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Treatment of poultry slaughterhouse wastewater using a down-flow expanded granular bed reactor

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Abstract

This study evaluated the performance of a novel high rate anaerobic bioreactor system for the treatment of poultry slaughterhouse wastewater (PSW). The new system consisted of a granule-based technology operated in a down-flow configuration, with the assistance of medium-sized pumice stones used as packing materials for the retention of the anaerobic granules, to avoid challenges associated with the use of the three-phase separator of up-flow systems and the washout of the anaerobic biomass. Furthermore, a recycling stream was applied to the system to improve the mixing inside the Down-flow Expanded Granular Bed Reactor (DEGBR), i.e. the influent distribution to the granular biomass, and the implementation of intermittent fluidization when required to alleviate the effects of pressure drop in such systems. The DEGBR was operated under mesophilic conditions (30–35 °C) and achieved total chemical oxygen demand (tCOD), five-day biological oxygen demand and total suspended solids average removal percentages >95%, and a fats, oils and grease average removal percentage of 93.67% ± 4.51, for an organic loading rate varying between 1.1 to 38.9 gCOD/L.day.

Key words: anaerobic granule-based technology, chemical oxygen demand, down-flow expanded granular bed reactor, high rate anaerobic bioreactor system, poultry slaughterhouse wastewater treatment

INTRODUCTION

The efficacy of anaerobic digestion for the secondary treatment of low to high strength wastewater has been highly acclaimed since the development of high rate anaerobic bioreactor systems (HRABs) (Metcalf & Eddy 2003; Chernicharo 2007; Henze *et al.* 2008). HRABs heavily rely on the development of anaerobic granular sludge and improved biomass retention (Hulschoff Pol *et al.* 2004), which culminates in effective solid retention time (SRT) and suitable hydraulic retention time (HRT) (Alphenaar 1994; Henze *et al.* 2008). This results in enhanced wastewater treatment performance in terms of effluent quality and processing time. In comparison to the aerobic treatment of wastewater, the anaerobic treatment has numerous advantages including a reduced plant footprint (Henze *et al.* 2008; Debik & Coskun 2009); less energy requirement, which is usually associated with the supply of dissolved oxygen in aerobic systems (Chernicharo 2007; Henze *et al.* 2008); low initial and operating costs (Debik & Coskun 2009); less sludge generation, which does not require further treatment but can be used for inoculating another biodigester and therefore reduce the start-up time (Henze *et al.* 2008); and biogas production, whose methane content represents an alternative source of energy (Chavez *et al.* 2005). Following the success of the up-flow anaerobic sludge blanket (UASB) (Lettinga & Hulschoff Pol 1991; Hulschoff Pol *et al.* 2004), various HRABs, such as the expanded granular sludge bed (EGSB) reactor (Kato *et al.* 1994; Basitere *et al.*

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2016), the internal circulation (IC) reactor (Driessen *et al.* 1999), up-flow anaerobic filter (UAF) (Yilmaz *et al.* 2008), static granular bed reactor (SGBR) (Ellis & Evans 2008; Basitere *et al.* 2017) or the anaerobic baffled reactor (ABR) (Bachmann *et al.* 1985), among others, have been developed for the biological treatment of low to high strength wastewater. However, some challenges were encountered during the operation of such bioreactors, including; the washout of solids and the difficulty associated with the operation of the three-phase separator for bioreactors operating under an up-flow configuration (Ellis & Evans 2008; Henze *et al.* 2008; Basitere *et al.* 2016); the weakened distribution of substrate to the anaerobic biomass and weak dispersion of toxicants within the system due to the pressure loss, which affects the mobility of these substances within the anaerobic bed (Gerardi 2003; Ellis & Evans 2008; Basitere *et al.* 2017); and the energy requirement associated with the pumping and recycling lines in reactors such as UASB, EGSB, UAF, and IC, which were addressed through the development of the SGBR that offers a down-flow configuration that reduced the overall energy requirements of the system and eliminated the need for a three-phase separator (Ellis & Evans 2008). However, this configuration also came with some challenges related to head losses (Basitere *et al.* 2017), which translated to the loss of the fluid and gas kinetic energy, resulting in the limitation of substrate distribution to the biomass, gas entrapment and subsequently the accumulation of toxic substances such as ammonia and hydrogen sulphide within the anaerobic granular bed of such system (Gerardi 2003; Yamamoto *et al.* 2009; Meier *et al.* 2011).

Thus, this study aimed at addressing these shortcomings through the development of the down-flow expanded granular bed reactor (DEGBR) that was designed to alleviate the aforementioned challenges for an enhanced performance of HRABs in the treatment of medium to high strength wastewater. In this study, the performance of the DEGBR was assessed by using poultry slaughterhouse wastewater (PSW), whose discharge to surface water represents a threat to human health and the environment, as it contains biological contaminants, pathogens and is being produced in significant quantities (Borja *et al.* 1998; Barbut 2015). However, it should be noted that attention was not given to the removal of pathogens in this study.

The poultry industry represents the largest segment of the South African agriculture industry (Bolton 2015). The processing of birds in poultry slaughterhouses is associated with a significant consumption of potable water. Northcutt & Jones (2004) reported that the processing of a single bird in a poultry slaughterhouse usually requires an average of 26.5 L/bird; thus, depending on the throughput of a poultry slaughterhouse, which is highly influenced by the demand of poultry products, availability of broilers and processing capacity, huge volumes of potable water is usually used in such facilities (Barbut 2015), despite water scarcity challenges. This high consumption of potable water originates from the requirements imposed by high hygienic standards to which poultry industries should abide to in order to ensure the supply of safe products (Bustillo-Lecompte *et al.* 2016). While significantly contributing to the processing of birds, the potable water is then contaminated with blood, fats, faeces, bones, meat trimmings as well as other pollutants, to form poultry slaughterhouse wastewater (PSW), which is characterised by a high concentration of chemical oxygen demand (COD), fats, oil and grease (FOG) or biological oxygen demand (BOD_5), and thus culminates in a wastewater that can be harmful to the public health and environment, while being a source of financial penalties to the producing industry, if discharge standards were not adhered to (Debik & Coskun 2009; Barbut 2015; Bustillo-Lecompte *et al.* 2016). The extent of the treatment of such effluent is prescribed by the legislation in different countries. However, to reduce the potable water intake in such facilities, the option of water recycling may be adopted and therefore stringent treatment methods are required to avoid the contamination of poultry products being processed.

The treatment of PSW has been attempted by various researchers. Basitere *et al.* (2017) used a SGBR and achieved a COD, TSS and FOG removal of 93%, 95% and 90%, respectively. The SGBR was also used by the Debik & Coskun (2009), which resulted in an average COD removal >95% for an organic loading rate (OLR) varying between 0.25 and 5 gCOD/L.day. Furthermore,

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Basitere *et al.* (2016) also evaluated the treatment of PSW using an EGSB reactor for a COD removal of 57% with the highest OLR being 1 gCOD/L.day. In this study, the washout of solids, facilitated by the attachment of the biomass to the FOG, the up-flow configuration and the limitations of the three-phase separator, were highlighted as factors significantly contributing to the limitations of the performance of the EGSB for the treatment of PSW. The EGSB is a variant of the UASB, which was used by Del Nery *et al.* (2001) for the treatment of PSW in a full-scale operation that resulted in tCOD and sCOD removals of 65 and 85%, respectively, for an average OLR of 1.64 kgCOD/m^3.day. Another variant of the UASB, the hybrid up-flow anaerobic sludge blanket (HUASB), was also assessed for the treatment of PSW under mesophilic conditions by Rajakumar *et al.* (2012), which culminated in the removal of tCOD and sCOD varying between 70 to 80%, and 80 to 92%, respectively, for an OLR of 19 kgCOD/m^3, which resulted in a methane gas concentration of 72% at a rate of 1.1 and 5.2 m^3/m^3.day. Rajakumar *et al.* (2011) also evaluated the treatment of PSW using an UAF under low up-flow velocity that resulted in a tCOD and sCOD removals of 70 and 79%, respectively, using a non-granular sludge as inoculum, with anaerobic granules varying between 1 and 2 mm. Sindhu & Meera (2012) also evaluated a bioreactor presenting similar features as the UAF, the up-flow anaerobic packed bed reactor (APBR), which was randomly packed with PVC pipe pieces as packing material, which achieved a COD, TDS, and suspended solids removals of 88, 15 and 85–98%, respectively, for an ammonia nitrogen reduction of 30% with an OLR varying between 4 to 5 kgCOD/m^3.day.

The performance of HRABS highly depends on the maintenance of suitable environmental conditions to induce the growth of the required anaerobic biomass, which may agglomerate in granules when suitable conditions prevail. Opinions diverge on these conditions, but, besides the standard anaerobic operation conditions, the ones often listed include the up-flow distribution of the effluent, and presence of inert carriers as well as suitable organisms (Hulschoff Pol *et al.* 2004; Henze *et al.* 2008). These anaerobic granules are characterized by good settling velocities and high specific methanogenic activity (Henze *et al.* 2008); therefore, these characteristics of anaerobic granules result in the success of bioreactors such as the SGBR, IC or EGSB (Ellis & Evans 2008; Basitere *et al.* 2016, 2017; Henze *et al.* 2008). Anaerobic granules are represented by an arrangement of spherical and well-defined surface conglomerates of anaerobic micro-organisms. This arrangement can be visualised as a packed bed of granules, whose diameter typically varies between 0.15 and 4 mm (Henze *et al.* 2008). The resistance to fluid flow generated by these anaerobic granules may culminate in PSW pressure loss inside the bio-reactor, which may result in a limitation of substrate distribution and ultimately promote biogas entrapment, poor effluent collection in down-flow configurations, and/or weakened dispersion of toxic substances such as ammonia and hydrogen sulphide contained in the entrapped biogas. As a result, this toxicity may reduce the methanogenic activity. Therefore, it is deemed necessary to develop an innovative configuration, such as the one provided by the DEGBR, to address the aforementioned challenges.

METHODS

Experimental set-up

The PSW used in this study was collected from a poultry slaughterhouse processing an average of a million birds a week, located in the Western Cape, South Africa. The experimental set-up was composed of three different stages including pre-treatment, bio-digestion and gas processing systems, as illustrated in Figure 1.

The first stage of the experimental set-up consisted of the removal of coarse solids, feathers, and part of the FOG content from the PSW through filtration using a 9.51 mm aperture size metallic sieve.

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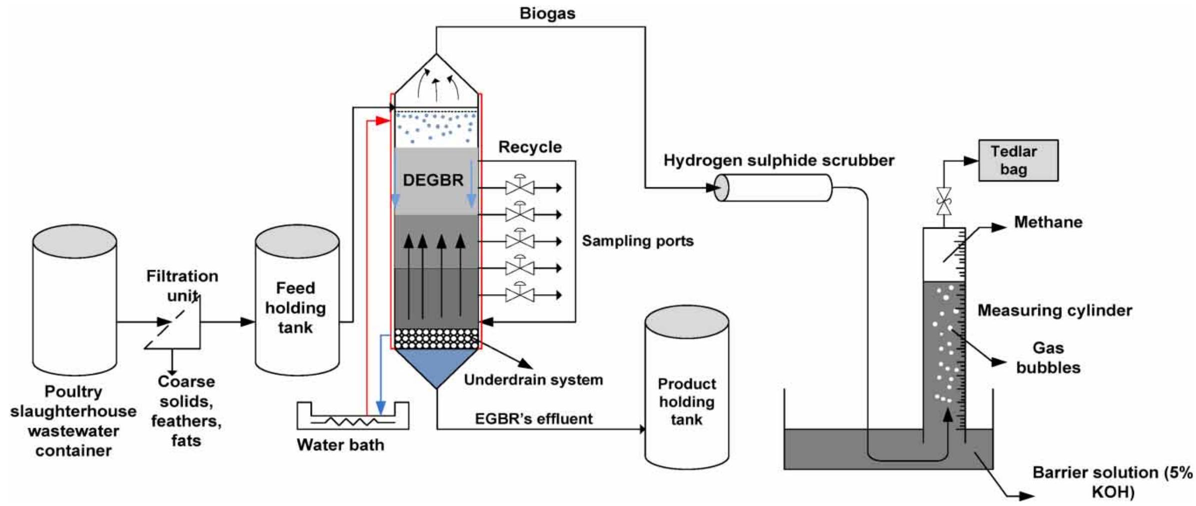

Figure 1 | Experimental set-up.

This phase was followed by the storage of the DEGBR feed in a feed holding tank, prior to feeding the PSW to the bioreactor. The DEGBR consisted of 86 mm ID PVC cylinder (2 mm wall thickness) that had a total height of 69 cm, when including the top (4 cm) and bottom (5 cm) cones that served to collect the biogas and effluent, respectively, from the DEGBR. The latter was surrounded along its height by a coiled water jacket connected to a water bath, whose temperature control system served to ensure that the intended operating temperature range is maintained, mesophilic (30–35 °C). Inside the DEGBR, a sieve of 25.4 mm mesh size was placed at the base of the bottom inverted cone to carry the packing material that served to retain the biomass within the reactor. Three factors were taken into consideration when selecting packing materials, including the affordability of the material, the inertness of the material to mechanical and/or pneumatic mixing and microbial attack, and the availability of the material. However, to select the most suitable packing material from a pre-selection consisting of pea gravels, white pebbles, ceramic marbles and pumice stones, other parameters were considered, namely:

- The porosity,
- The head loss induced by the selected materials,
- Its sludge retention capacity, and
- The permeability of the packing material.

From these series of tests, the pumice stones demonstrated the ability to be the most suitable packing material, as it induced less pressure drop, had a better retention of the anaerobic sludge and provided the best permeability. The packing materials were placed at the bottom of the reactor and occupied a height of 5 cm. The pumice stones are volcanic rocks characterized by a rough vesicular texture, which provides a greater surface area than a typical rock of the same diameter. Their sizes vary, but the ones used in this study had an equivalent diameter varying between 6 to 14 mm and a sphericity of 0.66. The DEGBR was inoculated with an anaerobic granular sludge collected from an operating UASB reactor treating a local brewery wastewater (SABMiller, Newlands, South Africa), and stored at 35 °C prior to the inoculation. During the inoculation, 3 L of the anaerobic granular sludge was poured into the DEGBR. To acclimatize the inoculum to PSW, 1 L of PSW and 50 mL of a 20% (w/v) dry milk solution were also poured into the DEGBR, which was hermetically closed and maintained at mesophilic conditions for two days under a batch condition prior to running the system under a continuous flow.

The third stage of the experimental set-up served to treat and collect the biogas produced from the system. The first step of this stage entailed the minimisation of hydrogen sulphide from the biogas

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using a scrubber, which consisted of a 15 cm long and 2.5 cm ID transparent PVC cylindrical tube filled with uncoated iron oxide mesh (steel wool). Mogomnang & Villanueva (2015) assessed this technology for H_2S removal and reported an efficiency >95%. Following the gas scrubber, a water displacement set composed of a 2 L glass container filled with a 5% (w/v) barrier solution of potassium hydroxide (KOH), and 100 mL measuring cylindrico-conical cylinder connected at its end to a valve that controlled the flow of the gas to a 500 mL Tedlar bag.

Operating conditions

During the first two weeks of the DEGBR operation, its feed was diluted with an equivalent amount of potable water to reduce the concentration of COD and thus facilitate the acclimation of the biomass to the PSW. As illustrated in Figure 1, the DEGBR was operated in a down-flow configuration and possessed a recycle stream that contributed to improve the distribution of the influent to the anaerobic biomass, and to develop a counter-current flow inside the bioreactor for enhanced mixing of its content. The distribution of the influent was improved by the provision of another inlet of PSW to the anaerobic granular bed by the recycle stream. This secondary inlet was located at the bottom of the granular bed to circumvent the head loss induced by the latter. The circulation of influent in bioreactors operating in down-flow configurations is hindered by the pressure loss as it flows down the bioreactor. Therefore, to address this challenge, the DEGBR aims at improving the circulation of influent in such a bioreactor configuration by providing another inlet to the bioreactor located under the level of the main inlet. This improves the contact between and organic influent and the biomass, which culminates in good methanogenesis at every level of the anaerobic biomass and the release of biogas. The elevation of the latter creates some channels that can be used by the organic influent to stream down the bioreactor.

Furthermore, this recycle stream, which was collecting PSW from the top of the DEGBR to feed its bottom part, was controlled by a separate pump that altered the flow rate of the recycle stream according to operational requirements. In the event of channeling or accumulation of the influent inside the DEGBR, intermittent fluidization was implemented through a significant increase of the recycle stream flow rate, which could generate an up-flow velocity as high as 10 m/hr.

To provide a smooth operation, the recycle stream flow rate was similar to the one of the influent PSW, which varied with the change of the system HRT. The latter varied between 15 and 40 hours, for an OLR varying between 1.1 to 38.9 gCOD/L.day. To prevent shock loading, the system was initially operated at an HRT of 35 hours, which corresponded to an OLR varying between 1.1 to 4.5 gCOD/L.day. This HRT was increased to 40 hours after four weeks of operation due to a periodic temperature upset that led to the alteration of the DEGBR performance. However, after regaining stability, the HRT was step-wisely decreased to 24, 20 and then 15 hours for increased OLRs. Despite being used for providing an upflow circulation of the influent within the granular bed at low up-flow velocities (varying between 0.12 to 0.8 m/hr), the recycle stream was also used for intermittent fluidization (10 to 15 mins) of the granular bed, when required, to alleviate the pressure effects on the granular bed and thus to allow the dispersion of toxic substances, emergence of the biogas and improvement of substrate distribution. In this study, the intermittent fluidisation was performed twice, at days 23 and 35, after the occurrence of a temperature anomaly and the clogging of the granular bed, illustrated by an accumulation of the influent inside the DEGBR. To tackle this challenge, intermittent fluidisation was implemented through the increase of the recycle stream flow rate to achieve the minimum fluidizing velocity of the granular bed. The fluidization re-opened the path for the circulation of the PSW and allowed the dispersion of toxicants entrapped in the bottom part of the anaerobic granular bed. The sampling ports placed along the height of the DEGBR served to collect samples from the reactor and could be connected to the recycle stream when the influent needed to be redistributed at a certain height of the granular bed. However, the location of

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the recycle stream was not moved throughout the course of this study, but this alternative can be used in other experiments should the requirement arise.

Analytical methods

The performance of the DEGBR was monitored using the tCOD, BOD_5, FOG, volatile fatty acids (VFAs), total suspended solids (TSS), turbidity, total dissolved solids (TDS) and alkalinity. These analyses were performed according to the APHA Standard Methods (APHA 2005). The pH and the temperature were measured daily; whereas, the TDS and turbidity were measured every two days; and other parameters, such as the tCOD, BOD_5, FOG, VFA and alkalinity were measured every week, as values tended to be similar over a week. Furthermore, the BOD_5 analysis took five days per sample. The biogas production was determined on a daily basis using the water displacement set, and the biogas sample collected in the Tedlar bag was analysed using a Geotech Biogas 5,000 portable gas analyser for determining its composition.

RESULTS AND DISCUSSION

The characteristics of the DEGBR influent and effluent are tabulated in Table 1. The efficiency of the DEGBR on PSW treatment was clearly noticed by the decrease of contaminants concentration noticed in the effluent. The parameters used to quantify these contaminants include the turbidity, FOG, TSS, tCOD, and BOD_5. Only the concentration of the TDS increased in the effluent, suggesting an increase of the conductivity of the effluent as compared to the influent. The improved appearance of the effluent as compared to the influent was illustrated by a lower average turbidity in the effluent, as well as its TSS and FOG concentrations. The performance of the DEGBR in the treatment of PSW under mesophilic conditions is further discussed in subsequent sub-sections.

Table 1 | DEGBR influent and effluent characteristics

PSW	Influent		Effluent	
Parameter (mg/L)	Range	Average	Range	Average
TDS (mg/L)	639–1,740	1,250 ± 302	836–2,670	1,410 ± 350
Turbidity (NTU)	328.5–864.5	758 ± 158	11.46–286.5	33.65 ± 45.17
TSS (mg/L)	291–5,044	1,750 ± 1,124	4.25–231.46	51.64 ± 45
tCOD (mg/L)	1,664–32,375	8,284 ± 7,309	125–449	222 ± 97
BOD_5 (mg/L)	850–20,500	5,132 ± 4,549	25–225	77.33 ± 56.83
FOG (mg/L)	280–8,228	1,655 ± 1,880	34–116	57.47 ± 22.37

Stability of the DEGBR

Throughout this study, the stability of the DEGBR during the treatment of PSW was highlighted by a pH remaining in a range of 6.5 and 8, as well as the VFA/Alkalinity ratio remaining under 0.3, as illustrated in Figure 2, translating to a suitable biodegradability of the influent organic matter. This stability was also deduced by the concentration of VFA as acetic acid in the effluent maintained <500 mg/L, as depicted in Figure 2. To maintain stable methanogenic activities, it was essential to monitor the concentration of VFA, alkalinity and pH throughout the study. Furthermore, the ratio of VFA/alkalinity of the DEGBR's effluent was used to assess the stability of the process.

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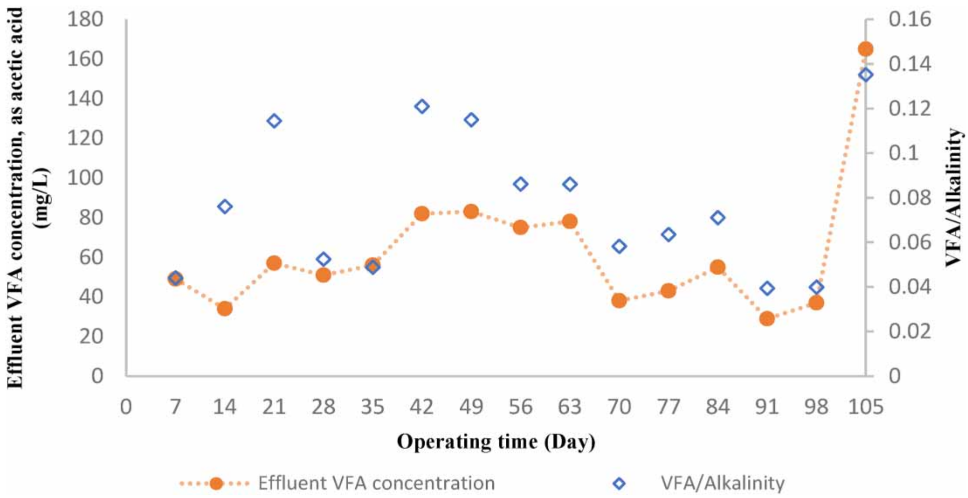

Figure 2 | DEGBR effluent VFA concentration and VFA/alkalinity ratio.

Total COD removal

The control of the tCOD removal is essential to wastewater treatment. At the beginning of this study, the tCOD removal was lower (73% after a week of operation) than the consistent trend that followed. This can be explained by the acclimation of the anaerobic biomass to the new type of wastewater, as the previous one (brewery wastewater) presented different characteristics in terms of the quality of the organic matter content present in the wastewater. In this study, the highest tCOD removal achieved was 99.61%, as illustrated in Figure 3. This high removal percentage was related to the high influent tCOD concentration (32,375 mg/L), which was higher than the average tCOD concentration (8,284 mg/L), for an effluent presenting similar characteristics. This high tCOD concentration in the sampled PSW could be explained by the prevailing poultry slaughterhouse operation at the time when the PSW was collected from the poultry slaughterhouse. Another reason may be the quantity of potable water that was used for the processing of birds before the PSW collection, as the quantity of used potable water has an effect on the dilution of contaminants in the PSW. However, the tCOD removal percentage was maintained above 90% from the second week of operation, despite a slight depreciation of the DEGBR performance from week 4 to 5, as a result of a temperature anomaly due to a failure of the water bath control system. The correction of the anomaly led to the stabilisation of the tCOD removal around 95%, despite further decreases of the HRT that translated

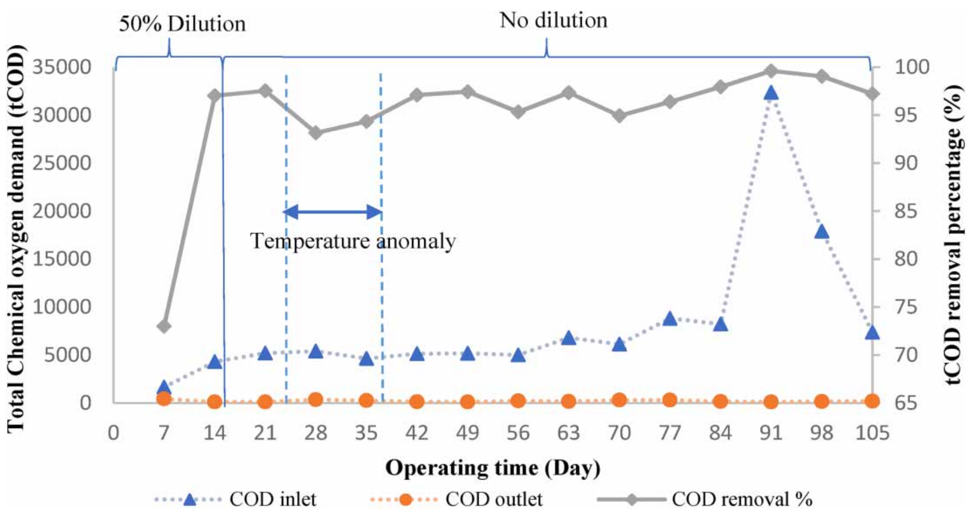

Figure 3 | Variation of the DEGBR influent and effluent tCOD during the study.

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to increases of the OLR. In anaerobic treatment, tCOD removal corresponds to its conversion into biogas during the methanogenesis or its accumulation within the bioreactor in the form of recalcitrant or, to some extent, biodegradable solids, partly due to a poor efficiency of the hydrolysis, which, similarly to the methanogenesis, is a limiting phase in the anaerobic digestion (Gerardi 2003; Henze *et al.* 2008). However, the configuration of the DEGBR allowed a better distribution of the organic matter contained in the PSW to the anaerobic biomass, which culminated in improved degradation and subsequently, the conversion of the organic matter. Unlike the EGSB and the UASB that have an up-flow configuration (Del Nery *et al.* 2001; Henze *et al.* 2008), the DEGBR takes advantage of the gravity as a supplementary force to improve the transport of PSW through the granular bed. The up-flow configuration of bio-reactors, such as the EGSB and UASB, has a higher energy requirement first to overcome the gravitational forces and then to compensate for the friction losses through the granular bed. Furthermore, the DEGBR has an added advantage over the SGBR (Ellis & Evans 2008; Debik & Coskun 2009; Basitere *et al.* 2017) by the fact that it uses a recycle stream that adds another PSW distribution port at different locations within the bio-reactor to improve the PSW distribution. Moreover, the down-flow configuration of the DEGBR eliminates the requirement of the three-phase separator as the effluent was collected at the bottom of the reactor, while the gas was collected on top of the reactor while the biomass was retained inside the DEGBR by a selected underdrain system. As demonstrated by previous studies (Henze *et al.* 2008; Basitere *et al.* 2016), the three-phase separator did not guarantee a complete retention of the anaerobic biomass raised to the top of up-flow anaerobic reactors, such as the EGSB and the UASB, from the emergence of biogas bubbles. In this study, the anaerobic sludge retention capacity was evaluated in various packing materials (pea gravels, white pebbles, ceramic marbles and pumice stones), which culminated in the selection of pumice stones as packing materials for an improved sludge retention capacity, reduction of head loss and suitable permeability. Furthermore, throughout the study, the quality of the effluent, as demonstrated by the concentration of tCOD, VSS, TSS, TDS or BOD_5, confirmed a good retention of anaerobic granules, which constituted the required biomass for the anaerobic digestion and the methanogenic activity.

Further evaluation of the DEGBR performance

Further evaluation of the DEGBR performance was done by monitoring the tCOD, FOG and BOD_5 removals with respect to the variation of the OLR throughout the study (Figure 4). It resulted from this

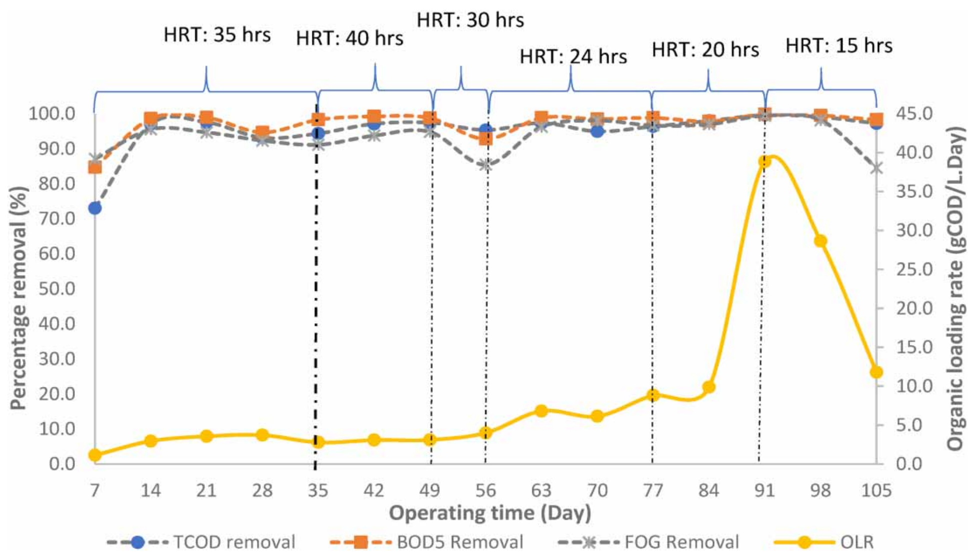

Figure 4 | Evaluation of the DEGBR performance VS the OLR variation.

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approach that the trends of the FOG and BOD_5 were quite similar to the one of the tCOD. An increase in the removal percentage of the three parameters evaluated was noticed after a period of acclimation facilitated by the dilution of the DEGBR feed with an equivalent quantity of tap water. After this period, it was also noticed that the percentage removal of the BOD_5 was the highest among the three, with values ranging between 94.7 to 99.8%, suggesting a very good conversion of the organic matter within the DEGBR despite the variation of the OLR. However, the FOG trend showed some deviations from the other trends at day 56 and 105, where the values of the percentage removal were under 90%. This was explained by a lower concentration of the FOG in the influent for a similar effluent quality. However, herein, the variation of the OLR didn't affect the performance of the DEGBR, despite the effects of the temperature anomaly, which continuously happened between days 15 to 37, as demonstrated by the alteration of the DEGBR performance during that phase.

This performance of the DEGBR could be compared to the one of other anaerobic bio-reactors used in previous studies for PSW treatment. Basitere *et al.* (2016) assessed the treatment of PSW using an EGSB and achieved a tCOD removal of 65% at an OLR of 1 gCOD/L.day. Thereafter, Basitere *et al.* (2017) evaluated the anaerobic treatment of PSW using a SGBR and achieved an improved performance characterized by tCOD, TSS and FOG removals of 93%, 95% and 90%, respectively, at an OLR varying between 1.01 and 3.14 gCOD/L.day. Debik & Coskun (2009) also used the SGBR for PSW treatment and achieved a tCOD removal of 95%. Lastly, Del Nery *et al.* (2007) evaluated the treatment of PSW using a UASB and achieved 85% soluble COD removal and 67% tCOD removal, at an OLR of 1.6 ± 0.4 kgCOD/m^3.day and an up-flow velocity of 0.3 ± 0.1 m/h. Table 2 summarizes and compares the results of the DEBGR to the ones of previous studies whereby the treatment of PSW was approached using similar technologies. From this comparison, the DEGBR displayed the best results and can be considered as a good option for the treatment of PSW.

Table 2 | Comparison of the DEGBR's results to the ones of similar bioreactors used for the treatment of PSW

Reference	Technology used	Parameters	Results
Del Nery *et al.* (2007)	UASB	OLR: 1.6 ± 0.4 KgCOD/m^3.day; up-flow velocity: 0.3 ± 0.1 m/h	85% soluble COD removal; 67% total COD removal
Basitere *et al.* (2016)	EGSB	OLR: 1 gCOD/L.day, Operational temperature: 30–35 °C	65% total COD removal
Basitere *et al.* (2019)	SGBR	OLR: 1.01 to 3.14 gCOD/L.day, Operational temperature: 30–35 °C	93% COD, 95% TSS, and 90% FOG
Rajakumar *et al.* (2011)	Up-flow anaerobic filter	Low up-flow velocity: 1.38 m/day; mesophilic temperature (29–35 °C), Inoculation with non-granular sludge; 147 days to complete the start-up	70% total COD removal; 79% soluble COD; Methane yield at maximum removal efficiency: 0.24 m3CH_4/ KgCODremoved.day
Chavez *et al.* (2005)	UASB	OLR: 32 KgBOD_5/m^3.day; Operational temperature: 25–39 °C	95% BOD_5 removal
This study	DEGBR	Temperature: (30–35 °C), OLR varying between: 1.1 to 38.9 gCOD/L.day	99.6% COD Removal, 99.8% BOD_5 removal; 93.7% FOG removal

Biogas production

The continuous production and collection of biogas was a requirement that motivated the design of the DEGBR, as the entrapment of biogas within the granular bed or poor production of biogas are challenges that often affect the collection of biogas from some anaerobic systems (Yamamoto *et al.* 2009; Basitere *et al.* 2017). The continuous production and collection of biogas was accomplished as illustrated in Figure 5. The collected biogas showed a composition of 80.8% of CH_4, 3.6% of CO_2, 12,1% of O_2, 0.5% of H_2, 0% of H_2S and traces of other gases. The lack of H_2S in the

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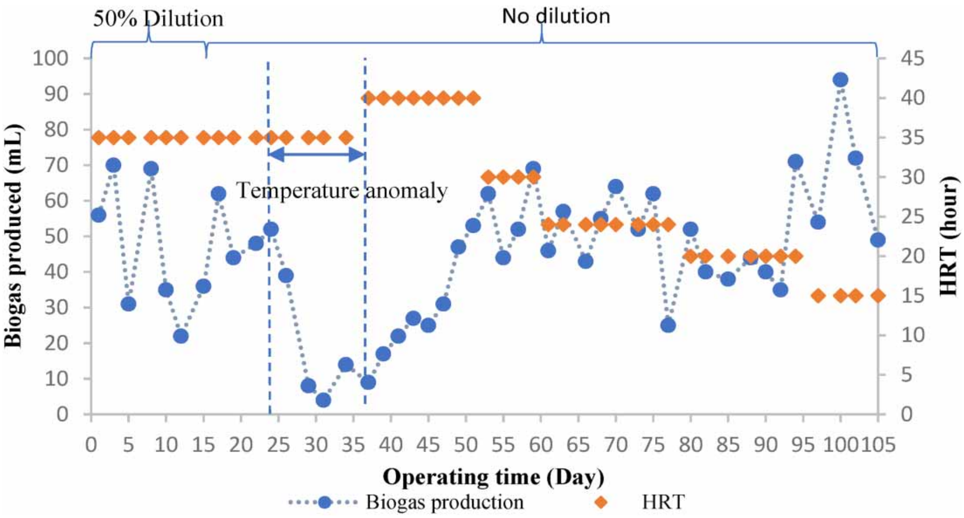

Figure 5 | Biogas production VS HRT variation.

biogas composition attested the efficiency of the uncoated iron oxide scrubber on the removal of H_2S. Furthermore, the low concentration of CO_2 proved the efficacy of the barrier solution (5% w/v KOH) in the dissolution of CO_2, as a higher concentration is normally expected from anaerobic digestion. However, the high concentration of O_2 was also noticed from this analysis. This could result from the penetration of air through a unit of the biogas treatment and collection set such as the Tedlar bag. Overall, the temperature anomaly highly influenced the biogas production, as the DEGBR was no longer operating under mesophilic conditions between day 24 and 37. To facilitate the re-adaptation of the system after the correction of the temperature anomaly, the HRT was increased to reduce the OLR until the system showed a return to a consistent biogas production at day 51. This return to appreciable biogas production rate was followed by step-wise reductions of the HRT for increased OLRs. Ultimately, this increase of OLR contributed to an increase in the production rate of biogas.

CONCLUSION

Overall, the bench scale DEGBR showed a good performance in terms of contaminants removal and biogas production, while addressing the challenges usually encountered in HRABs. These challenges included the difficulty associated with the operation of the three-phase separator, the washout of the biomass, head losses, biogas entrapment, limitation in the distribution of the organic matter to the biomass, and poor dispersion of toxic substances. All these challenges were addressed through the configuration and features of the DEGBR. The DEGBR was operated in a down-flow configuration to avoid the use of a three-phase separator and prevent the washout of the anaerobic biomass; with a recycle stream to improve the organic matter distribution to the biomass and subsequently its conversion, as well as the implementation of granular bed fluidization when required to improve the collection of biogas as well as the contact between the biomass and substrate, mixing of the granular bed, and dispersion of toxic substances.

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