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Up-flow vs downflow anaerobic digester reactor configurations for treatment of fats-oil-grease laden poultry slaughterhouse wastewater: a review

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Abstract

The process of anaerobic digestion has been and still remains the most efficient, cost effective and environmentally benign treatment process for poultry slaughterhouse wastewater (PSW). The PSW is characterized by a high concentration in chemical oxygen demand (COD), biological oxygen demand (BOD) and fats, oil including grease (FOG). The reactor configuration influences the performance of such anaerobic systems in the treatment of such oily wastewater. The up-flow reactor configuration provided by the Up-flow Anaerobic Sludge Blanket (UASB) Bioreactor or the Expanded Granular Sludge Bioreactor (EGSB) are highly dependent on up-flow velocity, which often contributes to periodical sludge washout during the treatment of PSW with high FOG and total suspended solids (TSS) concentration, resulting in poor reactor performance in comparison with downflow reactors such as the Static Granular Bed Reactor (SGBR), which achieves high organic load removal efficiency particularly when treating PSW due to its ability to retain sludge granules and solidified residue within the reactor. The washout of the sludge results from sludge flotation, which is induced by the inhibition of the anaerobic granular biomass by the accumulation of long chain fatty acids (LCFAs) from poor hydrolysis. The aim of this review is to highlight reactor configuration deficiencies, and to elaborate on the advantages of using anaerobic digestion for the treatment of FOG-laden PSW, with a focus on reactor performance. Additionally, a comparative analysis between up-flow reactors, such as the UASB including EGSB, and downflow reactors, such as SGBR, was performed.

Key words: expanded granular bed reactor, fats-oil-grease, poultry slaughterhouse wastewater, static granular bed reactor, Up-flow anaerobic sludge blanket reactor

INTRODUCTION

The agricultural sector uses a large quantity of fresh water, with a global average usage exceeding 70% of surface water (Bustillo-Lecompte *et al.* 2016). The increase in water utilization in the agricultural sector poses environmental challenges related to water pollution, as a large quantity of untreated wastewater is released to surface water (Bustillo-Lecompte & Mehrvar 2015), which further exacerbates environmental pollution. Some industries in the agricultural sector, such as poultry processing facilities; that is, slaughterhouses, utilize a large quantity of fresh water to sustain their operations. The collection of the water and debris generated from these operations culminates in the generation of a large volume of wastewater which has the potential to pollute freshwater sources if not treated appropriately prior to its discharge into receiving freshwater sources such as rivers (Gerber *et al.* 2007). This problem is endemic in developing countries, such as South Africa, where water is getting increasingly scarce and the municipal councils impose levies to industries discharging wastewater not meeting regulatory standards.

Microbial wastewater treatment technologies such anaerobic digestion (AD) can play a major role in remedying the environmental concerns posed by poultry slaughterhouse wastewater (PSW) generation. The process of anaerobic digestion is considered to be the most appropriate wastewater treatment technology due to its affordability, limited plant footprint and ease of operation. This type of technology has been used for treatment of industrial wastewater and domestic wastewater in several studies (McCarty & Smith 1986; Lim 2011). Historically, the anaerobic digestion process has been considered appropriate for treatment of wastewater in large-scale operations. Currently, it still remains the preferred treatment method in the food processing industry due to numerous advantages, such as low energy consumption, reduced production of waste biological solids, low nutrients and chemical requirements, high COD reduction, pathogen deactivation, even at high loading rates. including the production of methane biogas, which can be combusted to generate heat and electricity or refined into renewable natural gas and other fuels (Bustillo-Lecompte & Mehrvar 2015; Basitere *et al*. 2016). However, anaerobic digestion does present some disadvantages, such as its sensitivity to pollutants, which may reduce the metabolic function of organisms constituting the sludge biomass; it has an elongated start-up procedure, which can be difficult to stabilize when operated by semi-skilled personnel, the resultant treated wastewater might require further post-treatment; that is, using tertiary treatment systems, in order for the effluent from the process to meet regulatory discharge standards (Lim 2011; Harris & MaCabe 2015). Generally, an anaerobic digester is a robust and stable treatment reactor if the operational system is well understood and implemented (Lim 2011). Furthermore, the anaerobic digestion process can be used to play a vital role in waste management and in the reduction of greenhouse gas emissions (Harris & MaCabe 2015) and the digestate can be used as value-added organic fertilizer for soil amendment (Basitere *et al*. 2016).

The high strength PSW produced by poultry slaughterhouses in South Africa is characterized by 35% more proteins than the local sewage water, resulting in high COD ranging from 2,133–4,137 mg/L, BOD ranging from 1,100–2,750 mg/L and FOG in the range of 131–684 mg/L (Basitere *et al*. 2016, 2017). Although the anaerobic digestion process is effective in the degradation of other substrates in PSW, FOG presents several challenges, such as FOG accumulation in pipe walls which results in pipe blockages (Harris *et al.* 2015; Basitere *et al.* 2016). This review highlights best practice when selecting anaerobic digestion reactor configuration (downflow vs up-flow), in particular, for the treatment of PSW with a high FOG content. Additionally, different challenges when using either reactor configuration are also discussed.

OVERVIEW: POULTRY SLAUGHTERHOUSE WATER USAGE, WASTEWATER GENERATION AND ITS ENVIRONMENTAL IMPACT

Poultry processing plants enable the processing of live birds to various consumable meat products (Avula *et al.* 2009). Poultry product processing steps can be divided into three categories, namely: (1) bird slaughtering, de-feathering and the evisceration of the poultry carcass for the production of whole birds; (2) cutting of the carcasses into various parts and deboning; and (3) the production of value added foods for consumers (Kiepper *et al.* 2008; Avula *et al.* 2009). The most critical control step in a poultry processing facility is the evisceration process, which is geared towards reducing the contamination of the products, in particular to limit and/or eradicate any leakage from the birds' gut, which harbors pathogens. Visual inspection is always done to segregate carcasses that might be exposed to gut; that is, faecal contamination and subject birds suspected to such contamination, to reprocessing procedures. During this process, there is a potential for coliforms such as *Escherichia coli* and *Salmonella* sp., to contaminate bird carcasses (Shih *et al.* 1980; Avula *et al.* 2009). The contaminated carcasses should be rewashed prior to trimming. Furthermore, temperature should be controlled to minimize proliferation of pathogens to edible parts of the bird (Avula *et al.* 2009). Overall, a poultry slaughterhouse water usage per bird and wastewater generated can be substantial, which can result in product and environmental contamination if such a processing facility does not possess adequate measures, such as waste handling facilities and wastewater treatment processes.

Average water usage per bird

Poultry slaughterhouse industrial plants use relatively high quantities of fresh water with an average of 26.5 L/2.3 kg bird during the primary and secondary processing of live birds to meat (Avula *et al.* 2009). During the initial stages, freshwater usage is attributed to the bleeding and scalding process whereby the water is used to wash-off blood subsequent to the immersion of the bird into hot water at a temperature of 50 °C to ease defeathering (Bustillo-Lecompte & Mehrvar 2015). Thereafter, water is also used to rinse the scalded carcass with rotating and pressurized water jets. Subsequently, chilling of the bird to 4 °C takes place – a process that involves the immersion of the carcass into chilled water (Bustillo-Lecompte & Mehrvar 2015). The chiller requires an average of 1.9 L/bird of potable water, which results in the use of 475,000 L/day of water in a plant that process 250,000 birds/day (Shih *et al.* 1980; Avula *et al.* 2009). Overall, water is used during bird washing, chilling, evisceration, cutting /deboning and packaging, as indicated in Figure 1.

Furthermore, water is also used as a transport medium for the by-products of slaughtering; that is, for the mobilization of offal including feathers, heads and viscera (Avula *et al.* 2009).

Another major pollutant in the poultry process water is residual protein from carcass debris, blood, FOG and feathers (Avula *et al.* 2009; Yordanov 2010). The poultry process water contains predominantly 35% of protein, resulting in a much higher BOD and COD being observed in the wastewater from such facilities, as opposed to municipal sewerage (Zhang *et al.* 1997; Avula *et al.* 2009).

Poultry wastewater generation and its impact on environmental health

The discharge of wastewater to the environment from poultry slaughterhouses in South Africa has become of significant environmental concern (Steinfeld *et al.* 1998; Basitere *et al.* 2016). Other processes, which utilizes a large quantity of water are associated with cleaning of equipment and surfaces including sanitation of facilities (Gerber *et al.* 2007). The wastewater generated during these activities also has a high BOD and COD concentration, due to other constituents such as nitrogen, phosphorous and disinfection by-products, when chemicals such as chlorine are used during sanitization procedures (Gerber *et al.* 2007). The wastewater contains a variety of contaminants including *Campylobacter* sp. and others (Sims *et al.* 1994), with numerous reports indicating that the waste generated can contain up to 100 different species of microorganism, some of which are prevalent in bird feathers, feet and intestinal contents (Gerber *et al.* 2007). PSW was estimated to contain 6.8 kg BOD per ton live weight killed (LWK) and 3.5 kg suspended solids (SS) per ton of LWK (De Haan *et al.* 1997). This suggests that if the PSW is not appropriately treated prior to being discharged, it has the potential to pollute land, surface water, thus to pose a risk to human health (Sims *et al.* 1994). The biodegradable organic compounds in PSW can cause a reduction in dissolved oxygen (DO) in surface waters, which can lead to the death of aquatic life (De Haan *et al.* 1997). The presence of macronutrients in the wastewater such as phosphorous and nitrogenous compounds has the potential to facilitate eutrophication in PSW-contaminated surface water bodies (Gerber *et al.* 2007). The subsequent algal growth has the potential to further have a deleterious cumulative effect on aquatic life due to the depletion of DO, which is consumed during algal proliferation in contaminated waters (Bustillo-Lecompte & Mehrvar 2015).

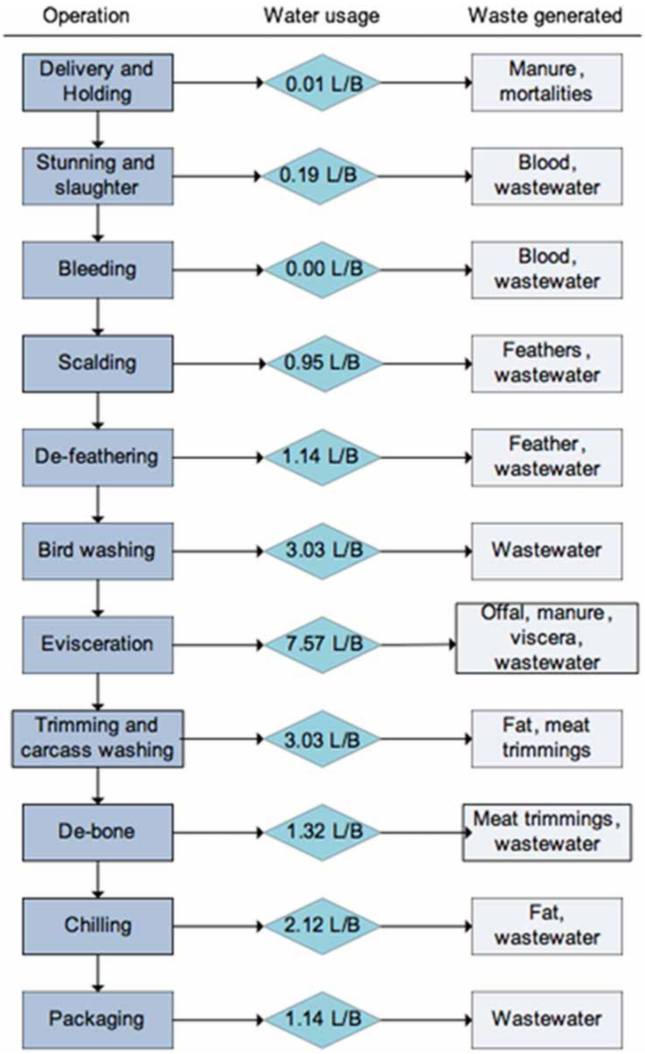

Figure 1 | Average water usage per bird during processing (Avula *et al.* 2009).

Composition of poultry slaughterhouse wastewater

Table 1 lists an averaged range of characteristics for PSW located in the Western Cape Province, South Africa, parameters quantified over a 9-week sampling period from several poultry product-processing facilities.

Legislation governing discharge of poultry slaughterhouse wastewater (PSW) in South Africa

In South Africa, regulation of water, wastewater management practices, and industrial discharge standards are governed by the National Water Act (Act 36 of 1998) and the Water Services Act (Act 108 of 1997), respectively. The Department of Water Affairs, South Africa (DWA) developed the Waste Discharge Charge System (WDCS). The charge system consists of two distinct charges (i.e. the waste mitigation charge and waste discharge levy), which was established under the National Water Act of 1998 and is primarily aimed at providing economic incentives and penalties to encourage water conservation and water use minimization practices (CSIR 2010; DWA 2012). Parameters such as salinity (electrical conductivity (EC), chloride, sodium, sulphates (SO_4^{2-})), nutrients (soluble phosphorous (PO_4^{3-}), nitrate (NO_3^-), ammonium (NH_4^+)), heavy metals (arsenic, cadmium, chromium, copper, mercury, lead, nickel, zinc), organics (BOD and COD), and pH, are taken into consideration by the WCDS.

Table 1 | Characteristics of poultry slaughterhouse wastewaters in the Western cape, South Africa (Basitere *et al*. 2017)

Parameter(s)	Unit	Range	Average
pH		6.5–8.0	6.88
Alkalinity	mg/L	0–489	489
Total chemical oxygen demand	mg/L	2,133–4,137	2,903
Soluble chemical oxygen demand	mg/L	595–1,526	972
Biological oxygen demand	mg/L	1,100–2,750	1,667
TKN	mg/L	77–352	211
Ammonia	mg/L	29–51	40
TKN	mg/L	77–352	211
Total phosphorus	mg/L	8–27	17
Fats, oil and grease	mg/L	131–684	406
Total dissolved oxygen	mg/L	372–936	654
Total suspended solids	mg/L	315–1,273	794
Volatile suspended solids	mg/L	275–1,200	738
Soluble proteins	mg/L	0–368	72
Volatile fatty acids	mg/L	96–235	235

Poultry slaughterhouses that have been granted permission to discharge wastewater into municipal sewer systems are required to abide by the municipal by-laws within each municipality as prescribed by the Water Services Act of 1997 (Molapo 2009; CSIR 2010). Poultry slaughterhouses located in Western Cape (South Africa) must, therefore, comply with the City of Cape Town Wastewater and Industrial Effluent By-law (2013). The associated discharge rates are calculated in accordance with Schedule 1 of this by-law and the Tariff by-law of the City. Additionally, municipalities enforce surcharges on transgressions, with slaughterhouses being penalized when their PSW does not meet the required discharge standards including volumes. The maximum limits of permitted discharge into municipal sewers in accordance with Schedule 1 of the City of Cape Town By-law (2013), are summarized in Table 2 (City of Cape Town 2014). Therefore, the implementation of suitable methods

Table 2 | South African industrial discharge (DWA 2010), SANS 241 (2011) drinking standard and municipal discharge standards (Western Cape and Mangaung)

Parameter	Units	DWA 2010 General limit	SANS241 Operational limits	Western Cape Not to exceed	Mangaug operation limits
Temperature at point of entry	°C	–	–	40	44
Conductivity	ms/m	70–150	<150	500	500
pH at 25		5.5–9.5	5.5–9.5	12	10
COD	mg/L	75	–	5,000	5,000
SS	mg/L	25	–	1,000	1,000
TDS at 105 °C	mg/L		<1,000	4,000	4,000
Total sulphates (SO_4^{2-})	mg/L		<400	1,500	1,500
O&G	mg/L	2.5		400	400
TP	mg/L	10		25	25
Faecal coliforms (per 100 ml)		1,000			
Turbidity	NTU		<1.0		
Amonia as nitrogen	mg/l		<1.0		
DOC	mg/l		<10		
Nitrates	mg/l	15			

is highly recommended, with some of the suggested PSW technologies treatment being used to generate biogas, which can be used as a source of energy.

POULTRY SLAUGHTERHOUSE WASTEWATER TREATMENT METHODS

Anaerobic degradation pathways and biogas generation

An anaerobic digestion process is a biochemical process that occurs in the complete absence of free molecular oxygen (Judd 2010). During the anaerobic wastewater treatment process, neither oxygen nor nitrates serve as the terminal electron acceptor (Massé *et al.* 2000), while organic compounds such as sulfates and ferric compounds serve as anaerobic electron acceptors. The redox potential of an anaerobic system lies between −300 mV and −400 mV, an indication of an environment devoid of oxygen (Massé *et al.* 2000). The process of anaerobic digestion of an organic complex involves both chemical and biological processes, as shown in Figure 2.

Metabolic processes in anaerobic digestion involve the decomposition of organic molecules into simple soluble compounds (amino acids, glucose and long chain fatty acids) by a process known as hydrolysis (Gerardi 2003). Extracellular enzymes excreted by hydrolytic and fermentative bacteria carry out the hydrolysis process, which is also considered to be the rate-limiting step of the overall anaerobic digestion process (Massé *et al.* 2000). Hydrolysed organic molecules are fermented into alcohol and volatile fatty

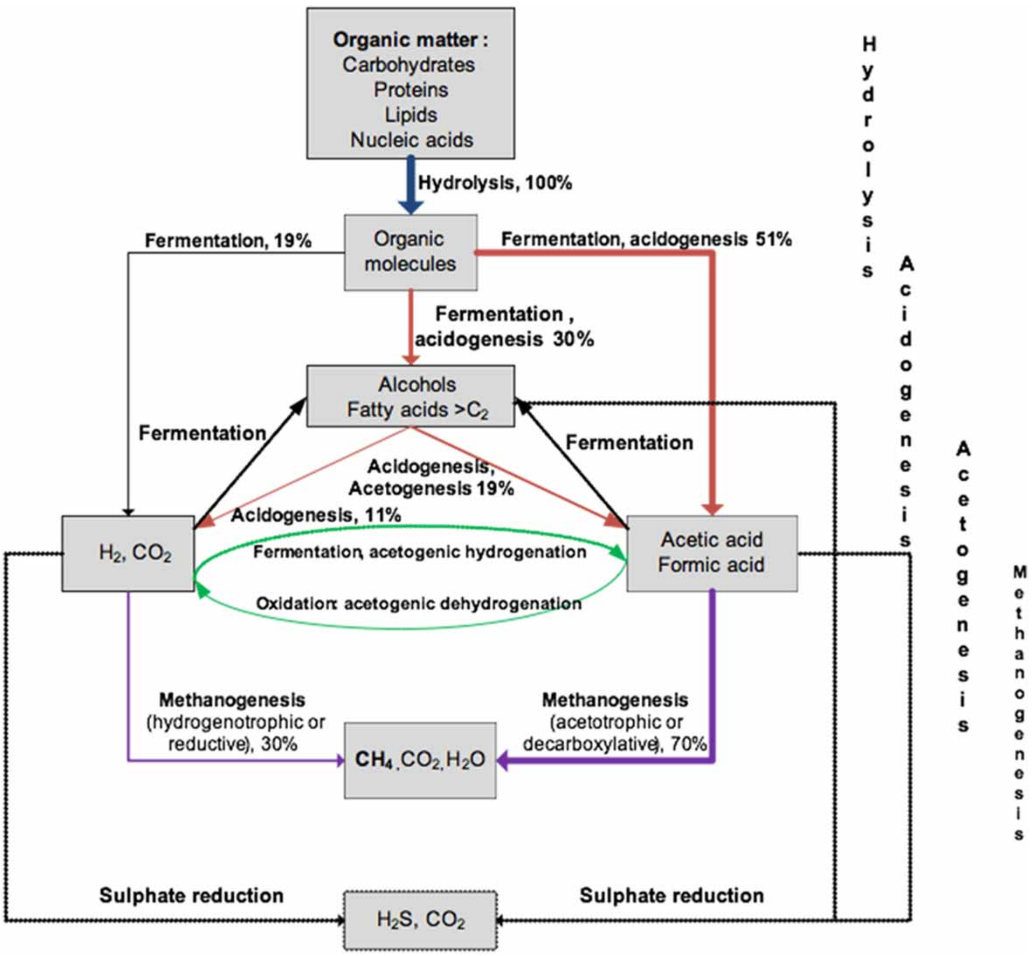

Figure 2 | Schematic of the different metabolic steps and microbe groups involved in the complete degradation of organic complex matter (Van Haandel *et al.* 1994; McInerney 1999; Poulsen 2003).

acids (VFA); that is, short chain fatty acids such as acetate, propionate and butyrate, in a process known as acidogenesis (McInerney 1999). During the acidogenesis process, short-chained fatty acids are degraded into acetate, hydrogen and carbon dioxide (CO_2), by hydrogen (H_2) producing acetogenic bacteria. Furthermore, about 66% of long chain fatty acids are oxidized into acetate while 33% go to H_2 through a process known as acetogenesis (Poulsen 2003). The acetate is converted in the final stage into CO_2 and methane (CH_4) by acetoclastic methanogens. Generally, 70% of the produced methane gas is from the acetate and 30% from CO_2 reduction by hydrogen oxidizing methanogens (Gerardi 2003). The methane produced can be used as energy to replace fossil fuels and reduce carbon dioxide emissions, contributing to the reduction of greenhouse gas production. However, reactor configuration in anaerobic digestion influences overall operability including treatment efficiency, depending on the volume and quality of the PSW being treated, particularly PSW with a high FOG concentration.

INFLUENCE OF REACTOR CONFIGURATION

Anaerobic digestion provides an efficient means of converting organic matter into biogas, and therefore contributes to the minimization of the effects of the discharge of unprocessed wastewater or organic waste into the environment (Martín-González *et al.* 2010; Njoya *et al.* 2019a). Anaerobic digestion was tested for the treatment of various types of wastewaters through different configurations, with the most popular being up-flow configurations such as the UASB, the EGSB or the internal circulation (IC) reactor (Avula *et al.* 2009; Basitere *et al.* 2017; Njoya *et al.* 2019b). However, due to the development of processing techniques that enable the migration of mature anaerobic granular sludge from one bioreactor to another, and the selection of suitable packing materials for reliable underdrain systems for the percolation of the water output, attention is also given to down-flow bioreactors, such as the static granular bed reactor, which offers a simple configuration that requires less energy for the internal transport of fluid within the bioreactor (Debik & Coskun 2009).

The treatment of various types of wastewater has been approached with anaerobic digestion, including poultry slaughterhouse wastewater, which has a high concentration of lipids (Basitere *et al.* 2017; Njoya *et al.* 2019a). This lipids content can be measured and quantified in terms of fats, oil, and grease (FOG) (Long *et al.* 2012). As noted in several studies (Kim *et al.* 2004; Long *et al.* 2012; Salama *et al.* 2020), a high concentration of FOG may contribute to augment the production of biomethane, or adversely reduce it if exposed to poor environmental conditions. These conditions are mostly defined by the anaerobic reactor configuration as well as the operating conditions and their maintenance throughout the treatment.

The challenges encountered during the treatment of FOG-laden wastewater include, but are not limited to:

- Foam accumulation,
- Inhibition of acetoclastic and methanogenic bacteria,
- Substrate and product transport limitation,
- Sludge flotation,
- Blockage of pipes and pumps, and
- Clogging of gas collection and handling systems

The inhibition of the anaerobic digestion from FOGs stems from the difficulty associated with the breakdown of long chain fatty acids (LCFAs) occurring through the β-oxidation pathway, which represents a rate-limiting step of the anaerobic digestion process (Martínez *et al.* 2011). Consequently, the accumulation of these LCFAs may inhibit acetogens and methanogens due to their toxicity. However, this inhibition can be prevented by improving the acclimation of the biomass to the FOG-rich substrate.

LCFAs can inhibit methanogens due to their cell wall, which is similar to that of gram-positive bacteria. Unlike gram-negative microorganisms, gram-positive bacteria can be inhibited with low concentrations of LCFAs (Chen *et al.* 2008; Cuetos *et al.* 2008; Martínez *et al.* 2011). These LCFAs have demonstrated a significant toxicity towards the anaerobic biomass through adsorption onto the cell wall. Furthermore, the sorption of a light layer of LCFAs to biomass may culminate in sludge flotation, which drives sludge washout from up-flow bioreactors (Chen *et al.* 2008).

Studies on the anaerobic biodegradation of oleic acid, which is a fatty acid that occurs naturally in various vegetable and animal lipids, showed that acclimation improved the biodegradation capacity and resistance of the biofilm to the presence of oleate (Chen *et al.* 2008; Martín-González *et al.* 2010).

According to Tan *et al.* (2006), the acclimation of an anaerobic biomass to a new substrate can be split into three stages:

- The adaptation of the anaerobic biomass to the new substrate by the formation of suitable bacterial microenvironments;
- The increase of the sludge specific gravity translated by the growth of the bacterial consortium; and
- The palletization or granulation of the sludge-forming anaerobic granules that form a layer of sludge blanket at the bottom of the reactor.

These steps heavily rely on the physical environment provided by the relevant bioreactor; therefore, its configuration. The conditions that should be maintained to ensure good acclimation and conducive anaerobic digestion include:

- The maintenance of a suitable operating temperature range (psychrophilic, mesophilic, or thermophilic);
- Maintenance of an environment devoid of oxygen;
- Good and uniform distribution of the substrate to the anaerobic biomass;
- Dispersion of inhibitory substances; and
- Preservation of a suitable VFA/alkalinity ratio.

These conditions can be respected through the implementation of a solid anaerobic digester configuration (see Figure 3), which enables the adaptation of its biomass content to various fluctuations, including the variation and/or increase of the FOG concentration in the substrate (Gerardi 2003). Different configurations are discussed in the following sub-sections, which elaborate on the consistency of the performance of the specified configuration on the treatment of FOG in PSW.

Up-flow configured anaerobic digesters: UASB and EGSB

Anaerobic treatment technologies such as up-flow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) are the most frequently used up-flow reactors for the biodegradation of organic pollutants in industrial wastewater (Karnchanawon *et al.* 2009). The UASB reactor was developed in the late 1970 in the Netherlands (Washington University) by Lettinga and his colleagues (Lim 2011). The first UASB reactor was successfully applied as a pilot system for a beet sugar refinery in the Netherlands with the reactor design consisting of a gas-liquid separator (GSS) for solids separation from influent and gas withdrawal (Lettinga 1980; Lim 2011). The reactor up-flow velocity ranges between 0.5 and 1.0 m/hr and the height to depth ratio range used was between 0.2 and 0.5 (Lim 2011). The design of the UASB is as highlighted in Figure 4.

The EGSB reactor system is a variant of the UASB anaerobic digestion concept, with the most distinguishing factor being the use of high up-flow velocity (typical maintained at higher than 6 ml/hr), which is applied with an effluent recycling stream contributing to sludge-bed expansion throughout the reactor height (Karnchanawon *et al.* 2009). The height to width ratio of the EGSB (Figure 5) is 4 to 5, which enables prolonged contact between the wastewater and sludge granules (Lim 2011; Basitere *et al.* 2016).

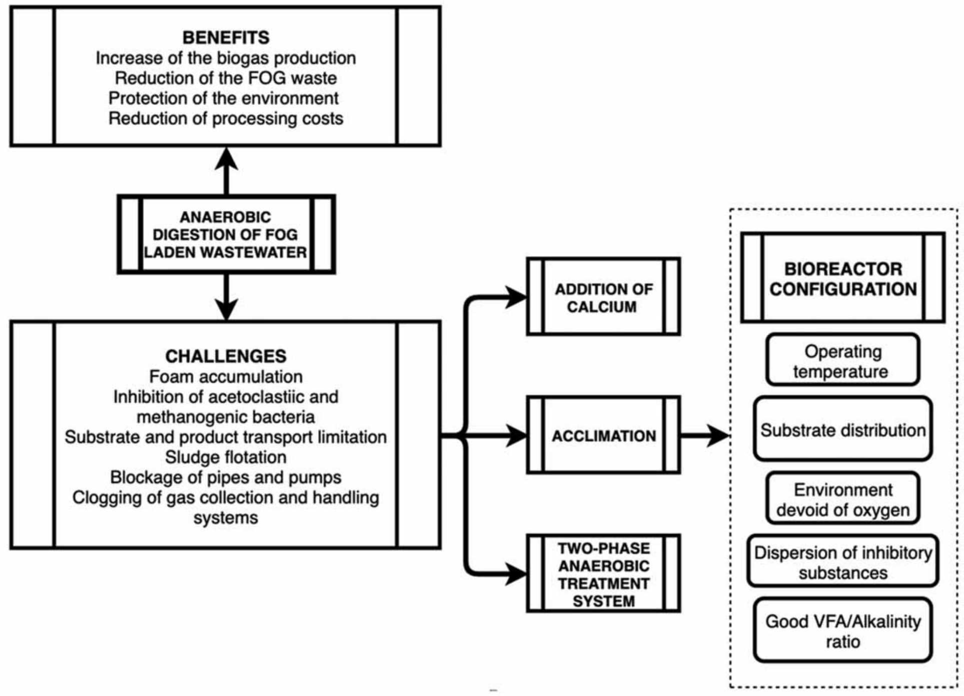

Figure 3 | Benefits, challenges and solutions towards conducive anaerobic digestion of FOG-laden wastewater.

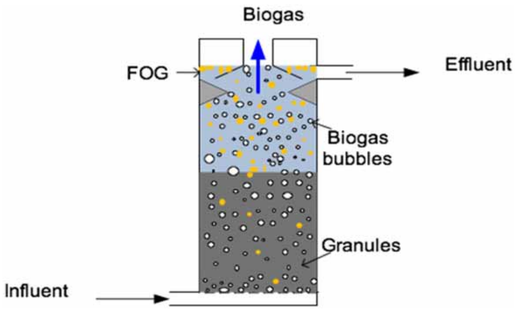

Figure 4 | The up flow anaerobic sludge bed reactor (UASB) (Basitere *et al.* 2016; Lim 2011).

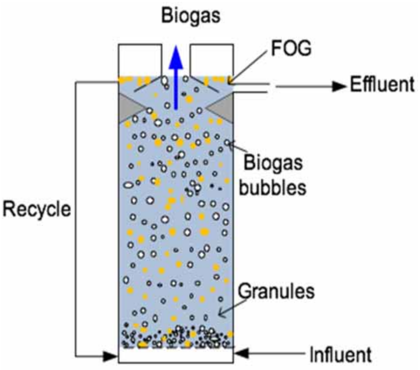

Figure 5 | The expanded granular sludge bed (EGSB) reactor.

Impact of up-flow reactor configuration for the treatment of FOG-laden PSW

Basitere *et al.* (2016) reported 65% COD removal rate using an EGSB reactor combined with an anoxic and aerobic reactor, treating PSW. The poor performance of the reactor was reported to be due to periodical sludge washout resulting from the collection of sludge near the outlet of bioreactor from sludge floatation. This sludge floatation results from the inhibition of LCFAs when they are not digested by the anaerobic biomass as a result of poor acclimation. Additionally, the buoyant forces, developed from the rise of biogas to the upper level of the bioreactor, contribute to exacerbate this sludge washout. The continuous sludge washout results in anaerobic system failure due to the decrease in methanogen activity requiring periodical system re-inoculation. Miranda *et al.* (2005) reported that an influent FOG/COD ratio above 20% has a detrimental effect on up-flow reactors, resulting in biomass-attached FOG being washed out of the reactor. Furthermore, an improvement of the performance of a UASB type reactor was reported to be at a FOG/COD ratio of 10% (Miranda *et al.* 2005). Basitere *et al.* (2016) further reported that the success of the up-flow reactor in treating PSW was dependent on an efficient primary treatment system such as dissolved air flotation, to reduce FOG and suspended solids prior to the anaerobic digestion system.

Downflow configured anaerobic digesters: SGBR

The SGBR (see Figure 6) is a competitive high-rate anaerobic reactor system used for the treatment of industrial and municipal wastewaters. The SGBR reactor was developed by Mach & Ellis (2000) at Iowa State University. The reactor is a simplified downflow high rate anaerobic granular reactor, which provides high performance with sustained removal efficiency at low cost due to its operational design and construction simplicity (Mach & Ellis 2000). The downflow reactor configuration mode enables simple inlet flow distribution. Furthermore, it also allows better separation of biogas from granules and wastewater due to its counter flow operation mode, which is bidirectional; that is, against the inlet flow. Additionally, the downflow mode of operation allows influent solids to be filtered through the granular bed. The reactor utilizes a bed of active anaerobic granules resting on a gravel and mesh wire underdrain for treatment of industrial wastewater with relatively small reactor volumes sizes (Mach & Ellis 2000). The SGBR reactor reduces operational costs associated with the purchase of packing material, and mixing equipment. Additionally, a recirculation system is not required. Due to its ability to retain a high concentration of the biomass within the reactor, the SGBR allows for maximized contact between the active biomass and dissolved organic matter in the wastewater, resulting in high organic removal rates (Mach & Ellis 2000).

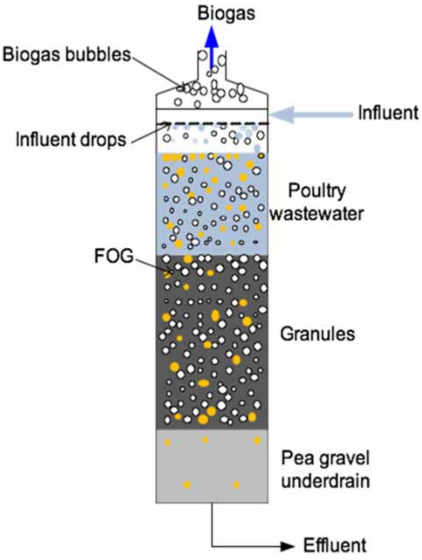

Figure 6 | The static granular bed reactor (SGBR).

1 Impact of downflow reactor configuration for the treatment of FOG-laden PSW

Debik & Coskun (2009) reported that PSW was successfully treated using a SGBR inoculated with anaerobic granular sludge. The success of this operation led the author to compare the performance of this bioreactor to a similar one inoculated with both anaerobic granular biomass and non-granular biomass. The average COD removal efficiencies were reported to be greater than 95% for both reactors. The difficulty encountered by up-flow reactors with regard to FOG inhibition was overcome here by a configuration that required no 3-phase separation system and offered a counter-flow between the generated gas and wastewater feed, as minimal quantities of granules were observed to be washed out of the reactor. Due to pneumatic forces facilitated by gas generation, FOG attachment to the granules is largely facilitated by flotation for less dense materials to the top of the reactor. This design does not have an exit port at the top of the reactor for both granules and FOG, thus they remain in the reactor for organic matter digestion. Basitere *et al.* (2017) also reported COD, TSS and FOG removal efficiencies of 93%, 95% and 90%, respectively, at both organic loading rates of 1.01 and 3.14 g COD/L.day using an SGBR reactor. The higher rate of COD, TSS and FOG removal using the SGBR reactor was attributed to biomass retention within the reactor. Although some disadvantages were reported by both Debik & Coskun (2009) and Basitere *et al.* (2017) with regard to the efficiency of PSW treatment using an SGBR, involving the accumulation of suspended solids at the bottom of the reactor resulting in clogging due to reduced porosity of the pea gravel used in the reactor which suggested that high solids concentrations, particularly those that are constituents of FOG in the influent, can reduce the operability of the system, thus resulting in reactor redundancies. Applying a backwash periodically, with solids withdrawal from the reactor, can result in improve system performance although such an operational strategy can result in additional cost and variation in the quality characteristics of the treated effluent.

Alternative approaches to the reduction of the inhibitory effects of FOG in anaerobic digestion

Application of calcium

The addition of calcium to an anaerobic digestion system has been proven to be effective for the minimization of LCFA inhibition (Pereira *et al.* 2004; Chen *et al.* 2008). This alternative (addition of calcium: 0.1–1%, W/V) for the minimization of the inhibitory effects of FOG was also investigated by Salama *et al.* (2020), who demonstrated that the addition of 0.5% w/v of calcium contributed to increase the production of methane sixfold. However, they also highlighted that an addition of calcium lower than 0.5% w/v of calcium does not prevent the inhibitory effects of FOG. However, this alternative cannot solve the challenge of sludge flotation (Chen *et al.* 2008).

The recourse to a two-phase anaerobic treatment system

The challenges associated with the processing of FOG-laden wastewater were approached in previous studies (Kim *et al.* 2004; Tan *et al.* 2006; Cavaleiro *et al.* 2009) using a two-phase anaerobic treatment system, which usually consists of a combination of a continuous stirred tank reactor (CSTR) and an anaerobic reactor. The anaerobic CSTR is used to promote the acidogenesis of the substrate. The CSTR product is then fed to an anaerobic reactor, where the methanogenesis takes place (Kim *et al.* 2004). Such processes have shown good results for the minimization of the inhibitory effects of LCFAs in an anaerobic system.

CONCLUSIONS

The anaerobic digestion process is a practical and useful treatment method to treat FOG-laden PSW. Although this process has numerous advantages, it is important to select an appropriate reactor configuration in order to achieve maximum performance at lower cost. While both up-flow and downflow configurations have been used to treat PSW, the downflow configuration seems to have achieved suitable treatment performance in comparison to the up-flow configuration with regard to both COD, TSS and FOG removal due to its ability to retain biomass. The challenges faced by up-flow reactors such as UASB and EGSB is the inability to handle high FOG concentrations, particularly at high up-flow velocity, which results in sludge washout and thus the alteration of the reactor performance. Furthermore, to prevent reduced reactor performance, it is recommended that a pre-treatment system, such as a dissolved air floatation system, is to be to utilized prior to the introduction of an influent for up-flow configured systems in order to reduce FOG, COD and TSS PSW, prior to anaerobic digestion.

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