Comparing the performance of UASB and GRABBR treating low strength wastewaters

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ABSTRACT

Anaerobic technologies have proved successful in the treatment of various high strength wastewaters with perceptible advantages over aerobic systems. The applicability of anaerobic processes to treat low strength wastewaters has been increasing with the evolution of high-rate reactors capable of achieving high sludge retention time (SRT) when operating at low HRT. However, the performance of these systems can be affected by high variations in flow and wastewater composition. This paper reports on the comparative study carried out with two such high rate reactors systems to evaluate their performances when used for the treatment of low strength wastewaters at high hydraulic rates. One of the two systems is the most commonly used upflow anaerobic sludge blanket (UASB) reactor in which all reactions occur within a single vessel. The other is the granular bed baffled reactor (GRABBR) that encourages different stages of anaerobic digestion in separate vessels longitudinally across the reactor. The reactors, with equal capacity of 10 litres, were subjected to increasing organic loading rates (OLRs) and hydraulic retention times (HRTs) of up to 60 kg COD m^{-3} d^{-1} and 1 h respectively. Results show that the GRABBR has greater processes stability at relatively low HRTs, whilst the UASB seems to be better equipped to cope with organic overloads or shockloads. The study also shows that the GRABBR enables the harvesting of biogas with greater energetic value and hence greater re-use potential than the UASB. Biogas of up to 86% methane content is obtainable with GRABBR treating low strength wastewaters.

Key words | acidogenic zone, biomass washout, GRABBR, hydraulic retention time, methanogenic zone, organic loading rate, phase separation, UASB

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INTRODUCTION

Anaerobic digestion presents a solution not only to sustainable waste treatment but also in terms of addressing future energy demands with biogas production. Anaerobic technologies have proven successful for treating high strength wastewaters with perceptible advantages over aerobic systems (Lettinga *et al.* 1997; Baloch 2004; Karim *et al.* 2004; Leitao *et al.* 2005; Aiyuk *et al.* 2006; McHugh *et al.* 2006; Li *et al.* 2007).

The treatment of high flow low strength wastewaters such as domestic wastewater requires the capability to handle large volumes of effluent with variable characteristics. Low strength, high flow wastewaters can cause washout of active biomass which may lead to an accumulation of organic acids due to the relatively low growth rate of the methanogenic bacteria (Harleman & Murcott 2001; Kalogo & Verstraete 2001, cited in Aiyuk *et al.* 2006). The performance of anaerobic systems treating this type of wastewater can also be affected by changes in wastewater flow rates and composition. Transient changes in influent characteristics can bring about improper balance between acidogenic and methanogenic microbes, leading to the dominance of the acidogenic phase and hence the accumulation of volatile fatty acids (VFA) (Droste 1997; Baloch 2004).

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One of the advantages of anaerobic treatment over aerobic is the production of biogas, in the form of methane. The quality (and quantity) of biogas produced during the treatment of low strength wastewaters is usually low, thereby making energy recovery and reuse less cost effective. Excessive decrease in the hydraulic retention time (HRT) (which is necessary in order to operate at a cost effective organic loading rate (OLR)) may result in increased redox potential within the reactor. This operation may lead to the dominance of acidogenesis over methanogenesis and thus the production of biogas with relatively low methane content.

The upflow anaerobic sludge blanket (UASB) reactor is the most commonly used anaerobic technology for the treatment of high strength wastewaters (Van Haandel & Lettinga 1994; Bodik *et al.* 2003; Baloch 2004). It relies on the development of a dense active biomass at the lower portion of the reactor (Droste 1997) and all the biochemical stages of anaerobic digestion process occur simultaneously within a single vessel. Loading rates to the UASBs can reach 40 kg COD $m^{-3} d^{-1}$ with hydraulic retention times (HRTs) of 24 h or less (Droste 1997; Baloch 2004; Aiyuk *et al.* 2006).

Phase-separated anaerobic technologies, where acid-forming and methane-forming microorganisms are encouraged to grow in different zones, have been reported to be capable of reducing the risk of process inhibitions due to VFA accumulation and thus possess good process stability and control characteristics (Pohland & Ghosh 1971; Anderson *et al.* 1994; Droste 1997; Liu 1998; Barber & Stuckey 1999; Baloch & Akunna 2003*a*,*b*; Baloch 2004).

The Granular bed baffled reactor (GRABBR) is a two-phase anaerobic technology. It is an anaerobic baffled reactor seeded with UASB anaerobic granules, thus it can be described as UASBs in series (Baloch *et al.* 2006). Like the UASB, the GRABBR has been successfully used in the treatment of high strength wastewaters (Baloch & Akunna 2003*a*,*b*; Baloch 2004; Baloch *et al.* 2006).

This paper reports on a study which compared the performance of both reactors for treating low strength wastewaters at high hydraulic rates. Both reactors were subjected to HRTs which varied from 20 to 1 hr, corresponding to OLRs of 3 to 60 kg COD $m^3 d^{-1}$. The main objective of this research was to understand the technological, process, operational and control requirements associated with anaerobic treatment of low strength high flow wastewaters.

MATERIALS AND METHODS

The physical description of the two anaerobic technologies used for this study is as follows.

UASB

The UASB reactor had a working volume of 10 litres, with a diameter–height ratio of 5.5. It consisted of two perspex cylinders placed concentrically (centred on the same axis) on a single sheet of Perspex. The outer cylinder served as the water jacket through which hot water was circulated to maintain the contents at 35°C. The inner cylinder tapered towards a central opening at the bottom through which the wastewater was introduced. Hot water was circulated to the outer cylinder through an orifice near the bottom of the vessel. Hot water was withdrawn from the outlet at the top of the outer cylinder to be circulated to the water heater. A three-phase separator (i.e. a facility that reduces biomass washout by the influence of upflow liquid movement and buoyancy caused by gas bubbles) consisting of a circular baffle and a central gas cap was carefully designed to direct the gas laden granules to the top and retain them from the effluent stream. Figure 1 shows a schematic representation of the reactor.

GRABBR

The GRABBR was also constructed using Perspex (Figure 2) and had a total working volume of 10 litres. It consists of five compartments of equal size with hanging baffles and three-phase separators. The intercompartmental areas were separated into an upflow and downflow section by hanging baffles. A water jacket enclosed the GRABBR on three sides for temperature control and the fourth side was left open for observation and sampling purposes. Sampling ports were provided for biogas, effluent and biomass in all the compartments. A schematic diagram of the GRABBR is shown in Figure 2.

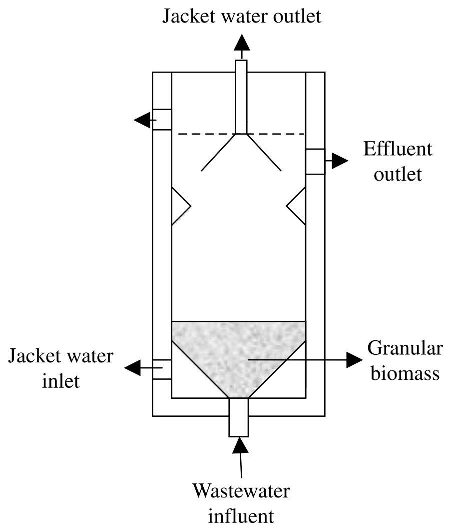

Figure 1 | Cross sectional view of the upflow anaerobic sludge blanket (UASB).

EXPERIMENTAL PROCEDURE

Both reactors were inoculated with the same volume of seed biomass of 2000 ml or 20% of effective volume. The seed sludge was obtained from an industrial scale UASB plant treating paper mill wastewater in Aberdeen, UK. For the GRABBR, the first and second compartments were seeded with 100 ml of the seed biomass, while the third, fourth and fifth compartments received 600 ml each of the sludge.

Both reactors were subsequently fed with a synthetic wastewater containing glucose as the only source of organic carbon. A concentrated stock solution of the synthetic wastewater was prepared and diluted with tap water to obtain an influent COD of 2,500 mg l^{-1}, and the pH adjusted to 7.5. The influent concentration was kept constant throughout the study. The composition of the feed was as follows: $C_6H_{12}O_6$ (2,500 mg l^{-1}), NH_4HCO_3 (500 mg l^{-1}), KH_2PO_4 (200 mg l^{-1}), $NaHCO_3$ (1,250 mg l^{-1}), $MgSO_4$ (2.5 mg l^{-1}), $FeCl_3$ (2.5 mg l^{-1}), $CaCl_2$ (2.5 mg l^{-1}), KCl (2.5 mg l^{-1}), $CoCl_2$ (0.5 mg l^{-1}) and $NiCl_2$ (0.5 mg l^{-1}).

The start-up HRT corresponded to an OLR of 3 kg COD $m^{-3}\,d^{-1}$. The reactors were subsequently subjected to OLRs of 10, 15, 20, 30 and 60 kg COD $m^{-3}\,d^{-1}$ by decreasing influent HRT to 6, 4, 3, 2 and 1 h respectively once steady state performance was observed. Steady state was said to be achieved when determinant values of three replicate samples obtained after three HRTs were relatively small or negligible. No effluent recycle or settling was carried out. The study was carried out over a period of about 120 days.

METHOD OF ANALYSIS

Reactor feeding was carried out using variable speed Masterflex peristaltic pumps. Temperature control was achieved by hot water, heated by a thermostatic heater (Camlab, UK) and recirculated using a Techne variable speed pump (Clifton Cambridge, UK). Soluble COD (SCOD) was determined by colorimetric method (Montgomery *et al.* 1962) using a direct reading DR/2500 Spectrophotometer (Hach, USA) as described in the Hach handbook (1992). pH values were obtained using a pH meter M420 (Coring, UK) fitted with Ross pH combination electrode 8102 (Orion, USA). Total suspended solids (TSS) and volatile suspended solids (VSS) were determined according to *Standard Methods* (APHA 1992). Gas volume was measured by liquid displacement method. Gas Com-

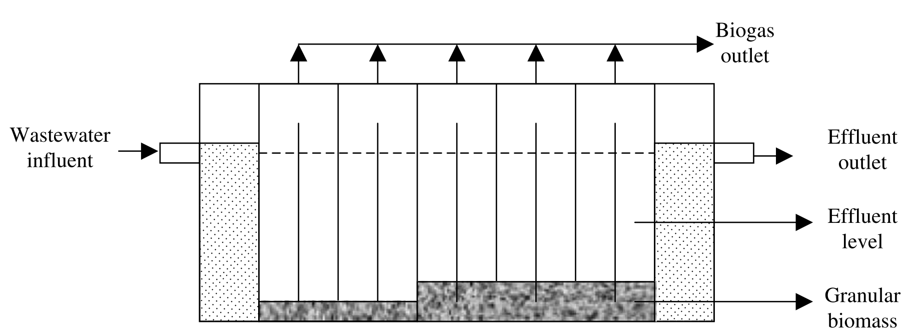

Figure 2 | Granular bed baffled reactor (GRABBR).

position was determined using a LFG gas analyser (Analytical Development Company, UK). Settling velocity tests were carried out on granular biomass using the UFT method (Michelbach & Wohrle 1993).

RESULTS

COD removal

Both reactors exhibited rapid start-up with high SCOD removal at steady state, as shown in Figure 3. For the initial OLR of 3 kg COD $m^{-3} d^{-1}$ the GRABBR and UASB achieved 93 and 88% COD removal respectively within 5 days of operation. Most of the SCOD reduction for this initial loading occurred within the first three compartments of the GRABBR as shown in Figure 4. At 1 h HRT (or OLR of 60 kg COD $m^{-3} d^{-1}$) severe wastewater bypassing and channelling were observed in both reactors. At this hydraulic loading the GRABBR and UASB achieved 57% and 51% SCOD removal respectively. For both reactors, effluent SCOD increased with decrease in HRT (or decrease in OLR), with the GRABBR demonstrating (slightly) superior process efficiency over the UASB.

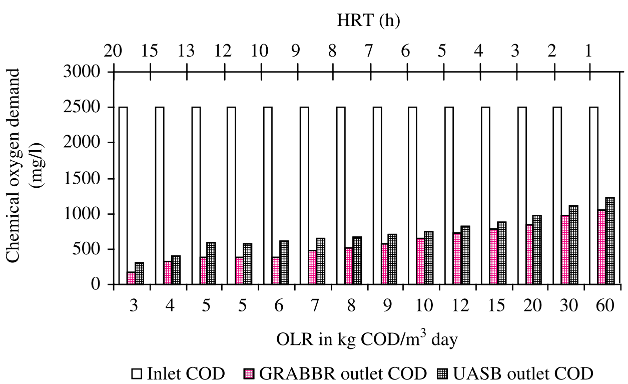

Figure 3 | Comparison of the influent COD and effluent COD from the GRABBR and the UASB.

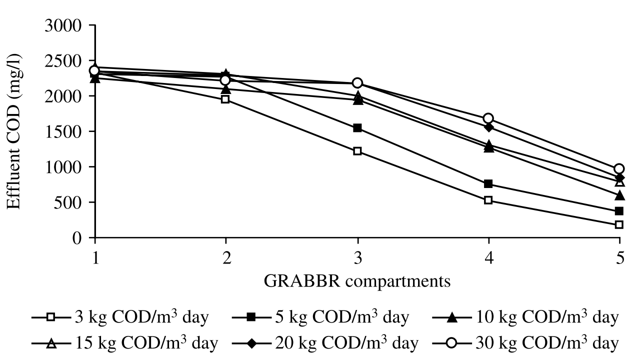

Figure 4 | Profile of influent COD breakdown in the GRABBR compartments.

Biomass washout

Excessive break-up of the granular biomass was observed in the earlier compartments of the GRABBR from 4.5 kg COD $m^{-3} d^{-1}$, giving rise to the production of predominantly greyish and slimy bacteria. These non-granular bacteria were carried away by the influent stream to downstream compartments. Initially, the denser granular biomass in the latter compartments 'filtered' out most of these non-granular biomass and this resulted in relatively low solids in the final effluent. However, lower HRT (or higher OLR) brought about increase in the production and movement of the non-granular biomass within the GRABBR compartments. This led to an increase in effluent suspended solids, made up of mainly the non-granular biomass. The non-granular biomass was believed to be predominantly acidogens produced at the inlet compartments while the granular biomass located mainly at the outlet compartments was believed to be mostly methanogens (Baloch & Akunna 2003*a*). The predominance of these two groups of microorganisms at two different locations was regarded as an indication of the occurrence of phase separation within the GRABBR.

Granular breakage was also observed in the UASB at higher OLRs but of lower magnitude than in the GRABBR. Granular breakage and fluidisation in the UASB brought about increased effluent solids.

For both reactors, decreasing the HRT brought about an increase in effluent suspended solids as shown in Figure 5. Effluent suspended solids values was found to be comparable for both systems except at very low HRT, where washout from the GRABBR was significantly lower despite the fact that upflow velocities were generally higher in the GRABBR compartment than in the UASB for all the experimental conditions. Upflow velocities within individual compartments of the GRABBR and UASB at HRT of 1 h were 2.86 $m h^{-1}$ and 0.65 $m h^{-1}$ respectively.

At the end of the experiments, the settling velocities of the granular biomass obtained from both reactors were

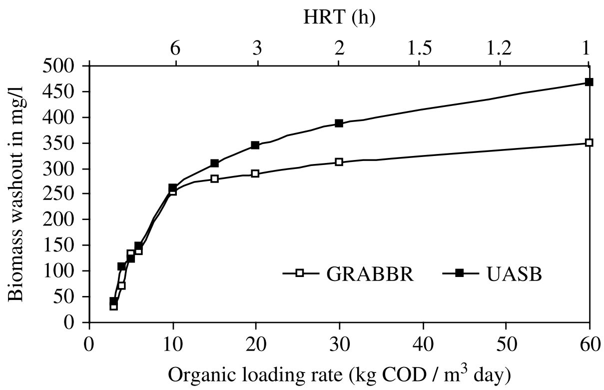

Figure 5 | Biomass washout profile of the GRABBR and the UASB at various OLRs.

determined. The approximate settling velocities of biomass in the earlier (first and second) and latter (fourth and fifth) compartments of the GRABBR were 2.1 m min^{-1} and 3.3 m min^{-1} respectively, and 2.9 m min^{-1} for the biomass from the UASB. These results suggest that the lower biomass washout obtained from the GRABBR could be attributed to the higher settling velocities of the biomass that occupy the methanogenic zone of the reactor.

pH profile

Figure 6 shows the pH profile of both reactors during the study. pH levels increased longitudinally along the compartments of the GRABBR with increasing OLR. Increasing OLR brought about a sharp pH drop in the earlier compartments of the GRABBR and moderate pH drop in the UASB. The higher pH levels in the UASB can be attributed to the greater dilution of the acidogenic byproducts with the entire reactor volume compared to the dilution within only the individual compartments for the GRABBR. pH levels of the UASB were comparable to the pH values of the fourth and fifth compartments of the GRABBR. Hence, the GRABBR offers the methanogenic zone greater protection from low pH levels usually associated with organic overload or shockloads.

Biogas production and composition

Biogas production increased with increase in OLR, ranging from 17 l d^{-1} to 101 l d^{-1} for the GRABBR and 17.5 to 116 l d^{-1} for the UASB as shown in Figure 7. Table 1 shows that the methane content of the biogas range from 48 to 68% for the UASB, 33 to 57% for compartments 1 to 3 of the GRABBR and 57 to 86% for compartments 4 to 5 of the GRABBR. The methane content of biogas from the UASB and compartments 1 to 3 of the GRABBR decreased with increase in hydraulic and organic loading rates, while the methane content of biogas from compartments 4 to 5 of the GRABBR was more or less constant up to OLR of 30 and 60 kg COD m^{-3} d^{-1} when the reactor showed signs of being overloaded. These results indicate that operating anaerobic reactors with low hydraulic retention times when treating wastewaters saturated with dissolved oxygen may lead to the production of poor biogas quality caused by increased aerobic processes within the reactor. Using the GRABBR enables the separation of biogas produced in the methanogenic zone from the gaseous by-products produced in the aerobic and acidogenic zone.

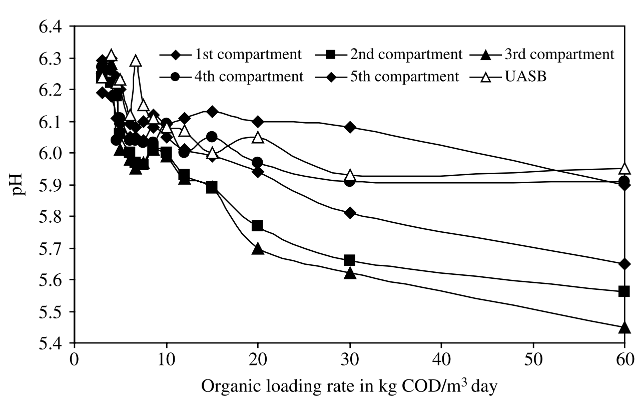

Figure 6 | pH profile of the GRABBR compartments and UASB at various OLRs.

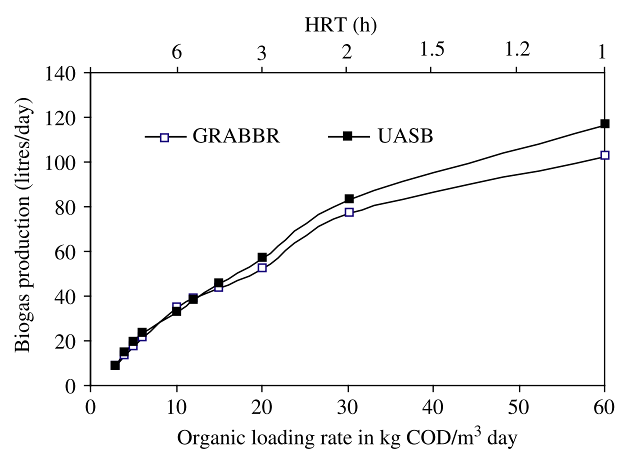

Figure 7 | Biogas profile of the GRABBR and the UASB at various OLRs.

Table 1 | Biogas composition of the reactors at various HRTs and OLRs

		GRABBR	GRABBR compartments 1 to 3		GRABBR compartments 4 and 5		Upflow anaerobic sludge blanket (UASB)		
OLR (kg COD m^{-3} d^{-1})	HRT (h)	Total gas production (l.d^{-1})	Methane (%)	Carbon Dioxide (%)	Methane (%)	Carbon Dioxide (%)	Gas production (l d^{-1})	Methane (%)	Carbon Dioxide (%)
5	12	17.5	57	43	81	19	18	68	32
10	6	31.7	53	47	83	17	33.5	67	33
15	4	43.5	52	48	83	17	43	66	33
20	3	52	49	51	86	14	56.8	60	40
30	2	77	41	59	74	26	83	54	45
60	1	102	33	67	57	43	116	48	52

DISCUSSION AND CONCLUSION

Results from this study indicate that the GRABBR demonstrates greater processes stability than the UASB at relatively low HRT. Table 2 compares the outcome of this study with literature reports.

With the GRABBR, high hydraulic and organic loadings may bring about lower pH levels in the acidogenic compartments. This may require chemical pH correction to ensure continued protection of the methanogenic bacteria in downstream compartments from low pH induced inhibition. pH correction in phase-separated systems has been proposed by other researchers (Hutnan *et al.* 1999). The UASB has higher pH stability due mainly to its greater higher dilution capacity. Hence, the UASB seems to be better equipped to cope with organic overloads or shock-loads. However, with excessively high organic shockloads or overloads, the entire biomass in the reactor will be instantly affected by the resulting low pH values and this may lead to a total reactor failure. The GRABBR, on the other hand, offers greater opportunity for plant operators to redeem the adverse effects of organic overload or shockload before the more sensitive methanogenic zone is affected.

Biogas production within the UASB results in the build up of buoyancy within the biomass bed followed by turbulent eruptions causing partial to complete fluidisation of the granules. This can cause effluent short-circuiting and granular washout with corresponding loss of treatment

Table 2 | Performance of various low strength wastewater systems at mesophilic conditions

Authors	Reactor type	Substrate	OLR* studied kg COD m^{-3} d^{-1}	HRT† (h)	COD Removal (%)
Kumar *et al.* (2007)	AHR	Municipal wastewater	0.15–3.12	4–12	90–95
Rebac *et al.* (1999)	EGSB	Synthetic and malting wastewater	12	1.6	78–90
Sarti *et al.* (2001)	HAIB	Synthetic wastewater	0.5–2.3	2–10	68–82
Arnaiz *et al.* (2007)	ITBR	Wine distillery wastewater	9.5–30.6	11–29	70–92
Alderman *et al.* (1998)	AEBR	Municipal wastewater	–	1–10	35–77
Manariotis & Grigoropoulus (2003)	AF	Synthetic wastewater	0.34	24	84
Banik & Dague (1997)	SBR	Industrial wastewater	–	6–24	>90%
Bachmann *et al.* (1985)	ABR	Sucrose – protein	2.5–36.2	4.8–71	55–93
This study	UASB	Synthetic wastewater	3–60	1–20	51–89
This study	GRABBR	Synthetic wastewater	3–60	1–20	58–93

*Organic loading rate.
†Hydraulic retention time.
AHR: Anaerobic Hybrid Reactor, EGSB: Expanded Granular Sludge Bed, HAIB: Horizontal-flow Anaerobic Immobilized Reactor, ITBR: Inverse Tubular Bed Reactor, AEBR: Anaerobic Expanded Bed Reactor, AF: Anaerobic Filter, SBR: Sequencing Batch Reactor, ABR: Anaerobic Baffled Reactor, UASB: Upflow Anaerobic Sludge Blanket, GRABBR: Granular Bed Baffled Reactor.

efficiency. For the GRABBR, although turbulence and biomass fluidisation can occur due to biogas formation, their intensities decrease longitudinally across the reactor due to changes in the nature and quantity of organic compounds being treated along the reactor. These changes also bring about changes in the nature and type of the principal microbial groups occupying the individual compartments of the GRABBR, resulting in the concentration of the densest (or heaviest) microbial flocs (or granules) at the outlet compartments. The microbial flocs at the GRABBR outlet compartments have greater average settling velocity than those found in the UASB. This property of the GRABBR contributes to ensuring lower treated effluent suspended solids despite the much higher upward liquid velocities within the GRABBR compartments. Hence, the risk of excessive short-circuiting and biomass loss due to fluidisation at high OLR and low HRT is lower with the GRABBR than with the UASB.

Another important outcome of this study is the feasibility of harvesting biogas with higher energetic value with the GRABBR. With the GRABBR, biogas from the acidogenic and methanogenic zones can be separately collected. In addition to higher methane content, methanogenic zone biogas collection will ensure the reduction of hydrogen sulphides in the biogas. Hydrogen sulphide is produced in the anaerobic treatment of sulphate-containing wastewaters such as domestic and food processing wastewaters, and its occurrence in biogas in significant quantities increases the cost of beneficial use of the biogas. Thus, the potential for cost-effective biogas re-use is greater with the GRABBR.

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