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A Novel Anaerobic Reactor: Split Fed Anaerobic Baffled Reactor (SFABR)

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Abstract

Excessive substrate feeding during start-up can lead to the accumulation of volatile fatty acids and a concomitant decrease in pH in anaerobic reactors with plug flow characteristics. In addition, plug flow reactors fed with high strength wastewater are more likely to expose sensitive bacteria to toxic levels of inorganic and organic compounds. To overcome these difficulties, substrate feeding pattern to the reactor could be manipulated. Such a configuration, the split fed anaerobic baffled reactor, has been developed in the Environmental Engineering laboratories of Newcastle University. This concept is based on a modified feeding strategy for the anaerobic baffled reactor. By splitting the feed, a number of desirable characteristics can be encouraged, such as low organic loading rate, longer hydraulic retention time, longer cell retention time in the initial compartments and greater availability of food for the micro-organisms in the final compartment of the reactor. In addition, it is envisaged that a greater stability of pH should occur as a result of the lower concentrations of volatile fatty acids arising in the initial reactor compartments. These factors are likely to lower organic stress in the initial compartments.

Key words: Brewery wastewater, microbial ecology, reactor performance, split fed anaerobic baffled reactor (SFABR), trace analysis.

Introduction

In addition to its capacity to develop granular sludge, the anaerobic baffled reactor (ABR) manifests a number of additional advantages that make it one of the most stable anaerobic reactor configurations for wastewater treatment. Despite its many advantages, one potential problem that can be encountered with an ABR during the start-up period results from the near plug-flow characteristics of this configuration. The appearance of a substrate concentration gradient in high rate anaerobic reactors has long been a problem for the optimisation of sludge bed systems (van Lier *et al.*, 2001). In this context, the strength of the wastewater and organic loading rate are known to play an important role during the start-up period of any anaerobic reactor. Initial organic loading rates should be sufficiently low that the slow growing micro-organisms do not become overloaded. Moreover, excessive substrate feeding during start-up can lead to the accumulation of volatile fatty acids and a concomitant decrease in pH. In addition, high strength wastewater is more likely to expose sensitive bacteria to toxic levels of inorganic and organic compounds. To overcome these difficulties, a low organic loading rate (OLR), dilution of the feed and effluent recycling have been recommended (Bachmann *et al.*, 1983 and 1985; Barber and Stuckey, 1999). However, owing to its compartmentalised structure, these approaches may not be the best solution to the successful start-up of ABRs on account of the fact that whilst a low OLR may be suitable for the initial compartments of the ABR, the final compartments would usually be nutrient limited.

A more promising solution for stabilising an ABR during the start-up period and shock loading regimes would be to eliminate the harsh conditions in the initial compartments of the reactor and to provide sufficient substrate for the anaerobic bacteria in the final compartments of the reactor. This could be achieved by manipulation of the substrate-feeding pattern to the reactor. It might be argued that feed splitting in the split feed anaerobic baffled reactor (SFABR) would eliminate phase separation, one of the perceived advantages of ABR configuration over the other anaerobic reactors; however, it is well established that conventional ABRs do not exhibit a full phase separation, but show a partial phase separation where methanogens and acidogens coexist in each compartment (Nachaiyasit and Stuckey, 1995; and Uyanik *et al.* 2002a and b).

Materials and Methods

To investigate the effect of splitting the reactor feed and to make comparisons with normal feeding, two identical reactors (except for the feeding regime), 20 cm wide, 60 cm long, and 100 cm high, were set up using brewery wastewater. A schematic diagram of the reactors is presented in Figure 1. Construction was from perspex with the active reactor volume (100 l) being divided into four equal 25 l compartments, each separated by vertical baffles. Within each compartment downcomer and upcomer regions were created by a further baffle. The width of the downcomer was 4 cm, (associated wet volume of 6.67 l), and the upcomer was 11 cm, (associated wet volume of 18.33 l). The lower parts of the downcomer baffles were angled at 45 degrees in order to direct the flow evenly through the upcomer. This produced effective mixing and contact between the wastewater and anaerobic sludge at the base of each upcomer. A simple syphon at the effluent line controlled the water level in the reactors. The brewery wastewater comprised waste beer, i.e. out of date, returned to the brewery for biological treatment where it is mixed with process wastewater in a balancing tank before treatment. Brewery wastewater was chosen due to its simple degradation compared to ice-cream wastewater and its high COD values. In addition, it was easy to transport and store it in its concentrated state in the laboratory and then dilute it as necessary. A typical value of the stock brewery wastewater is given in the Table 1.

Reactor efficiencies were monitored throughout the 70-day experiment in which the OLR was progressively increased stepwise from 0.9 kg COD/m^3.day to 10.5 kg COD/m^3.day at predetermined time intervals (15 days for each OLR) by increasing the strength of the feed. Hydraulic retention times (HRT) at all OLRs were 2 days.

Table 1. Characteristics of the undiluted brewery wastewater feed.

Parameters	Concentration (mg/l)
COD	85,000
N	275.8
TKN	411.6
NH_3-N	140
PO_4-P	244.8
Iron (Fe)	70.6
Calcium (Ca)	9076
Sodium (Na)	102.6
Potassium (K)	352.7
Magnesium (Mg)	67.37
Zinc (Zn)	0
Copper (Cu)	0
Cadmium (Cd)	0
Cobalt (Co)	0
Nickel (Ni)	0
Manganese (Mn)	0
Alkalinity	90
pH	6.95

Two feed regimes were employed, (i) a Normally Fed Anaerobic Baffled Reactor (NFABR) and (ii) an SFABR. Trace analysis of split ratios was carried out to determine an ideal condition, intermediate between plug flow and completely mixed conditions (Smith *et al.*, 1996).

Supernatant liquor, gas and sludge samples were taken separately from each compartment for analysis, all according to standard methods (APHA, 1985). In addition, the gas production rate was determined separately for each compartment.

At the end of the experiment sludge samples were taken from each compartment of both reactors and the biomass examined by scanning electron microscopy (SEM). Samples were first fixed for 4 h at room temperatures with 2% (w/v) glutaraldehyde in Sorenson's phosphate buffer, and dehydrated through a graded series of water-ethanol mixtures (10%, 25%, 50%, 75%, 90% and 100%). The samples were brought to equilibrium in each mixture for 10 min and finally dried by the critical-point drying method before sputter-coating with gold particles. The samples were examined in a scanning electron microscope at 4 ∼ 8 kV and photomicrographs produced at magnifications between 10x and 15000x.

Results and Discussion

Hydraulic pattern

Trace analysis experiments were performed in empty reactors to investigate the effect of input splitting on mixing patterns. The optimum mixing pattern is a subject of much debate. Under plug-flow conditions, incoming substrate remains in the reactor for one retention time, allowing maximum time for conversion. However, the high substrate concentrations resulting from lack of dispersion may inhibit bacterial activity. On the other hand, excessive dispersion may result in short-circuiting of the substrate and would not be ideal for granule formation in some anaerobic reactor configurations. Consequently, an intermediate degree of mixing appears to be optimal for substrate conversion (Smith *et al.*, 1996). Grobicki (1989) studied the mixing pattern in ABRs and observed that with no biomass in the reactors, the system approximated plug-flow conditions. In this study the C-curve (normalised concentration vs. normalised time; Levenspiel, 1962) of the NFABR (Figure 2) produced a pattern similar to that identified by Grobicki (1989). However, when the split fed regime was applied, the pattern changed, corresponding to a higher degree of mixing within the reactor. The two split ratio regimes (fraction of load delivered to Compartments 1-4 respectively) examined in this study were 0.6, 0.25, 0.1, 0.05 and 0.4, 0.3, 0.2, 0.1 of which the latter ratio produced a mixing pattern which may be considered as an ideal intermediate between plug-flow and completely mixed reactors. Consequently, a split ratio of 0.4, 0.3, 0.2, 0.1 was applied to the SFABR in subsequent experiments.

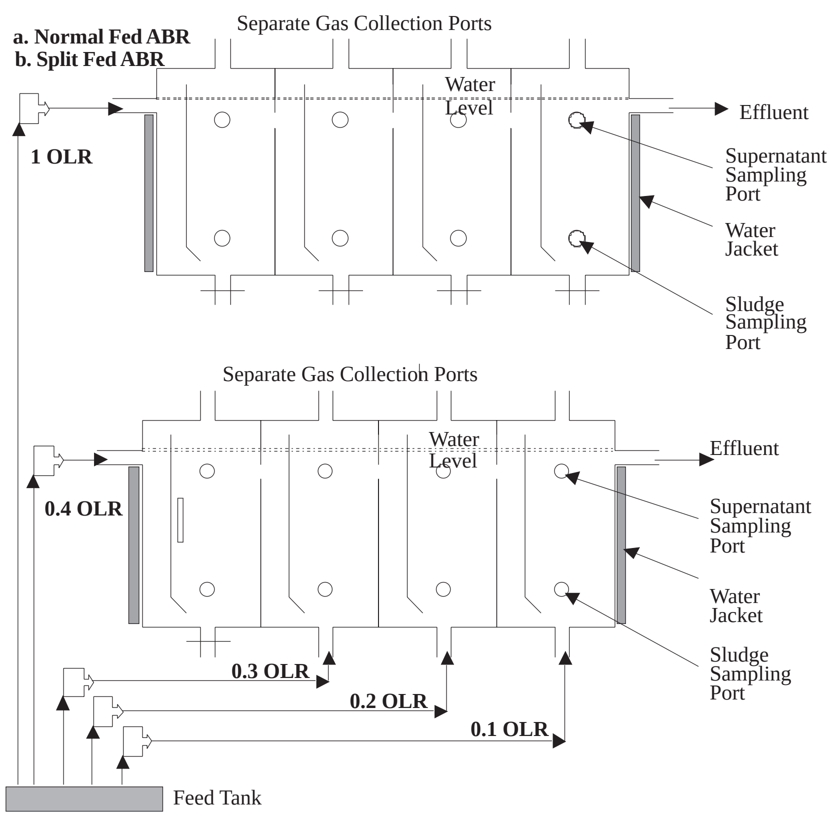

Figure 1. Schematic diagram of a Normally Fed Anaerobic Baffled Reactor (NFABR) and a Split Fed Anaerobic Baffled Reactor (SFABR) showing an example of the split feed ratio as a fraction of the total organic loading rate (OLR).

COD Profile

The profiles of residual COD concentrations in each compartment of both reactors showed considerable differences over the entire course of the experiment (Figures 3 and 4). The overall COD removal rate of the SFABR was always greater than that of the NFABR. The figures also show that the highest degree of % COD removal in the NFABR, occurred in Compartment 1 while the highest degree of % COD removal in the SFABR occurred in Compartment 3. Inter-compartmental differences for % COD removal in the NFABR were greater than in the SFABR illustrating that the compartments of the SFABR were relatively more homogeneous with respect to performance than those of the NFABR.

Methane yield

The methane yield (m^3CH_4/kg COD removed) was generally found to be greater in the SFABR than in the NFABR, with some exceptions (OLR of 2.75 and 5.5 kg COD/ m^3.day) where the final compartments of the NFABR yielded slightly better methane than those of the SFABR. This may be due to fact that owing to phase separation occurring in NFABR, the methanogenic population of the final compartments of this reactor was probably exposed to a high proportion of methanogenic substrates and consequently produced more methane. The compartments of the SFABR exhibited more uniformity than those of the NFABR due to uniform COD removal in the compartments of SFABR.

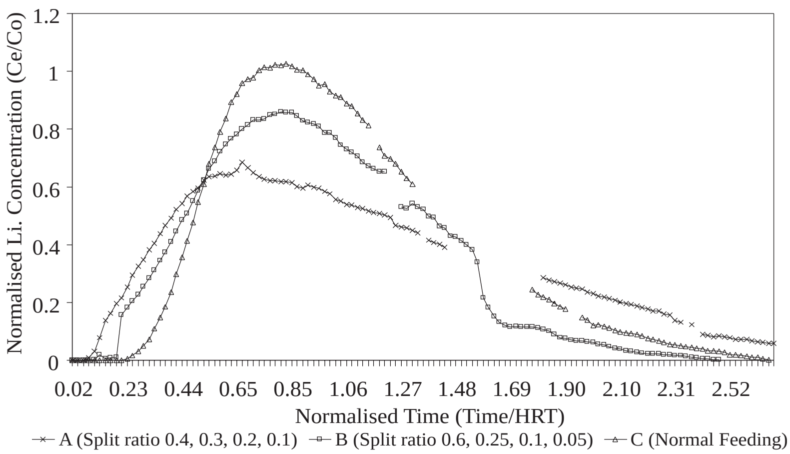

Figure 2. C-Curves for NFABR and SFABR with selected split ratios.

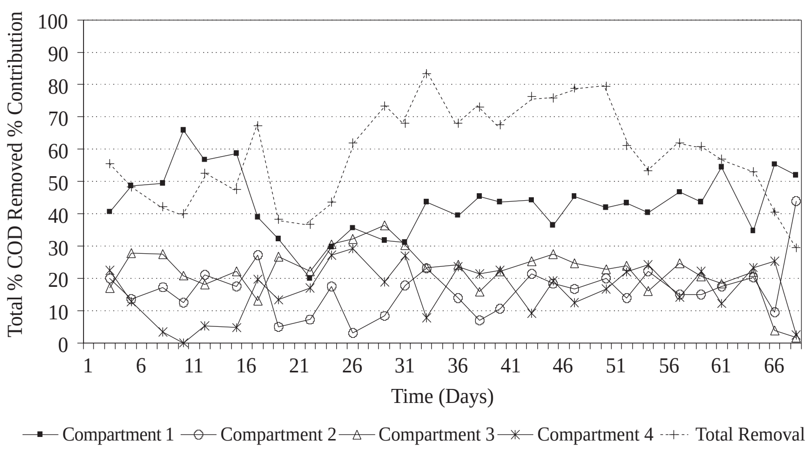

Figure 3. % Total COD removal of the NFABR and fractional contribution to the total COD removal by each compartment.

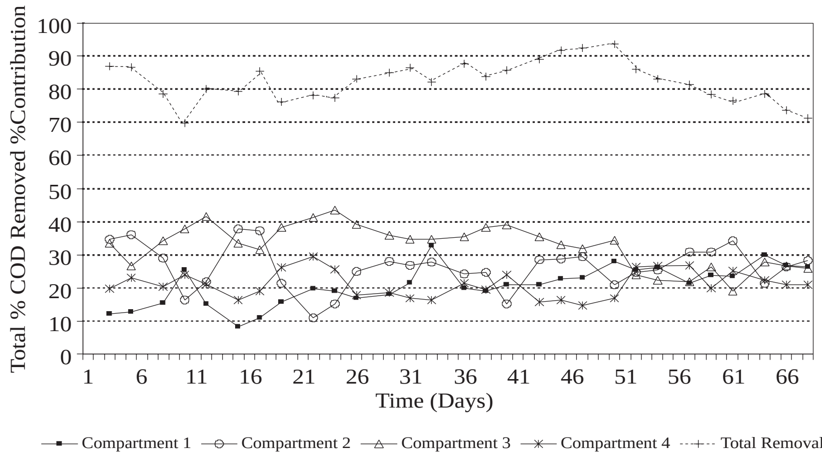

Figure 4. % Total COD removal of the SFABR and fractional contribution to the total COD removal by each compartment.

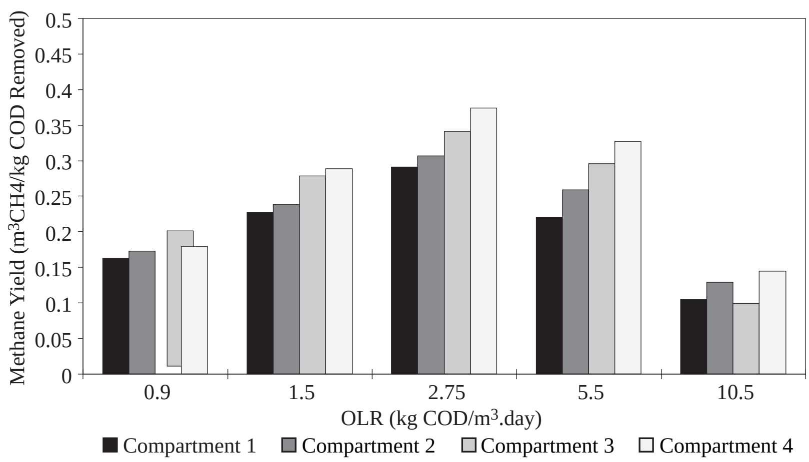

Figure 5. Methane yields in each compartment of the NFABR.

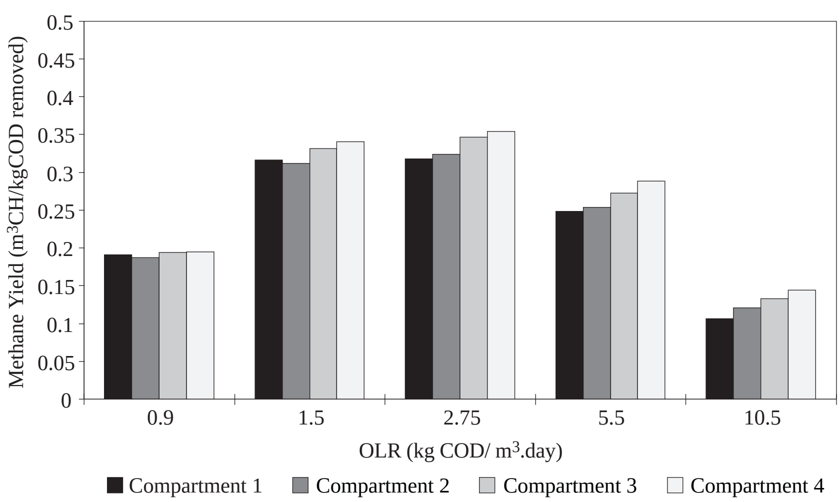

Figure 6. Methane yields in each compartment of the SFABR.

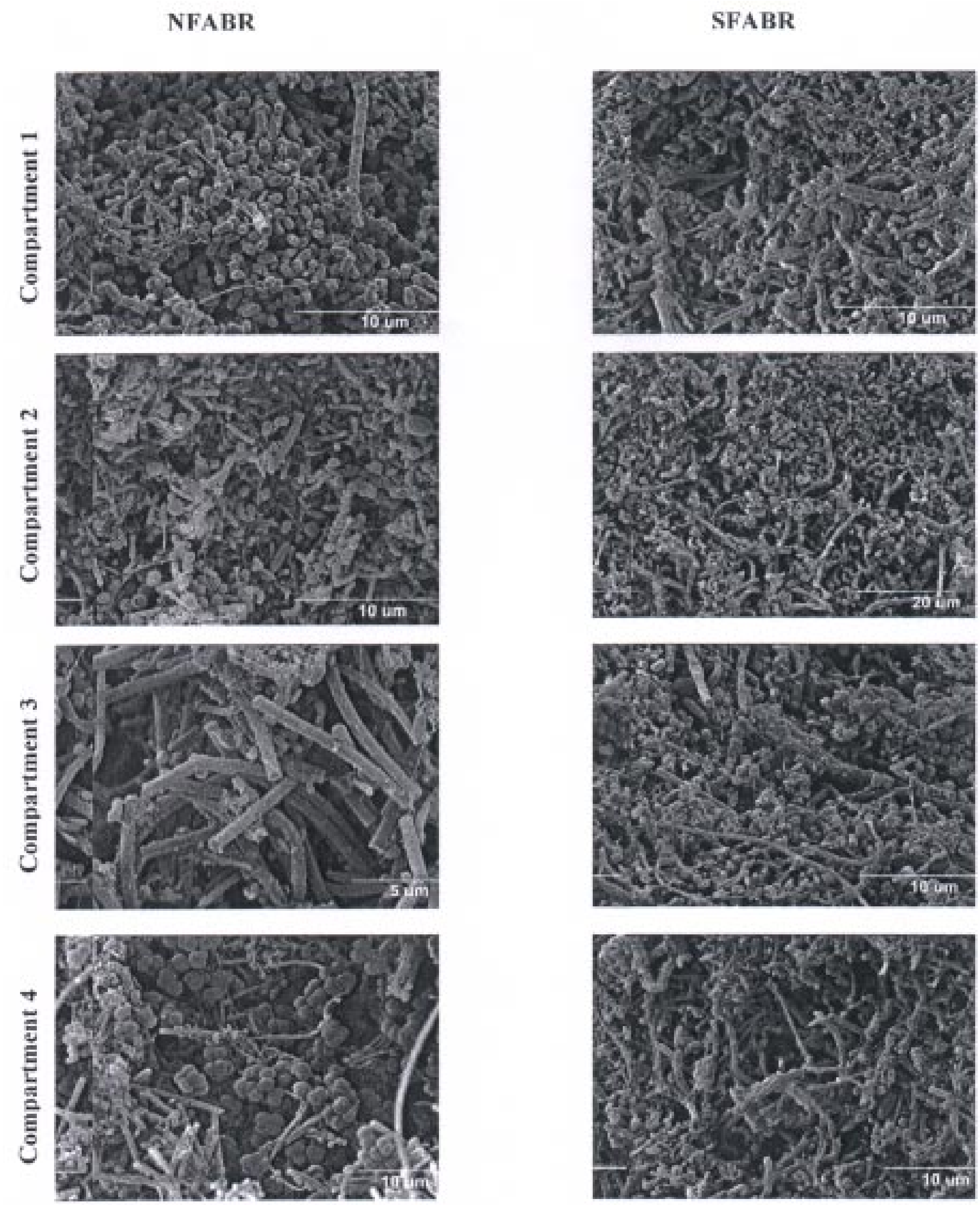

Figure 7. Microbial Ecology in the NFABR and SFABR.

Anaerobic bacteria in SFABR

The dominant bacteria in the initial compartments of the NFABR were those which could utilise H_2/CO_2 and formate as substrate, i.e. Methanobrevibacter and Methanococcus. Populations shifted to acetate utilisers, i.e. Methanosaeta and Methanosarcina. Similarly, long rod-shaped and filamentous bacteria became dominant in the final compartments (Figure 7).

The methanogenic populations that were observed in each and every compartment of the SFABR were those that could utilise H_2/CO_2, formate and acetate as substrate, and this appears to agree with the fact that each compartment received a more balanced substrate load (and hence composition) compared to the NFABR.

Conclusion

The SFABR has a number of potential advantages over the NFABR both during the start-up period and during continuous operation. These include a reduction in the severity of conditions (toxicity) in the initial compartments of the reactor (Compartments 1 and 2) and the provision of supplementary substrates to the anaerobic bacteria in the final compartments of the reactor (Compartments 3 and 4). Split feeding also promoted a more balanced gas production between compartments and consequently an improved mixing pattern in the reactor. Furthermore, the longer HRT that was established in the initial compartments of the SFABR provided anaerobic bacteria with a greater time for more effective substrate conversion. This resulted in overall performance of an organic loading rate of around 10.5 kg COD. $m^{-3}.d^{-1}$ with a COD removal efficiency of over 90% after only 70 days of operation.

The SFABR produced a more homogeneous microbial ecology in each compartment due to balanced substrate composition in the SFABR compared to the NFABR.

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