A new high rate anaerobic technology, the static granular bed reactor (SGBR), for renewable energy production from medium strength waste streams

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Abstract

A new high rate anaerobic treatment system has been developed for maximizing the conversion efficiency of organic matter to energy in the form of methane for medium strength (1–10 g COD L^{-1}) waste streams. The system, termed the static granular bed reactor (SGBR), utilizes a downflow hydraulic regime through a dense bed of active anaerobic granules that can accommodate higher suspended solids concentrations than its counterpart, the upflow anaerobic sludge blanket (UASB) reactor, which is susceptible to solids washout due to the high (up to 1 m h^{-1}) upflow velocities. Theoretical considerations for the SGBR are presented with results from SGBR treatment of synthetic (non-fat dry milk and sucrose) and actual (pork slaughterhouse and landfill leachate) wastewaters documenting the high efficiency (consistently greater than 90% conversion of COD) and excellent effluent characteristics (typically less than 50 mg L^{-1} total suspended solids and BOD_5). Transient hydraulic and organic loads have relatively little effect on the SGBR as evidenced by consistent performance during an instantaneous shift in the hydraulic residence time from 36 to 5 h. In addition, results from variable reactor seeding from 25 to 100% of bed volume showed relatively little dependence of granule bed mass on effluent characteristics. This finding confirms independent results showing that a large fraction of the granule bed is substrate limited and available as reserve biomass. These results help explain the excellent treatment performance and resiliency of the SGBR regardless of hydraulic and organic loading. Fatty acid methyl ester (FAME) analysis of the granules showed distinct microbial communities entirely dependent on the nature of the feed source. Furthermore, FAME profiles from an anaerobic sequencing batch reactor (ASBR) treating pork slaughterhouse wastewater showed distinctly different profiles than an SGBR treating the same wastewater. Energy production from the SGBR was close to the theoretical 0.35 L (g COD removed)$^{-1}$ for all waste streams evaluated.
Keywords: high rate anaerobic digestion, methanogenic, anaerobic granular sludge, UASB, EGSB, fatty acid methyl ester (FAME).

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1 Introduction

One of the major challenges for high rate anaerobic treatment is the development of a process that can operate over the entire range of ambient temperatures expected in the field and meet the required effluent standard for surface water discharge. Currently, no anaerobic process can achieve this due mainly to the periodic loss of solids from the reactor especially as the system experiences hydraulic fluctuations. The upflow anaerobic sludge blanket (UASB) reactor, for instance, uses an upflow configuration with a three-phase (solids/liquid/gas) separator at the top. Due to the upflow nature of the process and the fact that anaerobic sludge granules and flocculent sludge tend to float, UASB reactors are particularly susceptible to the washout of solids [1–4].

The three-phase separator in the UASB must collect the gas that is produced in the reactor, clarify the effluent, and keep the granular sludge in the reactor. The way this is accomplished is through the use of baffles and a gas collector. The gas bubbles are directed to the gas collector by perimeter baffles, and effluent has to pass around the baffles and out through the effluent weir. The intent is that the granular biomass will settle back to the sludge bed. There are several difficulties with this arrangement. The gas that is produced by the anaerobic granules is in the form of small bubbles at the surface of the granule. As the bubble size increases due to additional microbial activity, surface tension keeps the bubble on the granule exterior until the buoyancy force exceeds the surface tension. At the same time, the buoyancy of the granule changes due to the increased surface area and the change in density due to the attached bubbles. The only downward force on the granule is the force of gravity. Upflow forces include buoyancy forces and the upflow velocity. Depending on the movement of the granule there may also be drag forces counteracting the gravitational or buoyancy forces. At steady state operating conditions, maintaining the anaerobic granules in the UASB reactor requires that the force of gravity exceed the buoyancy and upflow forces. During hydraulic (influent flowrate) and temperature changes within the UASB, however, this becomes increasingly difficult.

Two things happen to the granule during an increase in the hydraulic loading in a UASB. The first is that the organic loading (mass of organic matter per volume per time) increases due to the increased flowrate. Consequently, the granules tend to produce more gas since more substrate is available. The additional gas production increases the buoyant force on the granule. Secondly, the upflow velocity increases due to the increased flowrate. As the forces from buoyancy and the upflow velocity become greater than the gravitational force, the granule rises to the top of the reactor. Depending on the efficiency of the gas/solids/liquid separator, the buoyant granule may be washed out of the reactor with the effluent. This same effect happens to flocculent biomass, but its loss is not necessarily detrimental to the UASB, since the granular biomass is preferred. Loss of either granular or flocculent biomass, however, significantly increases the effluent solids concentration. Temperature shifts tend to exasperate this effect since the changes in liquid density and biological activity are temperature dependent and result in a varied combinations of buoyancy, upflow, and gravitational forces.

To circumvent these problems, a new reactor configuration, called the static granular bed reactor (SGBR) was developed by researchers at Iowa State University [5–13]. The SGBR utilizes a bed of active anaerobic granules in a downward flow regime (see Figure 1). The innovation in this reactor configuration is that it uses the highly active anaerobic granules (just as in a UASB system), but it operates in a downflow mode. The advantage of a downflow configuration is that the biogas that is generated rises and is easily separated from the granules and the liquid at the top of the reactor. Granule buoyancy is not a detriment to process performance in the SGBR as it is in the UASB. In contrast to the UASB, there is no need for a sophisticated three phase solids, gas, and liquid separator. Neither is there a need for recirculation pumps, timers, mixers, or other ancillary equipment that are required for the UASB systems. Consequently, the effluent quality of the SGBR is improved in comparison to the UASB. The biomass granules are retained within the reactor by the use of a gravel underdrain and temperature and hydraulic loading changes are not expected to significantly affect effluent quality.

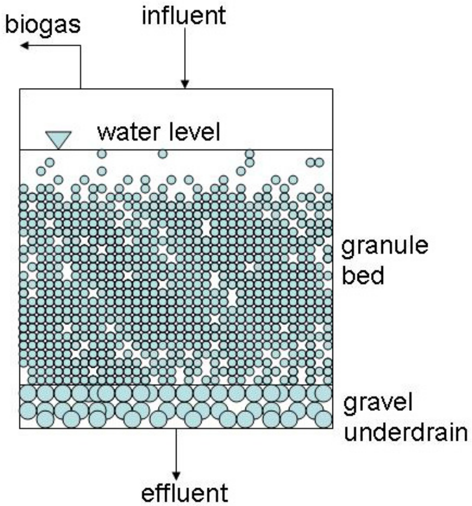

Figure 1: Schematic of the static granular bed reactor (SGBR). US patent #6,709,591.

The technological innovation of the SGBR is that it uses highly active anaerobic granular biomass in a downflow configuration. Other reactor configurations use a downward flow regime (e.g., the anaerobic filter can be operated in a downflow mode), but the SGBR is the first system to use anaerobic granules in a downflow mode. This configuration allows for an exceptional effluent quality, simple operating characteristics, and smaller volume requirements. In addition, there is no need to heat the SGBR in most cases, since the high retention of biomass ensures that there is sufficient microbial activity to degrade the organic portion of the influent wastewater, allowing more of the energy produced in the form of methane in the biogas, to be available for productive uses.

2 Materials and methods

Laboratory scale SGBRs were constructed from Plexiglas cylinders with working volumes from 1 to 10. A stainless steel mesh (15 mm) or pea gravel was placed in the bottom of the SGBRs to retain the granular biomass. A "T" connector was installed in the effluent line to maintain the desired working volume in the reactor. Seed granules were obtained from an operating UASB at CityBrew (formerly Heileman's Brewery) in LaCrosse, WI. Synthetic feed consisting of non-fat dry milk and nutrients was fed on a semi-continuous basis using a peristaltic pump. Feed and effluent were both stored at 4°C. Analytical parameters (alkalinity, COD, suspended solids) were determined using Standard Methods and performed weekly. The VFA concentration was measured by the titration method (Method 5560 C in Standard Methods) with an assumed efficiency of 70%. Gas composition was analyzed by a Gow Mac gas chromatograph and was tested bi-weekly. BOD_5 concentration was measured once during each HRT condition. In the first series of experiments, two different SGBR reactor height:width configurations were evaluated. The first reactor (SGBR 1) had an inner diameter of 101 mm and a granule height of 135 mm. SGBR 2 had an inner diameter of 64 mm and a granule height of 432 mm. Both were operated for approximately two years under several HRT conditions at ambient temperature (22 ± 2°C). In the next set of experiments, four 1-L SGBRs were seeded with varying amounts of seed granules (250, 500, 750, and 1,000 mL) to evaluate the optimum granule bed depth as a percentage of working volume. An evaluation of whole cell fatty acid methyl ester (FAME) was used to assess the microbial community structure similarities between SGBRs treating different wastewaters and other reactors treating the same wastewater. FAMEs were extracted using the Microbial Identification System anaerobic extraction protocol (Microbial ID, Inc., Newark, DE). Cells in the samples were saponified by heat and the presence of a strong base. In this step, fatty acids were separated from lipids. After the separation, the remaining FAs were methylated to form FAME and extracted into an organic solvent. Following extraction, FAME samples were analyzed on a HP 6890 (Hewlett Packard, Rolling Meadows, IL) gas chromatograph. Because of the large number of FAs present in each sample, principal component (PC) analysis was used to observe any changes in the FAME profiles. Principal component analysis explains the maximum variation in the data based on theoretical components, or principal components in the data. For this study, PC analysis was done by MIDI FAME's (Microbial ID, Inc., Newark, DE) Sherlock program.

3 Results and discussion

During all HRT conditions both SGBRs performed well with respect to COD and BOD_5 removals, and the effluent from both had low effluent VFA, BOD_5, and TSS concentrations (see Table 1). The poorest performance occurred at the initial start-up condition (36 h HRT) for SGBR 1. This could be due to the

Table 1: SGBR performance characteristics as a function of reactor dimensions.

SGBR 1 HRT	Effluent COD, mg/L	Effluent BOD, mg/L	TSS, mg/L	VFA, mg/L as CH_3COOH	H_2S in gas, Ppm
Start-up 36	523±120	NA	130	24±5	NA
24	45±28	10	20	14±5	650
16	30±15	10	6	14±6	600
12	30±19	26	16	18±7	600
8	79±29	47	8	17±2	1800
6	38±24	27	10	19±1	1400
5	39±15	22	12	17±5	120
36	46±18	13	8	16±2	600
5	40±22	10	19	9±1	300
SGBR 2					
Start-up 36	52±23	8	5	12±3	1700
24	59±15	NA	18	17±5	500
16	44±24	26	3	17±5	NA
12	50±21	21	6	17±1	850
8	33±15	14	5	14±1	600
5	24±12	12	7	12±5	800
36	41±19	10	5	11±1	1100
5	41±18	9	10	9±1	500

limited acclimation and washout of fine solids during start-up. After initial start-up, SGBR 1 and 2 maintained greater than 92% and 94% total COD removal respectively. Soluble COD removal in both was 95–97%.

Throughout the research period, SGBR 2 consistently had lower measured VFA concentrations. Gas chromatographic (GC) analysis, however, indicated that the titration method might have overestimated the VFA concentration. By GC analysis, acetic, propionic, butyric, and valeric acid concentrations were each measured at or below the detection limit of 1 mg/L. Suspended solids and BOD_5 consistently met (with the exception of the 8 hour HRT condition for SGBR 1) the NPDES requirement of 30 mg/L, which would allow the effluent to be discharged to surface water in areas where nutrient removal was not required.

In order to evaluate the organic loading turndown ratio in the SGBR, a hydraulic and organic loading transition was initiated by changing the HRT from 36 to 5 h. The transition was instantaneous and analytical testing was performed every 12 h to observe the non-steady state performance (see Figure 2). After the HRT was lowered (resulting in a corresponding increase in organic loading), the effluent total COD increased from 46 mg/L to 144 mg/L in SGBR 1 (the wider and shorter reactor). However, SGBR 2 showed no significant increase in effluent COD concentration. Both reactors showed an increase in TSS, but the concentration for both remained below 30 mg/L. Soluble COD increased initially, but returned to low levels (<30 mg/L) within 36 h. Other parameters such as the VFA concentration were not significantly affected. The VFA concentration remained low (<12 mg/L by titration method) during the transition period. The hydrogen sulfide concentration remained less than 150 ppm during the transition period, which was lower than measured during the previous HRT conditions (Table 1). The operation at the 5 h HRT remained exceptional. The organic removal remained high. COD removal in SGBR 2 improved slightly, but not significantly (95% at 36 h to 97% at 5 h). Gas production increased with the higher organic loading, and the methane content was 81% for both SGBRs.

In the experiments to test the effect of seed granule as a percentage of working volume, three feed strengths were evaluated (1, 2, and 4 g COD/L) resulting in OLR of 1.2, 2.4, and 4.8 g L^{-1} d^{-1}, respectively at a 20-h HRT. The results from the study (Table 2) suggest that the performance of the SGBR was relatively unaffected by granule seeding for the lower loadings (1.2 and 2.4 g L^{-1} d^{-1}). At the 4.8 g L^{-1} d^{-1} loading, the performance was more variable when the granule seeding was less than 100% of the working volume. A clear trend was not observed as the SGBR with 25% seeding performed similarly to the SGBR with 100% seeding, and the 50 and 75% SGBRs had poorer performance.

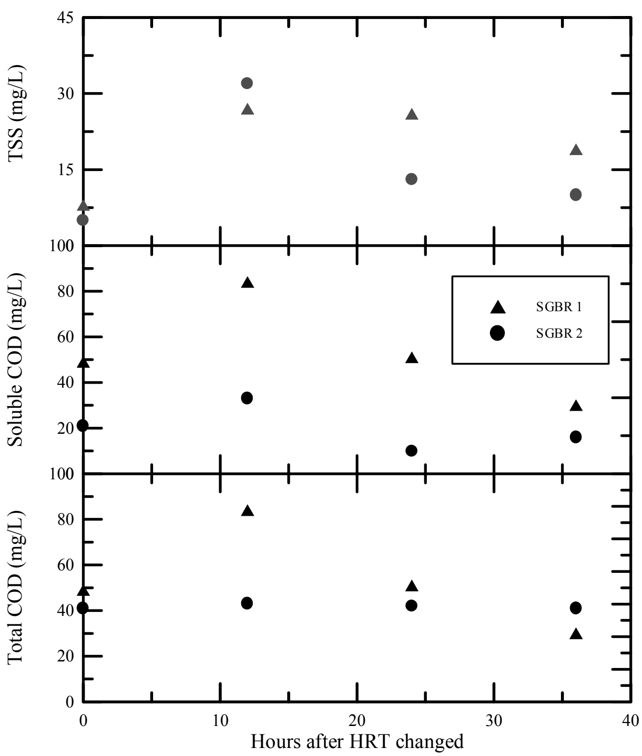

Figure 2: Effluent TSS and COD during transition period from 36 to 5 h HRT.

Table 2: Effluent characteristics as a function of granule seeding.

Bed fraction	1 g COD L^{-1}		2 g COD L^{-1}		4 g COD L^{-1}	
	COD	TSS	COD	TSS	COD	TSS
25%	28±17	26±14	42±22	40±15	304±153	146±12
50%	33±22	24±13	35±21	26±14	1121±456	184±8
75%	22±14	21±7	15±11	25±10	1043±534	113±9
100%	14±17	18±8	34±27	20±7	294±176	80±11

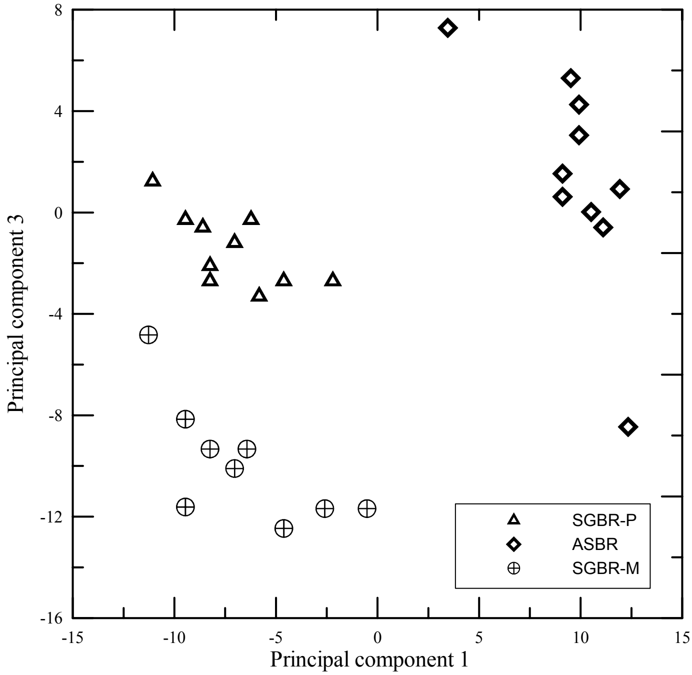

Figure 3: Two-dimensional principal component analysis of FAME profiles (SGBR-P and ASBR were fed pork slaughterhouse and SGBR-M was fed synthetic dairy wastewater).

In a parallel study, the microbial community in the SGBR was analyzed using FAME analysis. Two parallel reactors (an SGBR and an anaerobic sequencing batch reactor) treating slaughterhouse wastewater (1.9 g COD L^{-1}) were compared along with an SGBR treating non-fat dry milk (1 g COD L^{-1}). The FAME profiles and corresponding comparisons using principal component analysis indicate the similarities or differences in the fatty acid (FA) content of each sample. These profiles can be correlated to the microbial population during the different sampling times and conditions. From the principal component plot, distinct groupings of fatty acids profiles suggest homogeneity of microbial communities (see Figure 3). The ASBR had a slightly more homogenous population profile, which is consistent with the mixing and settling during the operation of the system, while the SGBR profile was more diverse.

To further evaluate the performance characteristics of the SGBR a number of studies have been performed on synthetic and actual wastewaters, and the detailed results have been presented elsewhere. A summary of these studies is useful, however, for comparison purposes. Figure 4 shows the performance of the SGBR [10,14] as a function of OLR in comparison to UASB [16, 17], anaerobic filter [17], and expanded sludge bed [18] reactors treating either slaughterhouse or landfill leachate wastewater. In all cases the response of the SGBR to an increase in OLR is relatively flat (i.e., unaffected by OLR increase), whereas the other high rate reactor configurations suffered noticeable decline in performance. The response of the SGBR can be related to the manner in which the SGBR retains solids in the reactor resulting in low food: microorganism (F:M) ratios regardless of OLR. Because of the high retention of solids in the SGBR (and resulting low F:M), failure In the SGBR is more likely due to hydraulic limitations than organic overloading [14].

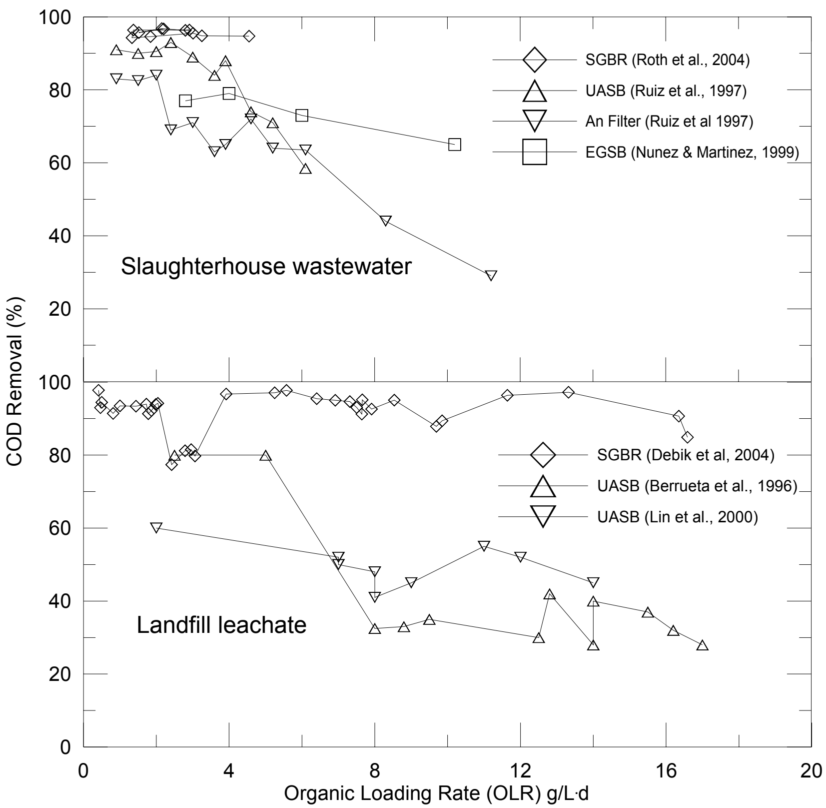

Figure 4: Performance characteristics of high rate anaerobic treatment systems as a function of OLR and wastewater type.

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4 Conclusion

From these studies, it can be seen that the SGBR holds promise as an innovative bioreactor design to broaden the range of substrates for high rate anaerobic digestion and concomitant conversion of organics to renewable fuel in the form of methane. The SGBR's unique configuration retains the active granular biomass in the reactor regardless of OLR and hydraulic loading and loading rate changes. This allows the SGBR an advantage over other high rate anaerobic treatment technologies that may be susceptible to solids washout, loss of granular biomass, and subsequent process deterioration.

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