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Article *in* Bioresource Technology · January 2007

DOI: 10.1016/j.biortech.2005.10.015 · Source: PubMed

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Bioresource Technology 97 (2006) 2383–2388

BIORESOURCE TECHNOLOGY

Development of sludge filterability test to assess the solids removal potential of a sludge bed

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Received 23 January 2005; received in revised form 15 April 2005; accepted 13 October 2005
Available online 28 November 2005

Abstract

A qualitative sludge characterisation technique called "sludge filterability technique" has been developed. This technique enables the determination of the sludge potential for the physical removal of solids, weighing the effect of different process parameters on solids removal and identifying the mechanisms of solids removal in an upflow anaerobic sludge bed system. In this paper guidelines for conducting the test are given and a "standardised" set-up is presented. The experimental set-up and protocol are simple and the results can be obtained in a period as short as a few hours. A sludge sample is added to an upflow reactor incubated at 4 °C, to limit gas production, washed with an anaerobically pre-treated and suspended solids free wastewater to remove solids washed out from the sludge, and then fed with a model substrate, prepared from fish meal with a standard procedure. Several experimental runs were conducted to validate and optimise the technique. The results showed that the technique is reliable, workable and reproducible.

Keywords: Anaerobic digestion; Solids removal; SRT; Test standardisation; Primary sludge

1. Introduction

The functioning of upflow anaerobic sludge bed (UASB) systems depends on both physical and biological parameters. The physical parameters, unlike the biological, have been scarcely researched and reported in literature. Several physical parameters are likely to have an effect on particle removal in the sludge bed of a UASB reactor. Mahmoud et al. (2003) argued that these parameters are mainly related to (1) reactor operational conditions (temperature, organic loading rate, hydraulic retention time and upflow velocity), (2) influent characteristics (concentration, particle size distribution and charges) and (3) sludge bed characteristics (particle size distribution, exopolymeric substances, charges, sludge hold up). At the same time, the sludge bed characteristics (point 3) depend on the reactor operational conditions (point 1) as illustrated in Fig. 1. The interdependence of these parameters renders the study of the influence of each separate parameter on solids removal a rather complex issue. At the same time, the investigation of the influence of these parameters under "steady state" conditions is time consuming, laborious and expensive. A method by which the effect of these parameters on sludge capacity for solids removal can be determined will therefore be useful for optimisation and development of anaerobic technologies. In order to be able to compare the potential removal capacity of different sludge types and/or different conditions, a technique has been developed, namely "the sludge filterability technique". This technique can be used to evaluate the capacity of sludge to entrap and adsorb solids under certain conditions. The sludge filterability technique is meant to be a qualitative sludge characterising technique that enables the determination of sludge capacity to remove solids and

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doi:10.1016/j.biortech.2005.10.015

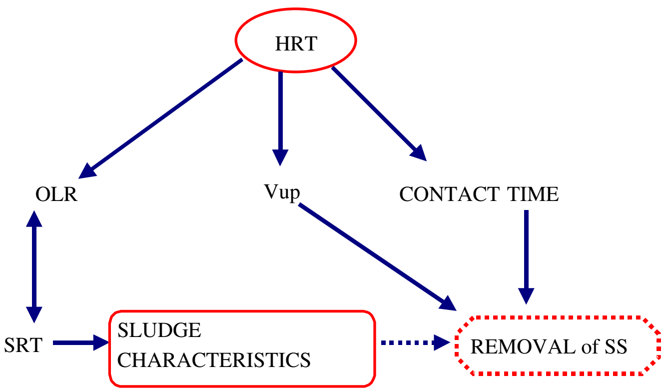

Fig. 1. The operational parameters which are expected to affect the solids removal in an upflow reactor. Where OLR, organic loading rate; SRT, sludge retention time; V_{up}, upflow velocity; HRT, hydraulic retention time; SS, suspended solids (source: Mahmoud et al., 2003).

a method to weigh the effect of different process parameters on the solids removal. The method can also be used for identifying the mechanisms that are involved in the removal of solids in an upflow sludge bed system, e.g., sedimentation, entrapment and adsorption. This paper describes that technique with the main emphasis on concept discussion and workability validation. In addition, guidelines for conducting the experiment are given and a "standardised" set-up is presented. In order to examine the reproducibility and to adjust the set-up and procedure, some experiments were conducted, and the results of these experiments are presented and discussed.

2. Methods

2.1. Experimental set-up

2.1.1. Reactor

The experimental set-up is presented in Fig. 2. A continuous upflow reactor, made from a plastic tube, was used with the following dimensions: working volume 1.11 l; diameter 5.3 cm; height 50.5 cm. The influent was introduced at the bottom of the reactor via a stainless steel tube

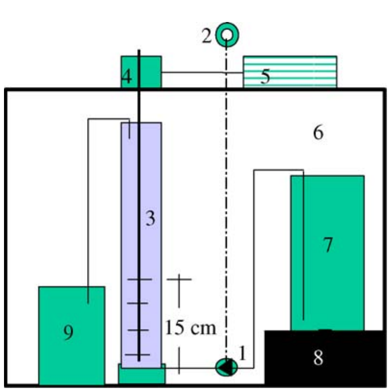

Fig. 2. Schematic diagram of the experimental set-up of the sludge filterability technique. 1, influent peristaltic pump; 2, timer; 3, upflow reactor; 4, mixer; 5, timer; 6, temperature-controlled room; 7, influent vessel; 8, magnetic stirrer; 9, effluent vessel.

with an opening matching the centre of the reactor and facing down. The influent was pumped with a peristaltic pump (Watson–Marlow 101 U/R, Falmouth, Cornwall, UK) from the influent vessel to the reactor. The lengths of the influent and effluent tubes were minimised to prevent solids removal in the tubes. The sludge bed of the reactor was mixed gently intermittently, every 2 min for 10 s at 25 rpm in order to prevent channel formation. The stirrer consisted of a vertical shaft to which 4 perpendicular plastic wires were connected to ensure that the sludge bed was gently mixed. The wires were distributed over the lower 15 cm of the reactor height, approximately 3 cm apart. The reactor and the influent vessel were placed inside a temperature-controlled room at 4 °C, in order to minimise biological conversion, viz. minimise gas production, and density currents caused by temperature differences.

2.1.2. Model substrate

A standardised influent for the experiment was prepared using fish meal (Nutra 3.0, Trouw France S.A.). The fish meal consisted of protein (55%), fat (16%), cellulose (1%) and the ash content was 12%. Of this fish meal, 20 g was added to 2 l of tap water inside an Erlenmeyer flask of 2-l working volume. This solution was mixed using a Kenwood A178 mixer for 4 min to break up larger particles in the fish meal. Thereafter, it was left to settle for 20 min to remove the easily settleable solids and to create a large fraction of non-settleable particles in the influent. After settling, 1770 ml of the supernatant was pumped and diluted two times with pre-cooled water. This resulted in a model substrate with a constant concentration of total suspended solids (TSS) and presumably with a constant particle size distribution. The influent was cooled to 4 °C, the temperature at which the experiment was conducted.

2.1.3. Sludge

The characteristics of the sludges used for the experiments are presented in Table 1. The primary digested sludge (A) was obtained from a full-scale digester at the wastewater treatment plant of Ede, The Netherlands. The other anaerobically digested primary sludges, viz. B, C and D, were obtained from lab-scale (15-l working volume) completely stirred tank reactors (CSTRs) operated at different solids retention time (SRT) and/or different temperature.

2.2. Analytical methods

The influent, effluent and background total suspended solids (TSS) concentrations and the sludge total solids (TS) and volatile solids (VS) concentrations were analysed in duplicate according to standard methods (APHA, 1998).

2.3. Procedure

A volume of flocculent sludge was added to the upflow reactor and washed with TSS-free anaerobically pre-treated wastewater introduced into the reactor at the same

Table 1
Characteristics of the anaerobically digested primary sludge used for conducting the sludge filterability test

Sludge	SRT (day)	Temperature (°C)	TS (g/l)	VS (g/l)	VS/TS
A	20	30	39.51(0.57)	n.m.	n.m.
B	10	35	14.90(0.50)	9.56(0.36)	64
C	15	35	14.12(1.02)	9.00(0.65)	64
D	20	25	15.19(0.66)	9.57(0.70)	63

Sludge A was obtained from the full-scale wastewater treatment plant of Ede, The Netherlands, while B, C, and D were obtained from lab-scale CSTRs. Standard deviations are presented between brackets; n.m.: not measured.

experimental upflow velocity, viz. 0.5 m/h. The sludge was washed to eliminate the interference of sludge bed solids, i.e., solids that could wash out, not from the influent TSS but from the sludge itself, at the applied upflow velocity. The sludge was washed with centrifuged (15 min at relative centrifugal force (RCF) 4964*g*) and filtered (Schleicher & Schuell 589[1], diameter 150 mm, pore size 5–7 μm) wastewater effluent from a pilot scale anaerobic system treating domestic sewage, which contained hardly any biodegradable material. Preliminary results showed that a stable background solid concentration remained in the washing effluent after more than 4 HRT of washing. Therefore it was necessary to determine the "background" concentration to correct the effluent concentration for present sludge TSS. The effluent of the last HRT before the end of the washing procedure was collected separately; the TSS content of this effluent was used as the "background" concentration. The amount and concentration of the TSS that had been washed out during the washing step was measured and used to characterise the sludge to be tested. Therefore, all the effluent of the washing process was collected and analysed for TSS content.

When the washing process was completed, all of the liquid above the sludge bed, representing 70% of the total water volume in the reactor, was wasted. That accelerated the experiment as it limited dilution of the subsequently introduced model substrate, i.e., fish meal wastewater, with the washing liquid remaining above the sludge. The reactor was considered to be a plug flow reactor as depth/width ratio was 9.5, and plug flow was confirmed by visual observation and also by turbidity measurements during the preliminary experiments. The contact time between sludge and fish meal influent was minimised in order to obtain the removal efficiency of "clean" sludge, i.e., alteration of the origin sludge sample was minimised. The effluent of the first 0.5 HRT after 0.7 HRT of introducing the fish meal was wasted. The period of 0.7 HRT was the period required to completely re-fill up the reactor as the washing liquid over the sludge bed was wasted. Thereafter, the sample for determining the effluent TSS concentration was taken by collecting the whole effluent over a period of 0.5 HRT in order to have enough sample size for analysis.

The amount of influent TSS that can settle at an imposed upflow velocity can be determined by operating a blank reactor without sludge. In this way a distinction can be made between settling and other removal mechanisms, e.g., entrapment and adsorption. The experimental procedure and conditions are summarised in Table 2.

Table 2
Experimental procedure used for conducting the sludge filterability technique

- 600 ml sludge was added to the reactor
- The TS and VS concentration of the sludge added were determined
- The sludge was washed with well-digested, TSS free wastewater at V_{up} of 0.50 m/h, corresponding to a HRT of 1 h, for a period of around 5 h
- The whole effluent of the washing step was collected and analysed for TSS concentration to obtain the background concentration
- The fluid above the sludge bed was removed after washing
- The fish meal influent was introduced
- The effluent of the first 0.50 HRT was wasted
- Thereafter, the effluent was collected for 0.50 HRT and analysed for TSS concentration

3. Results and discussion

3.1. Washout/background TSS concentration

The amount of sludge that had been washed out during the washing step and the background concentration obtained upon washing the sludge are presented in Table 3. The results reveal the importance of this step as the solids washed out from the sludge itself will be mixed with the solids from the influent, leading to erroneous results for effluent solids concentration. Several preliminary experiments aimed at follow up of sludge washout over time revealed that a washing period of around 3–4 HRT was required to achieve a stable solids concentration in the washout effluent. The results show that the washout solids reduced over the first 4 HRT as they decreased from an overall average value of 0.063 g TSS/l to a rather stable end value of 0.030 g TSS/l (example for sludge B). Moreover, the results of this experiment, which had been repeated four times, proved that the washing step is reproducible as can be seen from the low standard deviation of the solids concentration, viz. 0.030 (0.012). In another experiment (sludge A) the stability of the effluent washout was followed over a period of 4–7.5 HRT. The results showed that a background TSS concentration would exist even after this long washing period, but the washout solids concentration became stable which was clear from the very low standard deviation, viz. 0.004.

Table 3
Duration and reproducibility of the sludge-washing step of the sludge filterability technique performed on anaerobic digested primary sludge in order to achieve a stable effluent concentration

Sludge type	Number of experiments	Number of collected samples	Washing time (h)	Total volume of the washed-out effluent (l)	Washout (g TSS/l)	Washout (g TSS)	Background solids concentration (g TSS/l)
A	1	4[a]	7.5	n.m.	n.m.	n.m.	0.067(0.004)
B	4	1	4	4.48(0.46)	0.063(0.008)	0.282(0.020)	0.030(0.012)
C	3	1	4.4	4.89(0.86)	0.060(0.002)	0.294(0.059)	0.049(0.018)
D	3	1	4.9	5.43(0.36)	0.048(0.007)	0.260(0.024)	0.044(0.015)

Standard deviations are presented between brackets; n.m.: not measured.
[a] Samples collected over a period of 4–7.5 HRT.

Table 4
Sludge filtering capacity determined by the "sludge filterability technique" of different types of primary digested sludge

Sludge	Number of experiments	Rem − back (%)	Rem + back (%)	Influent (g TSS/l)	Effluent (g TSS/l)	Background (g TSS/l)
A	4	43.26(2.25)	30.65(11.08)	0.363(0.018)	0.251(0.033)	0.060(0.030)
B	4	47.79(2.17)	41.81(1.34)	0.565(0.008)	0.326(0.009)	0.032(0.005)
C	4	38.12(2.92)	30.73(1.32)	0.721(0.012)	0.498(0.009)	0.053(0.018)
D	3	48.38(1.31)	37.66(3.91)	0.589(0.037)	0.368(0.043)	0.064(0.019)

The data show the removal efficiency without (rem + back) and with (rem − back) subtraction of the background TSS. Standard deviations are presented between brackets.

3.2. Reproducibility and workability

The feasibility of this concept had been assessed based on the reproducibility of the results and workability of the set-up and the model substrate, i.e., fish meal. The low standard deviations of the influent and effluent concentrations and the TSS removal efficiencies (Table 4) prove the reproducibility of the results and the reliability of the technique. TSS removal is not only due to removal of the settling part of the influent solids, but also due to entrapment and adsorption. The amount of settling solids in the influent was determined by introducing the influent into the reactor without a sludge bed, the results showing that only 18% of the influent TSS was removed due to settling. The variation in the influent concentration (Table 4) is discussed in Section 3.6.

3.3. Experimental set-up

The reactor set-up is meant to be a "standard" configuration for the sludge filterability technique. The set-up is rather simple, compact, easy to operate and maintain and cheap. Small reactors with a high "height:diameter" ratio (7:12) show mixing behaviour which resembles plug-flow. In such reactors there is also less or no dead space, this ensures that all the sludge gets in contact with the wastewater (de Man, 1990). The mixing time and speed were reduced as much as possible to limit the disturbance of the sludge structure. The provision of gentle mixing in most cases proved to be sufficient to prevent channel formation and to assure complete utilisation of the sludge sample. However, during some experiments, persistent channels were formed, which needed to be disturbed manually as increasing the mixing time had no effect on these channels. The presence of channels during washing of the sludge could be traced by visual observation of the sludge bed.

3.4. Standard temperature

The experiment was conducted at 4 °C as some preliminary experiments showed that at a higher temperature gas production occurred. At those conditions, the liquid above the sludge bed was turbulent and a circulation in the fluid above the sludge bed was observed. Mixing of the sludge bed by the gas produced might influence the solids removal, but at a temperature of 4 °C, gas production is negligible and removal without the interference of gas production can be studied. de Man (1990) showed that mixing behaviour of the liquid in UASB reactors depends on the gas production, sludge characteristics, influent distribution and the geometry.

3.5. Washing liquid

The sludge was washed with well-digested wastewater, which hardly contained any biodegradable organic matter that might have resulted in gas production and alteration of the sludge characteristics. In addition, the concentration of the salts and therefore the ionic strength was presumed similar to that of the wastewater used in practice. Zita and Hermansson (1994) showed that the floc formation of activated sludge is influenced by the ionic strength. However, the influence of the washing liquid on the sludge capacity for solids removal is still to be researched.

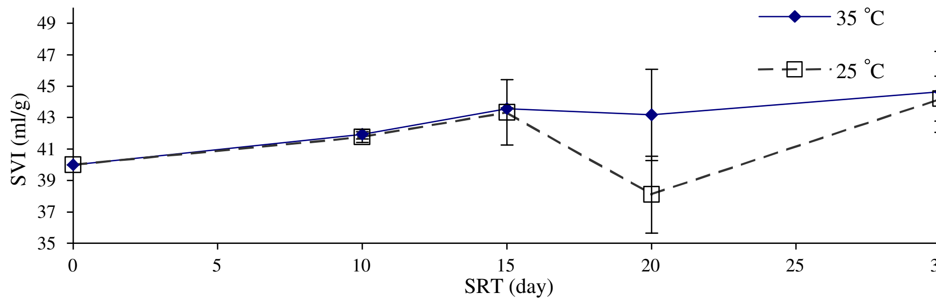

Fig. 3. Dependency of primary sludge settleability, expressed as SVI, on anaerobic digestion conditions (SRT: 0, 10, 15, 20 and 30 days; temperature: 25 and 35 °C) in CSTRs. SRT = 0 stands for the raw influent (source: Mahmoud, 2002).

3.6. Model substrate

The use of a model substrate that is prepared under identical conditions and therefore always maintains similar characteristics, e.g., TSS concentration, chemical composition and particle size distribution, is necessary to get reproducible results and to compare the results of different research projects. Fish meal was chosen because it is an easily available and cheap organic substrate, contains similar biopolymers, i.e., lipids, proteins and carbohydrates, to sewage and has been shown to be a workable model substrate, i.e., reproducible and contains particles. The results showed that the amount of settleable solids in the influent was a confounding factor, when testing the capacity of sludge, as the removal by settling is not related to sludge characteristics. It was rather critical to maintain a constant TSS concentration in the model substrate due to the methodology by which the substrate was prepared. The most critical step in preparing the model substrate was pumping the effluent after the settling period. However, when determining the amount of solids that settled in the reactor it was found that although the influent concentration varied considerably between 0.34 and 0.40 g/l, the effluent TSS concentration was rather stable, approximately between 0.31 and 0.29. This indicates that the variation in the TSS concentration was due to pumping of a relatively larger fraction of settling solids (after settling the influent was pumped from a standardised height in the Erlenmeyer flask in which it was left to settle, this could not be done very accurately). Preparing the influent in a different way could eliminate this source of error. After preparing the influent as described before, the influent could be introduced into the upflow reactor, operated at the required experimental upflow velocity, without sludge. The effluent would contain no settling solids. In this way more insight into the adsorption and entrapment process could be obtained. Another possibility would be to determine the sludge capacity based on effluent concentration rather than removal efficiency.

3.7. Sludge bed height/volume

The sludge bed height is a principal variable in performing the sludge filterability technique, similar to the granular-medium filters (Metcalf and Eddy, 2003). This seems to be the most important parameter to make results of different experiments comparable. Solids adsorption and entrapment are believed to be contact time and sludge bed height dependent. Another important variable is the total amount of solids (TS) added to the filter initially, as it controls the amount of surface available for influent solids to be entrapped and adsorbed. However, Mahmoud (2002) showed that during anaerobic digestion of primary sludge in CSTR reactors operated at 10, 15, 20 and 30 days at process temperatures of 25 and 35 °C the sludge volume index is independent of the sludge digestion conditions (Fig. 3), which suggests that a fixed sludge volume might contain fixed solids content. In this research, the sludge bed height was fixed at 15 cm. During the reproducibility experiment, 600 ml of sludge (liquid height 28 cm) was added to the reactor. That resulted, after washing, in a sludge bed height of around 15 cm. However, more investigations are still needed to elucidate the effect of upflow velocity on sludge bed height and concentration.

3.8. General discussion

The relationships between the reactor operational conditions (temperature and SRT) and bioconversion have been quite satisfactorily researched. In a study of anaerobic digestion of primary sludge in completely stirred tank reactors (CSTRs) operated at different SRTs of 10, 15, 20 and 30 days and process temperatures of 25 and 35 °C, Mahmoud (2002) observed different conversions with substantial sludge stabilisation achieved between 0–10 days at 35 °C and 10–15 days at 25 °C. This means that the techniques for investigating the relationships between the reactor operational conditions and sludge bioconversion are well developed. In line with that, Halalsheh (2002) investigated the bioconversion of primary sludge during anaerobic digestion in CSTRs operated at 5, 15, 30, 50 and 75 days SRT and at process temperatures of 15 and 25 °C, and also thoroughly investigated the influence of digestion conditions on the sludge potential to form a scum layer. The results of that research revealed that methanogenesis started only at a SRT between 30 and 50 days for reactors operated at 15 °C, while it started at a SRT between 5 and 15 days for reactors operated at 25 °C. The results also revealed that both SRT and temperature affect the extent of scum formation. That was explained by the degree of digestion, which has a clear effect on the concentration of lipids which have a strong tendency for sludge adsorption and floatation. In addition to that, the results showed that sludge with a high scum forming potential would only produce scum in the presence of gas production.

With the filterability test presented here, the relation between conversions and suspended solids removal can also be shown. This means that the sludge can be judged for potential solids removal in a UASB reactor without running huge reactors fed with sewage. In addition to the possibility of researching the characteristics of sludge, this set-up enables the examination of different wastewaters for their potential to have solids removed, but in this case standard sludge should be used.

4. Recommendations

1. Special attention should be paid to measuring the background TSS concentration since the experience gained while conducting this research showed that this was a major element in dictating the sensitivity of the experiment.
2. A set of 3–4 similar reactors can be operated simultaneously to obtain the required replicates. This will reduce the experimental time and errors, e.g., maintain similar sludge characteristics. Another two blank reactors can also be run in parallel to the experimental reactors to determine the background concentration. With such an experimental set-up, instead of using a model influent substrate, real wastewater that the sludge is normally exposed to, or will be exposed to, can be used, with or without reactors fed with a model substrate.
3. The experiment should be monitored carefully to ensure that there are no channels in the sludge bed.
4. The time required for the "background TSS concentration" to stabilise should be determined as it may be influenced by the sludge origin, e.g., from CSTR or UASB, and the conditions applied.
5. To obtain a sludge bed of standard height a pre-experiment is needed in which the amount of sludge that needs to be added is estimated.
6. Although the fish meal has been shown to be a workable model substrate, other substrates and methods of influent preparation can be proposed.
7. More investigations are required to elucidate the effect of the model substrate physico-chemical characteristics, e.g., pH and ionic strength, on the sludge capacity for physical removal.

Table 5
Final recommended protocol for conducting the sludge filterability technique

- The volume of sludge needed to reach a sludge bed height of 15 cm after washing is added to the reactor
- The TS and VS concentration of the sludge added is determined
- The sludge is washed with well-digested TSS free wastewater at the required upflow velocity
- The whole effluent of the washing step is collected and analysed for the TSS to obtain the background concentration
- The sludge is washed for ±5 HRTs until the background TSS concentration becomes stable
- The effluent of the last HRT of the washing step is collected separately and analysed for TSS concentration to determine the background concentration
- The fluid above the sludge bed is removed after washing
- The fish meal influent is pumped into the reactor
- The effluent of the first 0.50 HRT is wasted
- Thereafter, the effluent is collected for ±1 HRT and analysed for TSS concentration
- The VS and TS of the sludge after the washing step should be measured at least 3–4 times

8. The proposed procedure for the "standardised" experiment is presented in Table 5. Some of the recommendations have been included in this procedure.

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