
AHR	Upflow; pumping; suspended in lower portion and fixed film in upper portion; yes; no	Reduction in the cost of media, minimization in the risk of channeling and improvisation in solid retention (Bello-Mendoza and Castillo-Rivera 1998; Jafarzadeh et al. 2013)	Possibilities of plugging at high OLR and SS concentrations (Tufaner and Demirci 2020)	While placing media in the upper portion of the reactor, utmost care should be taken so that at any point of time, the media should not fall to the bottom. If it happens, the very purpose of AHR will not be fulfilled.
AnSBR	Stationary flow; pumping and mixing; suspended; no; yes (within the same reactor)	AnSBR can be loaded during the day and reaction taking place at night. No requirement of parallel AnSBR basin unlike their aerobic counterpart	Granule formation is a slow step and may take five to ten months and thus long start-up period of AnSBR can be regarded as one of the disadvantages of the process (Sung and Dague 1995; Wirtz and Dague 1996)	Mixing should be gentle such that no harm is caused to bacterial flocs and biomass shall remain in suspension to promote mass transfer (Akil and Jayanthi 2012; Pinho et al. 2004).
AnMBR	Upflow; pumping and solids-liquid separation using membranes; suspended; yes; fouling of membranes; no	An AnMBR removes all suspended solids and thereby results in complete retention of biomass. Pathogenic microorganisms are removed thus avoiding the need for disinfection (Dereli et al. 2012)	AnMBR is a promising technology, but its initial capital cost due to the membranes is in the range of 72% of capital cost (Lin et al. 2011)	Provision of gas sparging to reduce the membrane fouling shall be done (Aslam and Kim 2017; Paçal et al. 2019)

Table 4 Performance of UASB reactor treating slaughterhouse wastewater

Sr. no	Influent COD mg/L	OLR, kg COD/m^3.d	HRT hrs/d	Effluent COD mg/L	COD removal efficiency (%)	Biogas yield	Methane percentage (%)	Reference
1	1100–7250	3.5	10 hrs	330–2200	70	280 mL of methane/g COD removed		Manjunath et al. (2000)
2	2600	–	18 hrs	1140	56	–		Saghir and Hajjar (2018)
	5350	–	24 hrs	1439	73	–		
	4700	–	30 hrs	1112	76	–		
3	1630–1670	0.27	6 d	245	85	0.49 L/g of COD removed	High methane content of 75	Kwarciak-kozłowska et al. (2011)
		0.4	4 d	295	81	0.49 L/g of COD removed		
		0.55	3 d	350	78	0.45 L/g of COD removed		
		0.82	2 d	573	65	0.41 L/g of COD removed		
4	1086	2.5–4	9 hrs	488.7	56	40% COD converted to methane		Sayed et al. (1987)
	1310	6– 6.2	5 hrs	615.7	54	65% COD converted to methane		
	2724	11–16	5 hrs	1225.8	52	41% COD converted to methane		
5	5200–11400	1.03 ± 0.1	6.5 ± 0.5 d	585 ± 0.1	91.3 ± 0.8	0.22 ± 0.03 m^3/m^3 digester/d	56.4 ± 5.6	Veiga et al. (1997)
		2.92 ± 0.3	2.8 ± 0.2 d	896 ± 380	89.5 ± 4.5	0.69 ± 0.03 m^3/m^3 digester/d	61.2 ± 3.5	
		5.15 ± 1.3	1.7 ± 0.1 d	2244 ± 473	74.5 ± 5.0	1.17 ± 0.07 m^3/m^3 digester/d	58.9 ± 2.0	
		at OLR of more than 5 kg COD/m^3.d, reactor's performance was declined						
6	2800 ± 116	3.0 ± 0.2	22 hrs	470 ± 94	83.2 ± 3.2	0.555 ± 0.022 L biogas/g COD removed		Caixeta et al. (2002)
	3500 ± 135	6 ± 0.2	18 hrs	820 ± 26	76.6 ± 0.8	–		
	6500 ± 400	8.7 ± 0.5	18 hrs	610 ± 70	90.6 ± 1.1	0.192 ± 0.002 L biogas/g COD removed		
7	3143 ± 661	13 ± 2.9	7.1 hrs	–	76 ± 9	200-280 L methane/kg of SCOD removed was observed		Torkian et al. (2003)*
	3695 ± 662	16.7 ± 3.3	6.8 hrs		75 ± 12			
	4153 ± 364	17.4 ± 1.1	6.7 hrs		85 ± 6			
	4288 ± 564	27.4 ± 4.8	4.1 hrs		85 ± 8			
8	10,000	5	24 hrs	1000	90	–		Ali Musa et al. (2019)
	20,000	10		9200	54			
	28,000	14		14000	50			
9#	10,000	5		600	94			
	20,000	10		1200	95			
	28,000	14		7560	73			
10	1700	3.94	10 hrs	170	90	0.19 L CH_4/L reactor d		Vidal et al. (2019)
	3500	8.15		1015	71	0.35 L CH_4/L reactor d		

*All values are for soluble COD

#Studies were done with improved UASB (provision of flat round PVC mesh at the top)

UASB reactor and suggested the optimum HRT and OLR as 18 hrs and 7 kg COD/m^3.d. Vidal et al. (2019) achieved COD removal efficiencies of 90 and 70% at OLRs of 3.94 and 8.15 kg COD/m^3.d at HRT of 10 hrs.

Anaerobic baffled reactor

Anaerobic baffled reactor (ABR) uses a sequence of baffles to treat wastewater that passes over and under the baffles. The upflow velocity in chambers is maintained below 0.6 m/hr and the numbers of chambers are usually between 3 and 6. Chambers can be connected either with vertical pipes or baffles. ABRs can handle both low-strength wastewater (300 mg/L of COD) with 95% removal efficiency at 10-hr HRT and high-strength wastewater (5000 mg/L COD) with 94% removal efficiency at 6-hr HRT (Bachmann et al. 1985; Stuckey 2010). Various studies carried out to assess the performance of ABR for treating slaughterhouse wastewater is presented in Table 5.

Cao and Mehrvar (2011) found COD removal efficiency of 97.65% at HRT of 3.8 d and OLR of 0.62 kg COD/m^3.d. It was observed that more than 90% of COD removal efficiency was obtained after the first two compartments. The authors reported that COD removal efficiencies decrease with the decrease in HRT. It was found that when HRT was lowered down to 0.9 d; COD removal efficiency dropped to less than 60%. Polprasert et al. (1992) conducted experiments using ABR to treat dissolved air flotation pre-treated slaughterhouse wastewater. The study showed that at OLR of 0.87 kg COD/m^3.d, COD removal efficiency was 90% and progressively reduced with increase in OLR and decrease in HRT. During the experiments, alkalinity varied between 498 and 544 mg/L using $CaCO_3$ as the indicator. Al Smadi et al. (2019) operated the ABR to treat slaughterhouse wastewater at OLR of 0.65 kg COD/m^3.d and HRT of 16 hrs and achieved COD removal efficiencies of 75 to 84%. It is to be noted that the COD concentration in studies conducted by Al Smadi et al. (2019) and Polprasert et al. (1992) was in the range of only 320 to 550 mg/L as against 2302.5 mg/L in the case of Cao and Mehrvar (2011). Bustillo-Lecompte and Mehrvar (2017) found COD removal efficiencies of more than 90% at OLR of 0.24 kg COD/m^3.d and HRT of 8 hrs. Literature survey indicated that the studies on ABRs to treat slaughterhouse wastewater were performed with low-strength slaughterhouse wastewater with a maximum COD concentration up to 2302.5 mg/L and OLR of 4.73 kg COD/m^3.d except for Yousefi et al. (2018) wherein ABR was operated at higher OLR of 7 and 10 kg COD/m^3.d. The authors recommended the optimum OLR as 7 kg COD/m^3.d and HRT of 18 hrs for ABRs treating slaughterhouse wastewater. However, the COD concentration during the study period varied between 2000 and 10,000 mg/L. Thus, it is hard to find for how long period ABR was subjected to COD concentration of 10,000 mg/L. It appears that for a low-strength slaughterhouse wastewater, ABRs can be convenient. After primary treatment, if wastewater characteristics are in the range mentioned in Table 5, ABRs can be a suitable alternative. Researchers have also reported that significant COD reduction occurs in the first two to three chambers (75 to more than 90%). Thus, while designing ABRs, the number of chambers should be given consideration.

Table 5 Performance of ABR treating slaughterhouse wastewater

Sr. no	No. of chambers	Influent COD mg/L	OLR, kg COD/m^3.d	Upflow velocity cm/hr	HRT (hrs)	Effluent COD mg/L	COD removal efficiency (%)	Remarks	Reference
1	Four	2302.5	0.62	-	3.8 d	53.9	97.65	More than 90% COD removal efficiency was achieved after 2nd compartment	Cao and Mehrvar (2011)
2	Five	320–500	0.65	–	16	79.5	75 to 84%	Significant COD reduction in first three compartments	Al Smadi et al. (2019)
3	Four	490	0.87	24	13.6	50	90%	Significant COD reduction occurred in first two compartment (Nearly 75 to 80%)	Polprasert et al. (1992)
		550	1.82	1 to 17	7.2	110	82%		
		520	2.14		5.8	150	75%		
		510	4.73		2.5	130	72%		
4	Five	1950	0.24	–	8	205.64 ± 6.43	90%	–	Bustillo-Lecompte and Mehrvar (2017)
5	Four	2000–10,000	4	–	18	–	78.13	–	Yousefi et al. (2018)
			7	–	18	–	83.29	–	
			10	–	18	–	83.19	–	

Anaerobic filter

It is an attached growth contact process where wastewater passes over or through the fixed media as shown in Fig. 1 which favors microbial growth because of its high specific surface area. The choice of support media has a substantial influence on the rate of attachment and growth of bacteria (Show and Tay 1999). The surface of the media is an important element since the support media with a high surface roughness accelerates biofilm development, when compared to support media with a smooth surface (Cordoba and Sineriz 1990). Anaerobic filters (AF) can be run in both upflow manner and downflow manner with similar COD removal efficiencies (Fia et al. 2012). The performance of AF using different media to treat slaughterhouse wastewater is shown in Table 6.

Sindhu and Meera (2012) evaluated the working of upflow AF packed with randomly placed PVC pipes on moderately strong slaughterhouse wastewater (COD of 4000–5000 mg/L). The authors reported that COD reduction in the reactor was attained in two ways. Firstly, due to the settling of suspended solids and secondly due to anaerobic biological degradation. At higher OLRs, VFA/Alkalinity ratio increased beyond 0.4. A higher VFA/Alkalinity ratio indicates the accumulation of VFAs and a drop in pH of the reactor (Ciotola et al. 2014). Veiga et al. (1997) worked on AF filled with corrugated PVC Raschig rings to treat slaughterhouse wastewater having strong characteristics (COD of 5200 to 11400 mg/L of which nearly 70% were proteins, because blood was not recovered as a byproduct and mixed in the main stream). Ammonia produced during hydrolysis of proteins might have an inhibitory effect on methanogenic bacteria and as a consequence methanogenic rates are lower than acidification rates. The reactor performed well and achieved good COD removal efficiencies, i.e., 82.3 ± 2.5% at OLR of 1.45 ± 0.2 kg COD/m^3.d and 63.6 ± 6.4% at OLR of 5.26 ± 0.2 kg COD/m^3.d with no need to artificially regulate the pH. Kocadagistan (2014) used pumice stone as filter media to treat slaughterhouse wastewater and obtained 80% COD removal efficiency at OLR of 2.11 kg COD/m^3.d and HRT of 45–50 hrs. Gannoun et al. (2009) also achieved COD removal efficiency of more than 80% up to OLR of 4. 5 kg COD/m^3.d, and found decreased biogas yield at increased OLR of 6 kg COD/m^3.d. Ammonium concentration in the effluent was increased to 1270 ± 180 mg/L due to protein hydrolysis and ammonification rates since TKN in raw abattoir wastewater in this study was 530 to 810 mg/L which was approximately 9 to 13% of total COD. Giri et al. (2015) used an ultraviolet-stabilized media matrix having a specific surface area of 400 m^2/m^3 and a void ratio of 80%. The study showed good COD removal efficiencies of more than 85% at OLR of 0.8 to 3.2 kg COD/m^3.d at HRT of 24 hrs. León-Becerril et al. (2016) operated AF filled with spherical plastic media having a high specific area of 3600 m^2/m^3 and void volume of 95% for treating slaughterhouse wastewater. The study found that at OLR of 1.17 to 3.5 kg COD/m^3.d and HRT of 24 hrs, the initial COD concentration of 3500 mg/L was reduced to 500 mg/L. The OLR and HRT in the case of Giri et al. (2015) and León-Becerril et al. (2016) were almost the same, i.e., 3.2 to 3.5 kg COD/m^3.d and 24 hrs respectively. However, AF in the study done by León-Becerril et al. (2016) performed comparatively better. The reason can be attributed to the media used by León-Becerril et al. (2016) which provided a greater surface area for microbial attachment and in turn increased microbial concentration. Langone et al. (2019) treated blood serum water from the slaughterhouse with upflow AF and found more than 90% COD removal efficiency at OLR of 2 to 2.5 kg COD/m^3.d and HRT of 72 hrs. The specific surface area of media used in this study was 100 m^2/m^3. It is important to note that the performance of AFs decline at higher OLRs of 5 to 6 kg COD/m^3.d while treating slaughterhouse wastewater and results in biomass washout, increased acidification and loss of methanogenic activity (Sindhu and Meera 2012; Veiga et al. 1997; Kocadagistan 2014; Gannoun et al. 2009). However, the provision of a sedimentation tank ahead of AF may help to improve the COD removal efficiency. The same is demonstrated by Escalante-Estrada et al. 2019. The studies were conducted at higher OLRs of 9.7 ± 4.5 and 14.6 ± 5.9 kg COD/m^3.d at HRT of 9.6 ± 2.1 hrs and achieved COD removal efficiency of 55 to 60%. However, it is important to mention here that the COD removal efficiencies while operating AF at OLR less than 5 kg COD/m^3.d were well above 80% while

Fig. 1 Different media used in anaerobic filters (photographs by authors)

Table 6 Performance of anaerobic filter treating slaughterhouse wastewater

Sr. no	Media used	Influent COD (mg/L)	OLR, kg COD/m^3.d	HRT (hrs)	Effluent COD (mg/L)	COD removal efficiency (%)	Biogas yield	Methane percentage (%)	Reference
1	Randomly packed PVC pipe pieces	4000–5000	4 to 5	24	less than 900 mg/L	87 to 88	350 mL/g of COD removed	50–60	Sindhu and Meera (2012)
			5 to 6	18		82 to 85			
			At higher OLR (7.2 and 8.5 kg COD/m^3.d; VFA/alkalinity ratio exceeded 0.4)						
2	packed with corrugated PVC Raschig rings	5200–11400	1.45 ± 0.2	96 ± 4.8	1040 ± 161	82.3 ± 2.5	0.20 ± 0.05 m^3/m^3 digester/d	36.4 ± 8	Veiga et al. (1997)
			2.96 ± 0.1	50.4 ± 2.4	1785 ± 450	71.2 ± 8.5	0.57 ± 0.05 m^3/m^3 digester/d	61.2 ± 3.5	
			5.26 ± 0.2	38.4 ± 2.4	3056 ± 200	63.6 ± 6.4	0.95 ± 0.04 m^3/m^3 digester/d	58.9 ± 2.0	
			at OLR of more than 5 kg COD/m^3.d, reactor’s performance was declined						
3	Pumice stones	1000	2.11	45–50	200	80	–	–	Kocadagistan (2014)
		2200	4.65	45–50	500	77			
			at OLR of more than 5 kg COD/m^3.d, reactor’s performance was declined						
4	Flocor media	5800–6200	0.9	120	500–600	90–92	0.27–0.3 L/g of COD removed	77 ± 2.1	Gannoun et al. (2009)
			2.8	39.84	500–600	90–92	0.3–0.4 L/g of COD removed	72 ± 2	
			4.5	24	800–1200	80–85	0.25–0.28 L/g of COD removed	68 ± 2.3	
			6.075	18	1100–1400	77–80	> 0.2 L/g of COD removed	65 ± 3.1	
			at OLR of more than 6 kg COD/m^3.d, reactor’s performance was declined						
5	Ultraviolet-stabilized media matrix	804	0.8	24	66	91.80	0.295 m^3/kg COD added		Giri et al. (2015)
		1596	1.6		166	89.60	0.264 m^3/kg COD added		
		2401	2.4		293	87.80	0.226 m^3/kg COD added		
		3205	3.2		468	85.40	0.196 m^3/kg COD added		
6*	Tezontle (volcanic rock)	8968 ± 5382	5.3 ± 3	19.2 ± 2.4	–	60 ± 15%	–		Escalante-Estrada et al. (2019)
		4944 ± 1499	9.7 ± 4.5	9.6 ± 2.1	–	55 ± 18%			
		8842 ± 3891	14.6 ± 5.9	9.6 ± 2.1	–	59 ± 15%			
7	Spherical plastic media	3500	1.17 to 3.5	24	550	84.28 ± 1.73%	0.246 to 0.428 L/g of COD removed		León-Becerril et al. (2016)
8**	Plastic-corrugated cylinders	700–2500	0.18–2.5	24	–	77%	–		Langone et al. (2019)
		2500–4000	1.25–2	48	–	85–90%	–		
		6000–7500	2–2.5	72	–	More than 90%	0.52 ± 0.05 m^3/kg of COD removed		

*UAF coupled with settler

**Studies done with blood serum water

initial COD concentration was less than 5000 mg/L. At higher OLR in the case of Escalante-Estrada et al. 2019, COD removal efficiencies were limited to 60% even after the provision of the settling tank.

Anaerobic fluidized bed biofilm reactor

Anaerobic fluidized bed biofilm reactor (AFBBR) is an advancement in the attached growth process that employs small, inert, fluidized media for cell immobilization and retention. Upflow velocity should be maintained such that the higher shear forces caused by higher velocity should not disturb the biofilm layer over carrier media. Upflow velocities between 5 and 35 m/hr are considered adequate to prevent any damage to media by shear forces. A literature review indicated that very few studies have been carried out using AFBBR for treating slaughterhouse wastewater and one such study is presented in Table 7.

Borja et al. (1995) evaluated the performance of AFBBR over a wide range of OLRs to treat slaughterhouse wastewater. Bentonite clay was used as a support growth medium to facilitate bacterial growth. It was found that at OLR of 2.9 to 54 kg COD/m^3.d and HRT between 0.4 and 8 hrs; COD removal efficiencies obtained are in the range of 75 to 98%. The impressive performance of AFBBR at higher OLR was attributed to its potential to retain virtually all the biomass in the form of biofilm, increased surface area of bentonite media for microbial attachment, and reduced possibility of biomass washout due to the maintenance of adequate buffering capacity in the form of alkalinity. The study revealed that AFBBRs can achieve 75% COD removal efficiency at OLR of 54 kg COD/m^3.d, and provided alkalinity is maintained at 2500 mg/L. VFAs at this OLR was also less than 1000 mg/L, thus maintaining the VFA/alkalinity ratio below 0.4. Similarly, Stephenson and Lester (1985) worked on AFBBR using silica sand as a support media and achieved COD removal efficiency of 76% for slaughterhouse wastewater with initial COD concentration of 5000 mg/L at OLR of 9.5 kg COD/m^3.d. Concerning AFBBR, no recent studies to treat slaughterhouse wastewater were found. However, from the results, it seems that the AFBBR can prove to be beneficial to treat slaughterhouse wastewater at higher OLRs.

Anaerobic hybrid reactor

The anaerobic hybrid reactor (AHR) is a hybrid of suspended and attached anaerobic processes. It combines UASB with that of AF wherein the lower part of the reactor acts as UASB and the upper portion consists of fixed media for biomass attachment.

In a conventional UASB reactor, the upper portion of the reactor normally lacks a biomass/sludge blanket; whereas in AHR, the upper portion consists of filter media that provides

Table 7 Performance of AFBBR treating slaughterhouse wastewater

Sr. no	Support material characteristics	Bed expansion	Influent COD (mg/L)	OLR, kg COD/m^3.d	HRT (hrs)	COD removal efficiency (%)	Biogas yield and methane percentage (%)	Reference
1	Bentonite clay specific surface area = 250 m^2/g, porosity 63%	Bed Expansion 40% was maintained by effluent recycle	250	2.9 to 54	0.4 to 0.6	75 to 98	Up to about 0.32 L of methane produced per g of COD removed.	Borja et al. (1995)
			500		0.8 to.1			
			1000		1 to 6		Methane content decreased from 78 to 59% when OLR was increased from 2.9 to 54 kg COD/m^3.d	
			2000		1.5 to 8			
			3000 to 4500		2 to 8			
2	0.27-mm silica sand	Bed expansion 30% was maintained by effluent recycle	2500	1.8	–	70	Methane content 55%	Stephenson and Lester (1986)
			3750	4.8	–	71	Methane content 67%	
			5000	9.5	–	76	Methane content 78%	

Table 8 Performance of AHR treating slaughterhouse wastewater

Sr. no	Type	Media characteristics	Placing of media	Influent COD (mg/L)	OLR, kg COD/m^3.d	HRT (hrs)	Packing media COD removal efficiency (%)	Overall COD removal efficiency (%)	Biogas yield	Reference
1	Self-supporting cylindrical shaped with internal ribs and concentric section	Surface area = 100 m^2/m^3 Voidage > 95%	–	1060	0.998–1.06	24	–	93.58	0.326 m^3/kg COD added	Sunder and Satyanarayan (2013)
				2000		48		94.80	0.338 m^3/kg COD added	
				4048	3.98–4.11	24		89.60	0.286 m^3/kg COD added	
				7976		48		91.60	0.292 m^3/kg COD added	
				6014	6–6.02	24		86	0.268 m^3/kg COD added	
				11,974		48		88.10	0.276 m^3/kg COD added	
2	Polyurethane foam in the form of small cubes	Voidage = 50%	Top 1/3rd of the reactor was filled with media	10,410	7.71	32.4	18	95.9	–	Borja et al. (1998)
					10.41	24	33	95		
					13.88	18	35	93.9		
					20.82	12	32	93.4	0.345 L CH_4/g COD removed	
3	Cuttings from PVC pipes	Voidage = 85%	Top 1/2 of the reactor was filled with media	2060–3280	2.74–4.37	18		80	–	Farooqi et al. (2009)
				1620–3280	3.24–6.56	12				
				2400–4200	7.2–12.6	8				
4*	Pleated PVC rings	Surface area = 267 m^2/m^3 Voidage > 98.8%	top 1/3rd of the reactor was filled with media	3000–4800	9.27	10	3 to 11.5	86	0.32 m^3/kg COD removed	Rajakumar et al. (2012)
5	Hexagonal shaped filter media	specific surface area of 6700 m^2/m^3 = porosity = 80%	–	16,910	3.03–38.19	6–24	–	80-90	–	Loganath and Mazumder (2020)

*Values represents SCOD influent concentration and SCOD loading rate in kg SCOD/m^3 .d additional surface area for biomass attachment resulting in higher biomass retention. There is no fixed ratio of keeping the suspended/sludge and fixed film zone in AHR. Studies carried out using various media arrangements to treat slaughterhouse wastewater are presented in Table 8.

Sunder and Satyanarayan (2013) studied AHR to treat slaughterhouse wastewater and observed that with the increase in HRT, COD removal efficiency was also increased even at slightly higher OLR of 6 kg COD/m^3.d. However, the study suggested no further increase in HRT, as it will not be economical. In a similar study carried out by Borja et al. (1998), polyurethane foam in the form of small cubes was used as a media in the top 1/3rd portion of the reactor. This study using AHR showed promising results even at higher OLRs of 20.82 kg COD/m^3.d and at HRTs of 12 hrs. However, it is imperative to mention that the COD removal efficiency of packing media was between 18 and 35% suggesting that packed bed material has certainly some effect over COD removal. Moreover, the packing medium also contained a substantial amount of biomass of approximately 5000 mg of VSS/L, and the total biomass in the reactor was between 10.10 and 10.50 g VSS/L. Farooqi et al. (2009) used PVC pipes as a packing medium and placed them in the upper half portion of the reactor. The study showed that more than 80% COD removal efficiency over a wide range of OLRs, i.e., 2.74 to 12.6 kg COD/m^3.d. Rajakumar et al. (2012) evaluated the performance of AHR and found that OLR of 9.27 kg COD/m^3.d to be optimum at an HRT of 10 hrs, with overall COD removal efficiency of 86%. Residence time distribution (RTD) studies indicated that the dispersion number (D/μL) was 0.22 reflecting that there was a mixed flow pattern. This was attributed to the improved mixing in the sludge bed zone due to increased upflow velocity at shorter HRTs, reduction in clogging, and channeling due to packing media and increased gas production with reduced dead zones. Similar findings of improved mixing in the reactor due to an increase in upflow velocity in AHRs while treating slaughterhouse wastewater were mentioned by Borja et al. (1998), which ultimately led to even distribution of organic load on biomass. However, contrary to Borja et al. (1998), COD removal efficiency of packing media in the case of a study conducted by Rajakumar et al. (2012) was only 3 to 11.5% indicating packing media have a moderate effect on COD removal. The variations in removal efficiencies due to packing media can be attributed to the difference in media configurations and their biomass retaining capacities. Loganath and Mazumder (2020) carried out the studies using AHR to treat slaughterhouse wastewater by using media having a high specific area surface of 6700 m^2/m^3. Even at a high COD loading rate of 18.75 kg COD/m^3.d and HRT of 10 hrs, COD removal efficiency was around 95%. The results presented by Longanath and Mazumder (2020) indicate that the high specific surface area of the media has a positive effect on overall COD removal efficiency. It is noteworthy to mention that an AHR can operate at higher OLRs of more than 5 kg COD/m^3.d, unlike UASBs and AFs wherein reactor performance declined at OLRs greater than 5 kg COD/m^3.d (Veiga et al. 1997; Sindhu and Meera 2012; Veiga et al. 1997; Kocadagistan 2014; Gannoun et al. 2009).

Anaerobic sequential batch reactor

Anaerobic sequential batch process (AnSBR) is carried out in a single vessel under anaerobic conditions and is operated in a series of sequences, i.e., fill, react, settle, and decant. Since the AnSBR is a batch process, the problem of short-circuiting which is a common problem in other anaerobic technologies is avoided (Dahlan et al. 2013) and especially for slaughtering operations, AnSBR can be loaded during the day and reaction can take place at night. The maximum recommended OLRs are 4.5 kg COD/m^3.d for dilute wastewater and 6 kg COD/m^3.d in the case of concentrated effluent (Ruiz et al. 2001). The performance of AnSBR for treating slaughterhouse wastewater is shown in Table 9.

Myra et al. (2015) evaluated AnSBR for treating slaughterhouse wastewater with the influent COD between 1316 and 2080 mg/L and HRT of 16 hrs which resulted in COD removal efficiency of 96%. Masse and Masse (2000) compared the performance of AnSBR in two different scenarios wherein one set of reactors was inoculated with granulated sludge and the other with non-granulated sludge. At an OLR of 1.1 to 11.5 kg COD/m^3.d and constant HRT of 41 hrs, COD removal efficiencies were 78 to 95% for reactors inoculated with granulated sludge and 79 to 97% for reactors inoculated with non-granulated sludge. The study also showed good solid-liquid separation and TSS concentration in the effluent from AnSBR was as low as 347 (granulated sludge) and 233 mg/L (non-granulated sludge) resulting in 87 and 91% TSS removal efficiency, respectively. Handous et al. (2017) studied AnSBR at OLR of 0.8 to 3.2 kg VS/m^3.d and achieved maximum VS removal efficiency of 84% at OLR of 1.5 kg VS/m^3.d with the reaction period of 21 hrs. Mutua et al. (2016) studied AnSBR to treat high-strength slaughterhouse wastewater having COD concentration of 15812 ± 241 mg/L and achieved 79% COD removal efficiency at OLR of 12.8 kg COD/m^3.d.

Anaerobic membrane bioreactor

Anaerobic membrane bioreactor (AnMBR) is a promising treatment technology, and membrane fouling is the major hurdle or limitation in their widespread application (Dvořák et al. 2016; Gao et al. 2010). The performance of AnMBR with different membranes and at various flux rates to treat slaughterhouse wastewater is presented in Table 10.

Table 9 Performance of AnSBR treating slaughterhouse wastewater

Sr. no	Type	Influent COD (mg/L)	OLR, kg COD/m^3.d	Cycles	Effluent COD (mg/L)	COD removal efficiency (%)	Reference
1	Inoculum: granulated sludge	1316–2080	—	Filling:0.5 hrs Reaction: 16 hrs Settling: 7 hrs Decanting: 0.5 hrs	60-–99	96	Myra et al. (2015)
2	Inoculum: granulated sludge	6908	Loading was slowly increased from 1.1 to 11.5	Filling:01 hrs	1511	78	Masse et al. (2000)
		9665		Reaction: 41 hrs	1842	81	
		11,530			601	95	
	Inoculum: non-granulated sludge	6908			1450	79	
		9665			880	91	
		11530			365	97	
3	–	VS (% of fresh matter) 7 ± 0.9	0.8 kg VS/m^3.d	Filling:0.25 hrs Reaction: 21 hrs	VS removal efficiency 75%		Handous et al. (2017)
			1.6 kg VS/m^3.d		VS removal efficiency 84%		
			3.2 kg VS/m^3.d	Settling: 2.5 hrs Decanting: 0.25 hrs	VS removal efficiency 69%		
4	–	15812 ± 241	12.8	Filling:0.3 hrs Reaction: 41 hrs Decanting: 0.3 hrs	3554 ± 58	79	Mutua et al. (2016)

Table 10 Performance of AnMBR treating slaughterhouse wastewater

Sr. no	Membrane information	Permeate flux (L/m^2.hr)	Influent COD (mg/L)	OLR, kg COD/m^3.d	HRT (hrs/d)	Effluent COD (mg/L)	COD removal efficiency (%)	Reference
1	0.1 µm (polypropylene)	< 2, during most of the study period	4000–4600	4	24 hrs	250–400	90–95	Aslan et al. (2013)
2	Zenon ZW-10 Hollow fiber membrane	3 to 7	10,604	3–3.5	4 to 7 d	183	98	Jensen et al. (2015)
3	Stork WFFX 0281	Avg. 2.22	12330 ± 2310	4.37 ± 0.3	3.33 d	445 ± 20	96.4 ± 0.75	Saddoud and Sayadi (2007)
			12430 ± 3180	5.92 ± 1.28	2.5 d	1175 ± 320	90.6 ± 2.65	
			10174 ± 3310	8.23 ± 2.5	1.66 d	338 ± 60	94 ± 2.12	
			13270 ± 2600	13.27 ± 2.6	1.25 d	4556 ± 1350	62 ± 1.9	
4	Hollow fiber membrane	1.14 ± 0.02	2254 ± 1074	0.44 ± 0.2	5 d	412	–	Galib (2014)
		3.15 ± 0.04	2804 ± 723	1.43 ± 0.4	2 d	830	–	
		6.15 ± 0.37	2986 ± 971	3.14 ± 1.1	1 d	2354	–	
5	Zenon ZW-10 Hollow fiber membrane	3 to 7	11,536	3–4	3 to 7 d	325	97	Jensen (2017)

Aslan et al. (2013) studied AnMBR to treat slaughterhouse wastewater, wherein polypropylene membranes with a pore size of 0.1 μm were used and operated at HRT of 24 hrs and OLR of 4 kg COD/m^3.d. Under these operating conditions, COD removal efficiency varied between 90 and 95%. The authors in this study observed a decrease in membrane flux due to the formation of cake over the membrane surface. It is imperative to mention that the provision of gas sparging was not done in this study.

To disrupt the formation of cake on the membrane surface, biogas collected in the head spacer is recycled back below the membrane. The gas bubble shear off the bio-solids from the membrane surface prevents possible fouling of the membrane (Vyrides and Stuckey 2011; Casu et al. 2012). As the gas passes across the membrane surface, it creates shear and encourages membrane cleaning. When lift exceeds drag (low flux), fouling levels are low and sustainable. When drag exceeds lift, fouling is accelerated and operator intervention is required.

Studies conducted by Jensen et al. (2015) were done with the provision of gas sparging and operating an AnMBR at a high flux rate of 3 to 7 L/m^2.hr to achieve a COD removal efficiency of 98%. The authors found membrane fouling was quite low while treating slaughterhouse wastewater. This study suggested maintaining the biomass concentration below 20,000 mg/L to avoid membrane fouling. Saddoud and Sayadi (2007) conducted studies on high-strength slaughterhouse wastewater using AnMBR and found that the reactor performance drastically reduced at OLR of more than 13.27 ± 2.6 kg COD/m^3.d due to excess accumulation of VFAs. The biomass concentration during this study period was 10,100 mg VS/L. Galib (2014) studied AnMBR for treatment of slaughterhouse wastewater and found that the reactor performance declined at OLR of 3.14 ± 1.1 kg COD/m^3.d and HRT of 1 d. The MLSS concentration during the entire study period varied between 2000 and 2600 mg/L which is very less as compared with the values reported by other researchers. Despite such a low MLSS concentration, the membranes suffered fouling. This indicates membranes can also be fouled at low MLSS concentrations. Jensen et al. (2017) conducted studies with high-strength slaughterhouse wastewater at low OLRs and longer HRTs and achieved COD removal efficiency of 97%. The study recommended keeping the MLSS concentration of less than 40,000 mg/L to avoid membrane fouling and reported constant permeate flux rate when MLSS concentration was 30,000 mg/L. The study was conducted at HRT of 3 to 7 d. It is important to note that the SCOD was just 16% of the total COD. As a result, such long HRTs might have been required to degrade non-soluble COD. Although AnMBR is a promising technology to treat slaughterhouse wastewater, its initial capital cost due to the membranes is in the range of 72% of capital cost (Lin et al. 2011) thus indicating its non-viability.

Discussion

Upflow velocity in anaerobic reactors govern the reactor's performance since high values are associated with a reduction in HRT that causes the smashing of sludge granules and biomass washout. On the other hand, lower upflow velocities result in uneven distribution of organic load and formation of dead spaces (Torkian et al. 2003; Daud et al. 2018; Borja et al. 1998). However, the upflow velocity is case specific and depends upon the type of reactor being used for the treatment of slaughterhouse wastewater. UASBs can be operated with "V"$_{up}$ between 0.6 and 0.9 m/hr and an increase in "V"$_{up}$ beyond 0.9 m/hr results in biomass washout, reduction in COD removal efficiency, and biogas yield. At the same time, "V"$_{up}$ can be slightly increased in the case of AHR because of its specialty to arrest biomass from being washed out. On the contrary, "V"$_{up}$ in ABR is maintained below 0.6 m/hr since it has provisions of mixing within itself with the help of baffles/chambers. This helps to evenly distribute the organic load and avoid the formation of dead spaces within the reactor. In the case of AFBBR, higher velocities in the range of 5 to 35 m/hr have to be maintained to provide adequate fluidization of media by recycling of effluent.

The literature review for anaerobic treatment of slaughterhouse wastewater with different anaerobic reactors indicated that OLR is a crucial factor to determine the overall success of the treatment. As far as UASBs are concerned, the OLRs values up to 5 kg COD/m^3.d appear to be suitable to achieve more than 80% COD removal efficiencies (Veiga et al. 1997; Caixeta et al. 2002; Ali Musa et al. 2019; Vidal et al. 2019). UASBs can be operated at OLRs up to 8 kg COD/m^3.d providing sufficient HRT (18 hrs) is provided as demonstrated by Caixeta et al. (2002). OLRs above 8 kg COD/m^3.d may lead to a decline in the reactor's performance even at 24-hr HRT as reported by Ali Musa et al. (2019). For low-strength slaughterhouse wastewater with COD concentration below 500 mg/L, ABRs can be operated up to COD loading of 5 kg COD/m^3.d at HRT of 13 to 16 hrs to achieve COD removal efficiencies of more than 90% (Al Smadi et al. 2019; Polprasert et al. 1992). Slaughterhouse wastewater with COD concentration of 1950 mg/L can be managed with ABRs with 90% COD removal efficiencies at HRT of 8 hrs (Bustillo-Lecompte and Mehrvar 2017). For high-strength slaughterhouse wastewater with COD of 10000 mg/L, OLRs can be increased up to 10 kg COD/m^3.d provided 18-hr HRT is maintained (Yousefi et al. 2018). However, OLRs in the case of AFs are limited to 5 kg COD/m^3.d as reported by Veiga et al. 1997, Kocadagistan 2014, Gannoun et al. 2009, and Escalante-Estrada et al. 2019. It is important to note that the HRT in the case of AFs for treating slaughterhouse wastewater is maintained at 24 hrs (Sindhu and Meera 2012; Gannoun et al. 2009; Giri et al. 2015; León-Becerril et al. 2016; Langone et al. 2019). AFs, being an attached growth process, are operated at longer HRTs as compared with suspended growth processes like UASBs and ABRs. With regards to the quantification of biomass concentration in AFs treating slaughterhouse wastewater, no studies have been reported so far. Low biomass concentration in AFs as compared with suspended growth processes can also be one of the reasons limiting its operation beyond OLR of 5 kg COD/m^3.d. On the other hand, AFBBRs which is a blend of suspended and attached growth process can be operated at OLRs greater than 8 kg COD/m^3.d and HRT of 8 hrs and achieve more than 75% COD removal efficiencies (Borja et al. 1995; Stephenson and Lester 1986). However, studies to treat slaughterhouse wastewater with AFBBRs are limited and further research can certainly be helpful since the technology offers good COD removal efficiencies at higher OLRs and lower HRTs. This may reduce the reactor volume and thus the capital cost substantially. Although with the recurring cost for high recirculation ratios, operational difficulties to maintain uniform fluidization may limit its application. As compared with UASBs, ABRs, and AFs, the AHRs provide better COD removal efficiencies at higher OLRs and lower HRTs. AHRs can be operated at higher OLRs of 12 to 20 kg COD/m^3.d and HRTs of 8 to 12 hrs and achieve more than 80% COD removal efficiencies (Borja et al. 1998; Farooqi and Asifuzzaman 2009; Rajakumar et al. 2012). Provision of high specific surface area at the top portion of AHRs can also be beneficial to operate AHRs at higher OLRs up to 18.75 kg COD/m^3.d and HRT of 10 hrs as demonstrated by Loganath and Mazumder (2020). The selection of the packing media in the case of AFs or AHRs needs to be done with utmost care. Packing media with high specific surface area and low porosity may help to retain biomass within the reactor but may increase clogging of the media. On the contrary, a packing media with high specific surface area and high porosity reduce the clogging problems but the biomass retention within the reactor may be reduced. Thus, while selecting a media, a balance needs to be maintained between specific surface area and porosity. AnSBRs and AnMBRs are operated with continuous complete mixing. AnSBRs can be operated at higher OLRs of 11 to 13 kg COD/m^3.d and achieve COD removal efficiency of 79 to 97% as reported by Masse and Masse 2000, Mutua et al. 2016. However, in both the studies, HRT was maintained at 41 hrs, which is quite high as compared with UASBs, ABRs, AFs, AHRs, and AFBBRs. AnSBR is a reliable solution because of its flexibility to load during the day and react at night, thus avoiding the need for parallel SBR basins, unlike their aerobic counterparts. But in the case of slaughterhouse wastewater, this may not be the case. The minimum reaction period required is 41 hrs and hence a parallel AnSBR basin will be required for continuous operation. Similarly, higher HRTs are maintained in AnMBRs treating slaughterhouse wastewater. AnMBRs studied by Jensen et al. (2015), Saddoud and Sayadi (2007), Galib (2014), and Jensen et al. (2017) achieved COD removal efficiencies of more than 90% at HRTs of 2.5 to 7 d and OLRs of 3 to 8 kg COD/m^3.d.

Based on the discussion, it is reasonable to say that the AHRs may prove to be the most suitable option for managing slaughterhouse wastewater owing to its ability to operate at higher OLRs (8 to 20 kg COD/m^3.d) and lower HRTs (8 to 12 hrs). The cost of the packing media is certainly an additional expenditure as compared with conventional UASBs. Market survey indicated that the cost of round shaped polypropylene inert media having a specific surface area between 400 and 450 m^2/m^3 is around US$ 120.0–140.00 (Indian Rs. 9000 to 10,500) per cubic meter of media. A literature survey indicated that the AHRs were not studied with cross-flow filtration media which is arranged in a honeycomb fashion. The cross-flow filtration media has a specific surface area of 100 to 110 m^2/m^3 with a void ratio of more than 95% and costs around US$ 47.0–67.00 (Indian Rs. 3500 to 5000) per cubic meter of media. Alternatively, the locally available cheap material having a high specific surface area (Young and Yang 1989 suggested minimum 100 m^2/m^3) and porosity of at least 80% may be explored to overcome the cost constraints.

Slaughterhouse wastewater is characterized by the presence of high suspended solids contents, dissolved solids, organic load, and oil & grease concentrations. All these parameters are generated at various stages of the slaughtering process and show considerable variability. The authors feel that while carrying out the sampling from a slaughterhouse, a representative sample should be collected during its whole day of operation rather than a grab sample. In this article, the effect of OLRs and HRTs on COD removal efficiencies are discussed at length along with detailed physico-chemical characteristics of slaughterhouse wastewater, BMP, VFA/alkalinity ratios, biogas generation, and the effect of inhibitors such as O & G, sulfates. However, the effect of high concentrations of dissolved solids on anaerobic treatment of slaughterhouse wastewater needs to be addressed. Dissolved solids are introduced from the salts in the hide storage section, detergents/surfactants used for plant/equipment washing, and sanitizers for maintaining cleanliness. Moreover, the studies need to be carried out on primary treated wastewater rather than raw slaughterhouse wastewater. This will be helpful to realistically replicate the results of the studies on a field scale.

Conclusions

Anaerobic treatment of slaughterhouse wastewater is certainly an attractive option and presents techno-economic viability with value addition in terms of biogas generation and COD removal. Most of the anaerobic reactors can be safely operated at OLRs up to 5 kg COD/m^3.d to treat slaughterhouse wastewater without experiencing operational difficulties like biomass washout, acidification within the reactor, reduction in system efficiency and biogas generation. However, AHRs offer certain advantages to treat slaughterhouse wastewater as compared with other treatment technologies. AHRs can be operated at higher OLRs (8 to 20 kg COD/m^3.d) and lower HRTs (8 to 12 hrs). Exploring the low-cost media in AHRs that has high specific surface area and porosity may help to maintain the harmony between the capital investments and subsequent deliverables. Adequacy assessment of AHRs on a pilot or field scale on primary treated slaughterhouse wastewater, studies on the application of low-cost media to reduce the capital cost and standardization of operating conditions would be the way forward for anaerobic slaughterhouse wastewater treatment.

Acknowledgments Authors are thankful to Dr. (Mrs.) Anjana Singh, Environment Specialist, Gladstone Ports Corporation Limited (GPCL) QLD, Australia, for the proof reading that has improved the quality of the manuscript.

Authors' contributions Authors Akshay D Shende and Girish R Pophali have equally contributed in conducting the literature review and compilation of the manuscript.

Data availability All data generated or analyzed during this study are included in this published article.

Compliance with ethical standards

Ethics approval and consent to participate Consent to participate is not applicable.

Conflict of interest The authors declare that they have no conflict of interest.

Consent for publication Not applicable.

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