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Municipal Wastewater Treatment and Associated Bioenergy Generation Using Anaerobic Granular Bed Baffled Reactor

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Abstract: *This study assesses a modified anaerobic granular bed baffled reactor (GRABBR) which was assessed for municipal wastewater treatment at high organic loading rates (chemical oxygen demand ≥ 1,100 mg/l) under varying temperatures. For the two mesophilic temperatures tested (37 °C and 25 °C) under steady state conditions, the removal of Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) was 80 to 90 %. At lower organic loadings, the reactor operated as a completely mixed system with most of the treatment occurring in the first two compartments. The GRABBR also showed very high solids retention with low effluent suspended solids concentration for all organic and hydraulic conditions. Applications of GRABBR as a single unit, two-phase treatment system could be an economical option reducing the cost to achieve similar treatment goals for high strength wastewaters. The findings of this research suggest that the application of GRABBR is suitable for the treatment of multiple pollutants present in wastewater where each compartment acts as a specialised treatment stage with biogas production.*

Keywords: *Anaerobic baffled reactor, Bioenergy, Domestic wastewater treatment, Methane*

1. Introduction

Anaerobic digestion (AD) is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen, used for industrial or domestic purposes to manage waste and/or to release energy (Speece, 1983; Pescod (1992). One of the advantages of anaerobic treatment is the production of methane (CH_4) which could be used for energy production. Anaerobic processes are well suited for high strength wastewater and are able to stabilise water properties with little biomass production. During aerobic digestion, the oxidation process releases high energy which allows rapid growth of essential bacteria (an important stage for the degradation stage).

On the contrary, anaerobic process releases little energy as a result of slow microorganism growth. During the aerobic process organic pollutants are used for cells construction (a change of microbial form). The stabilisation of organic pollutants is better with anaerobic processes because organic matter is transformed in carbon dioxide and methane (Colleran *et al.*, 1995; Siewhui *et al.*, 2012). AD is a multi-step process, consisting of series and parallel biochemical reactions. It is begun with hydrolysis which transforms complex polymers (e.g., proteins, carbohydrates and lipids) into smaller complexes such as fatty acids, amino acids, sugars and alcohols (Barber and Stuckey, 1999; Lier *et al.*, 2008). It's an important step which permits the formation of simpler substrates for subsequent step. The fermentation step follows hydrolysis (lier *et al.*, 2008). Smaller complexes are transformed into intermediate by-products (fatty acid and alcohols) but can be directly transformed into the methanogens precursor (acetate, carbon dioxide and hydrogen).

Figure 1 illustrates the changes of organic matter (proteins, carbohydrates, lipids) via hydrolysis, fermentation, acetogenesis and methanogenesis (generation of bioenergy). Different routes could be taken by substrates during this step of the AD process (See Figure 1). The preferential pathway is the conversion process to acetate because it provides the fermenters with a high energy yield as well as supporting the direct methane precursor (lier *et al.*, 2008). An acetogenis reaction allows the transformation of volatile fatty acid and alcohols which result in the production of acetate, hydrogen and carbon dioxide. The final step is the methanogenesis phase. During this step, some bacteria could transform carbon dioxide and hydrogen into methane and water (Eq.1) and other microorganisms aid in the breakdown of acetate into methane and carbon dioxide (Eq.2).

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2H_2O \qquad \text{Eq.1}$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad \text{Eq.2}$$

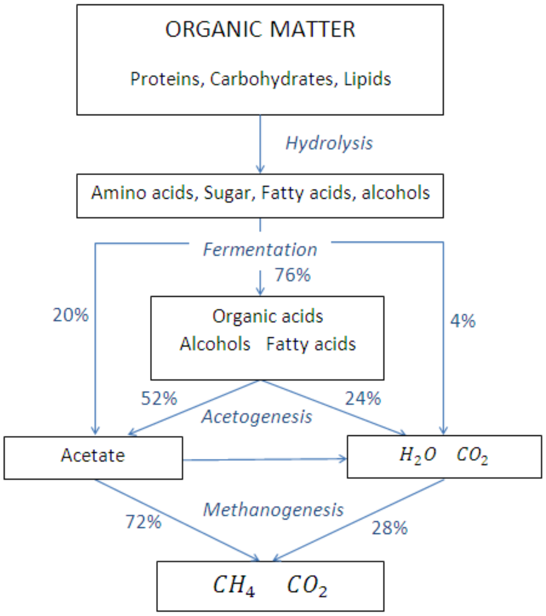

Figure 1. Methane Fermentation Stages
Source: After Miyamoto *et al.* (1997) and Lier *et al.* (2008)

According to Speece (1983), toxicity from the AD process is referred to as an adverse effect, not necessarily lethal on bacteria metabolism which can impair bacteria functions. Some substances are toxic for the biochemical reaction even at low concentrations such as oxygen. Nevertheless, other substances can become toxic if concentrations are too high such as ammonia, heavy metals, volatile fatty acids (VFA) and sulphides (Akunna, and Clark,1999; Barber and Stuckey, 1999). Monitoring pH levels gives an indication if the methanogenic reaction is inhibited or disturbed. If the methanogenesis phase is overloaded, VFA will accumulate in the reactor leading to a decrease in pH levels. The accumulated VFA can result in methnogenic toxicity. If this toxicity increases, the bacteria functions can be impaired and the methanogenesis capacity exceeded.

2. Anaerobic Granular Bed Baffled Reactors

The principles of an anaerobic granular bed baffled reactor (GRABBR) are based on a series of baffles between the inlet and the outlet, at the base of the reactor, wastewater passes through a sludge bed whereby microbes degrade organic loadings of various concentrations. The GRABBR produces low sludge and its performances permit having low hydraulic retention times (HRT). The wastewater treatment processes within GRABBR are really stable from hydraulic and organic shock loadings. Another significant benefit from GRABBR is its ability to separate acidogenesis and methanogenesis phases longitudinally. The GRABBR combines the advantages of a baffled reactor (phase separation) and of an upflow-anaerobic sludge bed reactor (UASB) (Granular sludge with good settable properties) for improved the process efficiency. This study aims to assess the performance of the GRABBR reactor for the treatment of municipal wastewater for different mesophilic temperature conditions (37°C and 25°C).

The interest of running the GRABBR at lower temperatures can result in a reduction of the overall treatment cost (decrease in energy requirements). The performance of the GRABBR was measured at varying hydraulic retention times (HRT) ranging from 2 hours (h) to 24 h. Lower HRT can lead to an increasing methane yield of the reactor based on a reduction in size. The operation of this reactor occurs where wastewater is pumped to flow across a series of baffles between the inlet and outlet, forcing the water to pass over and under the baffles. In the bottom of the reactor, water passes through a sludge bed where bacteria could degrade organic matter (Barber and Stuckey, 1999). Anaerobic Baffled Reactors (ABR) have several advantages which include: simple designs, no mechanical mixing, inexpensive to construct and to operate and special gas separation channels are not required.

The reactor is constructed to produce little sludge and its performance permitting lower HRTs. The process is relatively stable from organic shocks, hydraulic shocks and toxic materials as stated previously. However the most significant benefit of the ABR reactor is its ability to separate the acidogenesis phase and methanogenesis phase longitudinally (Barber and Stuckey, 1999). This phase separation property, which makes ABR reactor unique, is suitable for the treatment of complex substrates and contributes to the stability of the process (Baloch and Akunna, 2002). The ABR is very efficient as a result of optimising environmental conditions for methanogens and acidogens due to this phase separation. The stability of the system is explained by the buffer properties of the acidogenic phase which protects the methanogenic phase (Baloch, 2009). Despite all these advantages, at short HRT, the ABR performance is relatively low. In this case, the loss of biomass could be an issue leading to poor wastewater treatment. To resolve this problem, it is preferable to use a biomass that is structurally stable and possess good settling characteristics (Baloch and Akunna, 2003).

The GRABBR is an ABR reactor with granular sludge. It combines the advantages of a baffled reactor (phase separation) and that of an Upflow Anaerobic Sludge Blanket (UASB) digestion reactor (Granular sludge with good settable properties) for improved process efficiency (Chong *et al.*, 2012). Like the ABR, because of compartmentalisation, the GRABBR encourages phase separation with acidogens zone in the compartments closest to the inlet and a methanogens zone in compartments nearer to the outlet. If the metanogens phase is granular, the acidogens phase is mostly non-granular. The GRABBR generally shows a very high solid retention rate because of this phase separation with granular sludge in the last compartments (Akunna and Clark, 1999; Muhammad *et al.*, 2011). Furthermore, Akunna and Baloch (2003) found that the higher the organic load rate (OLR) the more stable the treatment becomes with an increased number of compartments involved. At low OLRs (up to 5kg COD/m^3/day), a single compartment is necessary for a complete wastewater treatment.

Moreover, Baloch and Akunna (2008) led a study on the granular sludge and its structure based on the performance of a GRABBR. A multi-layered structure and a vast diversity of microorganisms carracterized these granules within the sludge. The core of the grannular sludge was composed in its largely part of *Methanoseta*-like celles. According to (Baloch, 2009), this bacteria play a key-role in the formation of the granules, as well as environmental factors such as temperature, pH, wastewater origin and the avaibility of nutrients. Furthemore, minerals (calcium, iron, potassium, phosphorus, sulphur, magnesium and sodium) play an important part and a key-role in the stabilisation of these granules.

As stated previously, the GRABBR encourages seperation phases. Additionally, in the acidogenic zone, granular sludge is disintegrated and the formation of a non-granular microbial mass, widely composed by gram negative *Klebsilla pneumonia* was observed (Baloch and Akunna, 2003). In the methanogenic phase, the granules were found to be relatively stable with a regular surface. On the other hand, in the acidogenic compartment, granules showed broken parts and fissured surfaces. The presence of bacteriophage could explain this disintegration of the granular sludge in the acidogenic phase (Baloch, *et al.*, 2008). Granular sludge are less sensitive to substrate inhibition and oxygen toxicity than non-granular sludge which explain, partly, the improvement of performance of the GRABBR reactor in comparison with ABR (Baloch, 2009).

3. Material and Methods

3.1 The Granular Bed Baffled Reactor

The Granular Bed Baffled Reactor (GRABR) used in this study was a rectangular shaped bench-scale system. The reactor was divided in five equal compartments. A gap in the top of the baffle allowed wastewater to flow from one compartment to the other. Every compartment was divided in two parts due to a hanging vertical baffle angled at 45° at the base (see Figure 2). Three sampling ports were located in each compartment for liquid and gas collection and analysis. A second tray surrounded three sides of reactor with circulation of heated water, controlling the temperatures. American standard methods procedures were followed for analytical procedures and water quality analysis (APHA, 1992; Hach Company, 2002). Tables 1 and 2 show the design parameters of the laboratory pilot-scale GRABBR, and the equipment used for GRABBR water and energy resource recovery facility at pilot-scale, respectively.

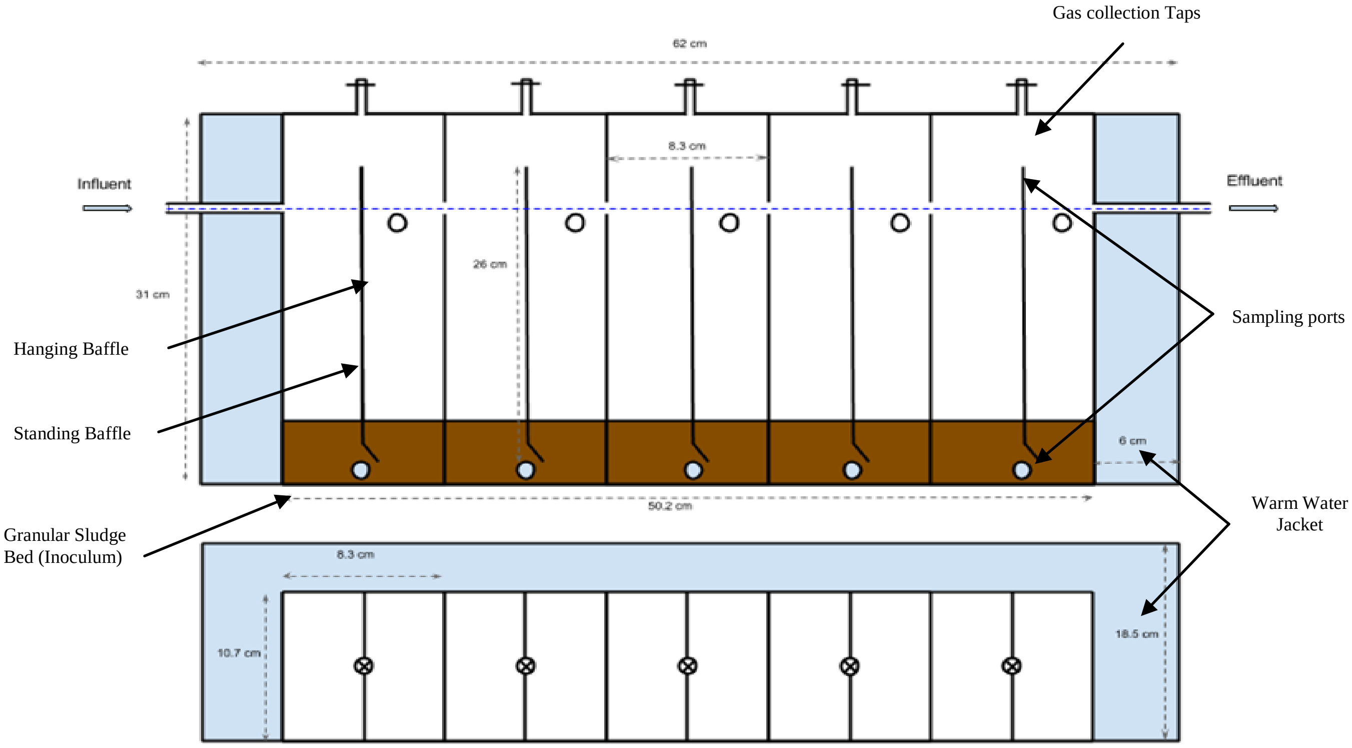

Figure 2: Schematic Diagram of Granular Bed Baffled Reactor (GRABBR) with Five Compartments

Table 1. Laboratory Pilot-Scale GRABBR Reactor Design Parameters

Parameter	Value
Reactor dimensions (cm)	50 × 12 × 31
Working Volume (Litres)	10
Number of compartments	5
Number of sampling ports per compartment	3
Depth of feed in the reactor (cm)	6
Thickness of standing baffle (cm)	1.2
Thickness of hanging baffle (cm)	0.6

Table 2. Equipment Used for GRABBR Water and Energy Resource Recovery Facility at Pilot-scale

Device	Brand	Model	Location/ Country
Air pump	Interpret	Avmini evolution	Surrey, UK
Peristaltic pump	Cole-Pamer	Masterflex L/S Model 77200-50	Barrington, USA
Thermometer	ATP	TK 260	Leicestershire, UK
Heating pump	Fisher scientific	Isotemp	Loughborough, UK

A peristaltic pump (Masterflex L/S) was used to pump the wastewater and sewage through the reactor and the effluent is collected in a small cistern. An air pump (Interpret) kept a high oxygen rate in the influent sewage tank (see Figure 3). The temperatures of each compartment and tank were checked periodically with a thermometer (ATP) using a probe in each compartment of the reactor. During the experimentation, temperatures of the reactor were raised to 25°C or 37°C, respectively. A Heating pump (Fisher scientific) boiled water in a nearby storage tank and circulated this water in the reactor's jacket. The wastewater treatment process was a closed-circuit, thus, the hot water which heats the GRABBR up to 25°C or 37°C returns into in separate hot water storage tank (see Figures 2 and 3). The reactor was seeded with anaerobic granular sludge obtained from Hatton Wastewater Treatment Works, Arbroath, Scotland, UK. At the beginning of the experiments, the COD was at 1448 mg/L.

3.2 Water Resource and Energy Recovery Pilot Plant Operational Strategy

The active volume of the reactor is 10 litres. At an operating speed 1, the pumping flow rates were 1.6 x 10^{-3} L.s^{-1}. Therefore, the pump required 2 hours 45 minutes to refill all the volume of the reactor. A hydraulic retention time (HRT) of 24 hours was required for the initial experiments. Therefore, we need to distribute the 2h 45mins of pumping time during 24 hours. The effluent flow which comes from wastewater treatment works, is not regular throughout the day. Between 7 am and 9am and between 7 and 9 pm, the flowrate is the highest when compared to the rest of the day.

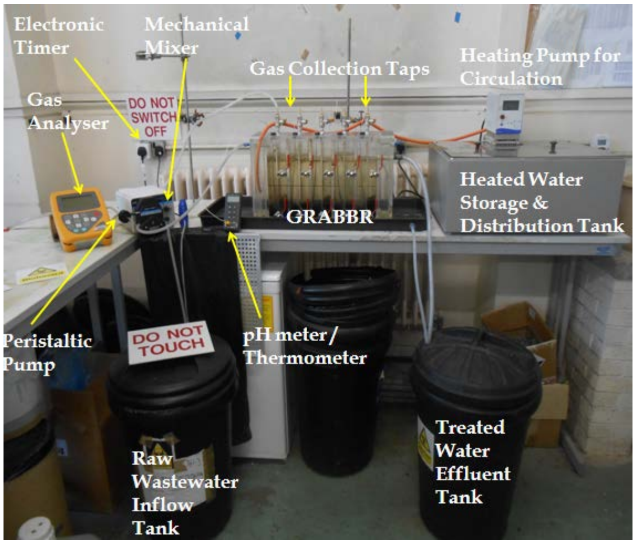

Figure 3. Wastewater Treatment Pilot Plant (water resource and energy recovery facility) using GRABBR Experimental Setup

In order to replicate these flow conditions and differences, the pumping time was doubled during the peak flow periods. Thus, the day was segmented into 5 periods, 2 for high flowrates and 3 for low flowrates. The pumping time was distributed in this way: 21 minutes per low flow rate periods, and 42 minutes per high flow rate periods. A timer allowed us to distribute the pumping time in ten periods (see Table 3).

Table 3. Pumping time distribution

Program	Start	End	Day period	Flow rate
1	0:00 am	0:04 am	0:00 am - 7:00 am	Low
2	1:24 am	1:28 am		
3	2:48 am	2:52 am		
4	4:12 am	4:16 am		
5	5:36 am	5:41am		
6	7:15 am	7:25 am	7:00 am – 9:00 am	High
7	7:45 am	7:56 am		
8	8:15 am	8:26 am		
9	8:45 am	8:55 am		
10	10:00 am	10:04 am	9:00 am – 5:00 pm	Low
11	11:30 am	11:34 am		
12	1:00 pm	1:05 pm		
13	2:30 pm	2:34 pm		
14	4:00 pm	4:04 pm		
15	5:15 pm	5:25 pm	5:00 pm – 7:00 pm	High
16	5:45 pm	5:56 pm		
17	6:15 pm	6:26 pm		
18	6:45 pm	6:55 pm		
19	8:50 pm	9:00 pm	7:00 pm – 12:00am	Low
20	10:40 pm	10:51 pm		

3.3 Municipal Wastewater Characteristics and Inoculums

The wastewater used for the experimentation was collected from municipal wastewater treatment plants which came from Haton wastewater treatment works and Guardbridge wastewater treatment works, Fife, Scotland, UK. Samples were collected twice weekly just after the screening process (see Table 4).

3.4 Analytical Methods

3.4.1 pH

The pH values of samples were measured using a 240 Corning pH meter (Orian model 420A with auto temperature compensation probe). The pH meter was calibrated by a pH 7.00 and 4.00 buffer regularly.

3.4.2 Chemical Oxygen Demand (COD)

The COD was measured with a colorimetric method using a direct reading DR 5000 Hatch Lange spectrophotometer (Hatch, Loveland, USA) as described in Hach (2002). A cuvette test (Hach Lange, model LCK 514 and LCK 314) was used for more precision. With this test, oxidizable substances react with sulphuric acid-potassium dichromate solution in the presence of silver sulphate. Chloride is masked by mercury sulphate. The green coloration of Cr3+ is evaluated.

3.4.3 Biological Oxygen Demand (BOD) at 5 day and 20°C

To measure BOD, samples required high dilution. In this way, oxygen isn't a limiting reagent. Distilled water was used for the required dilution and sample preparation. Four solutions were added at the concentration of 1 ml per litre of distilled water: calcium chloride solution, a phosphate buffer, a magnesium sulphate solution and a ferric chloride solution. One ml of allylthiourea solution is added to inhibit the nitrification. Distilled water is saturated in oxygen with an air pump. In the laboratory, flasks used have a volume of 275 ml, thus the dilution factors F selected were 1/275, 3/275, 1/55, 10/275 and 15/275. The oxygen rate was measured before the flasks that are placed an incubator at 20°C during 5 days: it gives the T_0 reading (Eq.3).

BOD measurements were made with a Hatch LDO oxymeter (model HQ30d flexi). Five days after, the oxygen rate is once again measured: it is the T_5 reading (Eq. 3). Two blank tests were made to make more accurate BOD reading and eliminate errors from the BOD result. The following equation was used to measure the BOD. The final BOD was computed by averaging the different BOD dilutions for the same sample.

$$BOD_5 = F(T_0 - T_5) - (F - 1)(D_0 - D_5) \qquad \text{Eq.3}$$

where

BOD_5 = *Biological Oxygen Defend at 5th day*
F = *Dilution Factor*
T_0 = *Oxygen rate in the sample at Day 0*
T_5 = *Oxygen rate in the sample at Day 5*
D_0 = *Oxygen rate in Blank at Day 0*
D_5 = *Oxygen rate in Blank at Day 5*

3.4.4 Gas analysis

A gas analyser (Geothermical instruments, Model GA2000, Leamington Spa, Warwickshire, UK) was used to measure the composition of biogases formed by the anaerobic reaction in the reactor. CO_2, CH_4 and O_2 were measured in percentage of the total composition and H_2S and CO were measured in parts per million (ppm). The Guardbridge wastewater influent was on average a higher strength waste stream when compared to that of the Hatton inflow. The Guardbridge average COD was 759 mg/L approximately three times as high as the Hatton COD inflow (244 mg/L). Similarly, the Hatton total suspended solids (TSS) were twice as low when compared to the influent wastewater from Gauardbridge wastewater treatment works.

4. Results and Discussion

4.1 Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) Removal

For the two mesophilic temperatures evaluated (37^{0}C and 25°C) under steady state conditions the GRABBR had good performances for the treatment of low-strength municipal wastewaters with high solid content. The removal of BOD and COD ranged from 80 to 90 %. For an HRT of 2 days, a temperature at 37°C and a BOD influent at 1,755 mg/L, the BOD removal was approximately 90%. Throughout the analysis the pH of the effluent remained stable between 7 and 7.5 for all organic loading rates (OLR).

Table 4. Influent municipal wastewater composition for pH, Chemical oxygen demand (COD), Biochemical oxygen demand (BOD) and Total suspended solids (TSS) for Haton wastewater treatment works and Guardbridge wastewater treatment works, Scotland, UK
Sample number n = 70 and period of analysis (January 2014 – August 2014)

Parameters	Mean Concentrations	Standard Deviation	Minimum	Maximum
pH	7.54 [7.22]	0.18 [0.15]	6.86 [6.89]	7.83 [7.74]
Chemical oxygen demand (COD) mg/l	244 [770]	98 [193]	170 [653]	360 [1200]
Biochemical oxygen demand (BOD) mg/l	106 [290]	46.4 [87.6]	70 [180]	200 [516]
Total suspended solids (mg/l)	27 [55]	14.8 [13.3]	11 [21]	46 [62]

Figure 4 shows an average measure of BOD and COD in each compartment of the GRABBR with Hatton and Guard Bridge Wastewater Influents, respectively. At lower organic loadings, the anaerobic reactor operated as a completely mixed system with most of the treatment occurring in the first two compartments. Temperatures at 25°C (not optimal temperatures for anaerobic reactions), with an HRT of 24 hrs, the BOD, COD and TSS removal were well within the EC Urban Waste Water Treatment Directive discharge standards (BOD < 25 mg/l ; COD < 125 mg/l). At both temperatures, the reduction of the HRT showed a good resilience on the water treatment performance of the reactor until the HRT dropped below 2 hrs. A 0.89 Organic Loading Rate (kg.COD/m3/day) with a HRT of 24 hrs gave an equivalent to 94% COD Removal and 98% BOD removal rates respectively from the mean inflow sewage and wastewater collected. The production of methane remained relatively low in all segments of the GRABBR throughout the experiments. The volume of CH_4 produced was around 10-20 mL in the entire reactor even thou the COD removal increased significantly from 10 to 100 g/day.

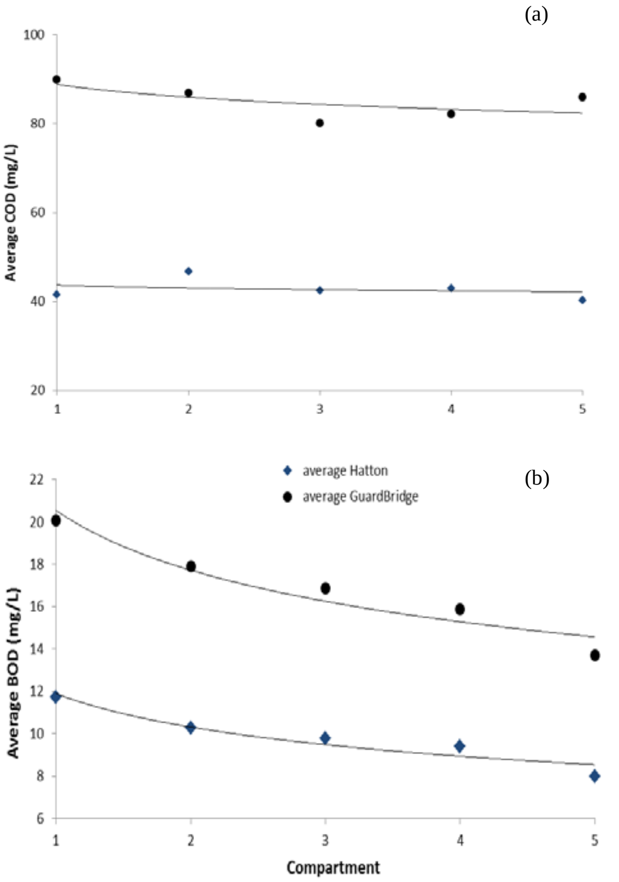

Figure 4. Average measure of (a) BOD and (b) COD in each compartment of the GRABBR with Hatton and Guard Bridge Wastewater Influents, with a HRT of 24 hrs. Sample number n = 70 and period of analysis (January 2014 – August 2014)

For this project, the influent for all waste streams was collected weekly from a wastewater treatment plant. Consequently, the characteristics of the inflow are variable due to the variability of the human activities or the weather (higher or lower levels of precipitation). Thus, the ORL did not increase linearly with the HRT decreasing. It is particularly clear when the HRT varies from 24 hrs to 18 hrs and the ORL remains nearly the same, or when the HRT ranges from 6 hrs to 2 hrs, the OLR increases by a factor of 5 during this time. Nevertheless, the OLR increases along all the experiments. Thus, the comparisons with the different HRT are important to the study. Figure 5 shows the increase of the COD in the compartments of the GRABBR during the experiments.

On two occasions, the COD measured of some compartments exceeded 125 mg/L the maximum concentration in COD according to European standard discharge. With a HRT of 2 hrs, the COD measured of the last compartment exceeded the standard discharge only once. More measures would be necessary to make a sound conclusion on its performance, but the overall performance of the GRABBR seems to be very efficient when the HRT is at 2 hrs with respect to the standard discharge requirements. Furthermore, the COD measures of the different compartments were not significantly different ($p > 0.05$). Despite an increase of the ORL, the most part of the COD removal took place in the first compartment of the reactor. Table 5 shows the COD and BOD removal in relation to the Hydraulic Retention time (HRT) and the Organic Loading Rates (OLR).

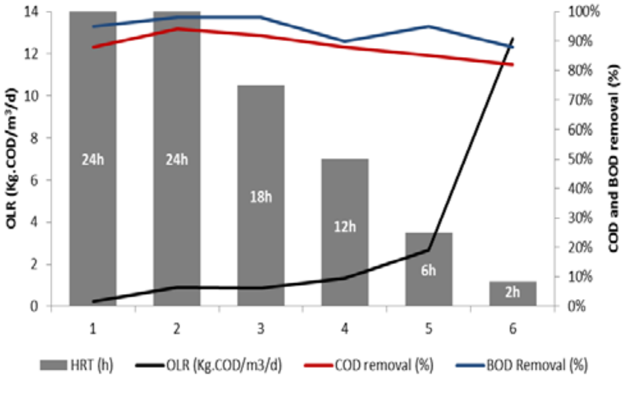

Figure 5. Chemical oxygen demand (COD) and biochemical oxygen demand (BOD) removal rates, organic loading rates (ORL) and decreasing hydraulic retention times (HRT) from 24 hrs to 2 hrs.

4.2 Biogas Production and Composition

The GRABBR in previous studies have good performances for the treatment of high strength wastewaters with high solid content like brewage processing waters (Baloch and Akunna, 2003). The treatment of brewery wastewater with a GRABBR

Table 5. COD and BOD removal in relation to the Hydraulic Retention time (HRT) and the Organic Loading Rates (OLR)

Wastewater	OLR (Kg.COD/m^3/d)	HRT (hr)	COD removal (%)	BOD Removal (%)
Hatton WWT	0.24	24	88	95
Guardbridge WWTW	0.89	24	94	98
	0.87	18	92	98
	1.33	12	88	90
	2.20	6	85	95
	12.7	2	82	91

consisting of 10 compartments showed a good removal efficiency of organic matter. The removal of BOD and COD ranged between 80% and 90% (Akunna and Clark, 1999). For an HRT at 2 days, a temperature at 37°C and a BOD Influent at 3,755 mg/L, studies by Baloch and Akunna (2003) and Akunna and Clark (1999) found a mean BOD removal of 90%. Furthermore, for varying GRABBR assessment, research conducted by Akunna and Clark (1999), Baloch and Akunna (2003) and Baloch, *et al.* (2007), found the pH of the effluent to be very stable between 7 and 7.5 for any OLR. Furthermore, Akunna and Baloch (2003) showed a high production of methane in the GRABBR: around 60% for an OLR from 20kg de COD.m-3.d-1 at a temperature of 35°C. In another study, the methane composition was found to range between 62% and 75% for on ORL between 2.16 and 13.38 kg COD.m-3.d-1 and a temperature at 35°C. The GRABBR inflow feed was brewery wastewater for those studies (Baloch *et al.*, 2007).

The production of methane remained low during all the experiment. The volume of CH_4 produced remained stable around 10 mL in the entire reactor even though the COD removal increases significantly from 10 to 100 g/day. Figure 6 shows the average composition of CO_2, CH_4 and O_2 in each compartment of the GRABBR.

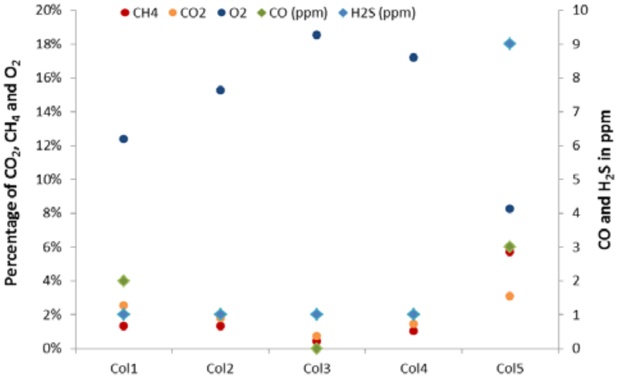

Figure 6. Average composition of CO_2, CH_4 and O_2 in each compartment of the GRABBR

Most of the COD removal took place in the first compartments where the acidogenesis phase prevails. The wastewater passing through the last compartments, where the methanogenesis takes place, has a lower concentration of organic matter which limits the production of methane. This hypothesis could explain the decrease of the methane production. The COD removal rates increases as the wastewater flows across the reactor but with little effect or change for the removal rates regarding the last two compartments where the methanogenesis phase occurs. Mathematically, the methane production decreases whilst the reaction stabilises as shown from the volume of CH_4 produced. The COD removal in compartments 3, 4 and 5 were not significantly different from each other throughout the experiments.

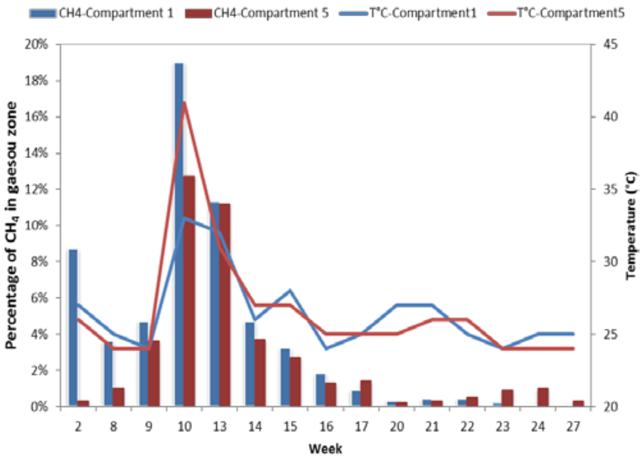

Figure 7. Percentage of methane (CH_4) present in gaseous zone within chamber and water temperature fluctuations between 25 to 40°C for compartments 1 and 5.

Furthermore, the decreasing of the HRT led to a reduction in time for the influent to be heated (25 °C or 35 °C) in the reactor as a result of the hot water circulating the GRABBR via the warm-water jacket. Thus, the temperature in the reactor decreases slowly with the reduction of the HRT even if the hot water in the jacket stays stable at 50 °C. Nevertheless, the temperature has a direct effect on the performance of the methanogenesis phase. The reduction of the temperature (operating at 25°C or lower) could explain the reduction in overall methane yield.

Table 5. Specific Methane (CH_4) yield and relative Hydraulic Retention Time (HRT)

HRT (hr)	Average of total volume of CH_4 in the reactor (L)	Average of COD removal (g/day)	Specific Methane yield (L/g.COD removed)
24	9.6×10^{-3}	7.9	1.2×10^{-3}
18	6.7×10^{-3}	7.4	9.0×10^{-4}
12	10.3×10^{-3}	11.2	9.2×10^{-4}
6	12.2×10^{-3}	16.5	7.4×10^{-4}
2	9.4×10^{-3}	106.9	8.7×10^{-5}

4. Conclusion

For the treatment of the municipal wastewater, the GRABBR shows excellent performance for the reduction of COD, BOD, and TSS. Even at lower mesophilic temperatures (i.e., 25°C) which is not an optimal AD operational temperature for the anaerobic reaction, and a HRT of 24 hours, the BOD, COD and TSS removal rates were well within the European wastewater treatment standard discharge regulations. At 35°C, the reduction of the HRT showed a good resiliency with respect to the performance of the reactor until the HRT drops below 2h. Nevertheless the good performance of the GRABBR for the removal of wastewater pollutants and the production of methane is one of the most interesting research areas of AD processes.

Recommendations for future research include ensuring that the reactor performs over a longer period of time to consolidate the performance and results for varying wastewater inflows. Measuring of VFS is important to assess the AD reaction and treatment performance in addition to understanding the reasoning behind lower production of methane. An improved temperature control of the reactor is needed, which allows better heat exchange between the hot water tank and the GRABBR improving the thermic exchanges between the jacket and the core of the reactor.

Insulating materials would not aid in the anaerobic process for the reactor. Heating the influent in order for the mesophlic bio-digestion phase to occur between 20°C and about 40°C, typically 37°C is most optimal to produce biogas, biofertilisers and sanitarisation mainly in tropical countries such as the Caribbean.

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