Operation of anaerobic digesters at increased solids concentrations

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Abstract

Conventional anaerobic digesters treating municipal sewage usually function with a hydraulic retention time of 30 to 60 d and at a total solids (TS) concentration of 1.5 to 3% (m/v). A cross-flow microfiltration unit was constructed at Northern Waste Water Treatment Works, Durban to concentrate sludge from a conventional anaerobic digester and to facilitate operation with a higher solids concentration. Semi-continuous digesters were, therefore, operated with a 30 d retention time and at an optimum temperature to investigate the efficacy of digesters supplied with concentrated digested sludge. The results showed that the rate of gas production from a digester supplied with 3.8% (m/v) TS was higher than the control (2% (m/v) TS) and a digester supplied with 3% (m/v) TS. Increased total solids concentrations (4.7% (m/v)), however, effected slightly lower gas production rates than the digester with 3.8% (m/v) TS. The volatile solids concentrations of all four digesters were similar, indicating neither favourable nor unfavourable effects from increased solids concentrations. The digesters operated at total solids concentrations 3.8% (m/v) TS produced higher concentrations of volatile acids than the control. The alkalinity concentrations (ca. 4 000 mg·ℓ^{-1}) were similar for all four digesters.

Introduction

For waste stabilisation, the anaerobic digestion process has several advantages over aerobic treatment. These include a significantly lower operating cost and sludge production rate per kilogram of organics oxidised, the potential for chemical energy production through methane and the generation of a sludge which is relatively odour-free and easy to dewater. The process is, however, limited by a low bacterial growth rate which, until fairly recently, has restricted the use of the process for the treatment of low volume streams such as raw sewage sludge (Malina, 1992; Treffry-Goatley et al., 1986).

In anaerobic digestion the methanogens are the slowest growing population and are also the most significant group with regard to waste stabilisation (Song et al., 1992).The generation times for methanogens range from less than 2 d to more than 20 d at 35°C (Malina, 1992; Lettinga and Hulshof Pol, 1991). Solids retention time (SRT) is recognised as a key parameter for successful design and operation of an anaerobic digester because it most accurately expresses the relationship between the catabolic bacterial population and the operating conditions (Pfeffer, 1968; Parkin and Owen, 1986). Zhang and Noike (1991) showed that a decrease in the solids retention time in an acidogenic reactor resulted in the washout of the methanogens utilising acetic acid, formic acid and methanol while the population sizes of the hydrogenotrophs, such as the hydrogen-utilising methanogens, homoacetogens and sulphate-reducing bacteria increased rapidly, with no washout apparent.

The degree of waste stabilisation is a function of retention time, waste characteristics and operating conditions (Pfeffer, 1968; Parkin and Owen, 1986). The more time the sludge spends in the digester in the presence of active biomass, the greater the volatile solids destruction. The volatile solids content controls the rate and volume of gas production. In conventional anaerobic digesters, volatile solids conversion to gaseous products and solids retention time is controlled by the hydraulic retention time and typical hydraulic retention times are 15 to 20 d (Pfeffer, 1968; Malina, 1992; Ouyang and Lin, 1992). The design criteria for anaerobic digesters must, therefore, take the time-dependency factor of volatile solids destruction into consideration (Malina, 1992; Lettinga and Hulshoff Pol, 1991).

Therefore, the ability to thicken sludge becomes an important design and operating consideration since, in the absence of thickening, digester loadings are limited. With thickened sludge the high solids loading reduces the operating digester volume for a given retention time (Malina, 1992). It is possible to increase the solids retention times (mean cell retention time) by accumulating biomass within the reactor by means of settling/concentrating, attachment to solids or by recirculation. Therefore, these systems are designed to facilitate the retention of slow-growing micro-organisms (especially the methanogens) by ensuring that the mean solids residence time becomes much longer than the mean hydraulic residence time (Malina, 1992; Lettinga and Hulshof Pol, 1991; Ouyang and Lin, 1992). Such systems must also improve contact between the biomass and waste water to overcome problems of diffusion of substrates and products from the bulk liquid to the biofilms or granules, and enhance the activity of the biomass through adaptation and growth (Iza et al., 1991; Parkin and Owen, 1986).

The Renovexx cross-flow microfiltration (CFMF) process aims to improve anaerobic digestion by increasing the sludge concentration within the digester, thus effecting a higher biological solids retention time. This process should effect the retention of the active biomass which would otherwise be lost as a waste product (Bindoff et al., 1988). The Renovexx CFMF process operates by pumping slurry, tangentially, through a flexible woven fabric tube (25 mm dia.) under pressure, which causes the suspended matter to be deposited on the inside of the filter tube. The slurry permeates through the filter cake depositing more suspended matter and leaving a clear filtrate which is collected for additional processing. The concentrate is then recycled (Gosling and Brown, 1993; Pillay, 1991; Bindoff et al., 1988). This process operates on a high recycle and a low water recovery basis to produce a clear permeate, for return to the head of the works, and

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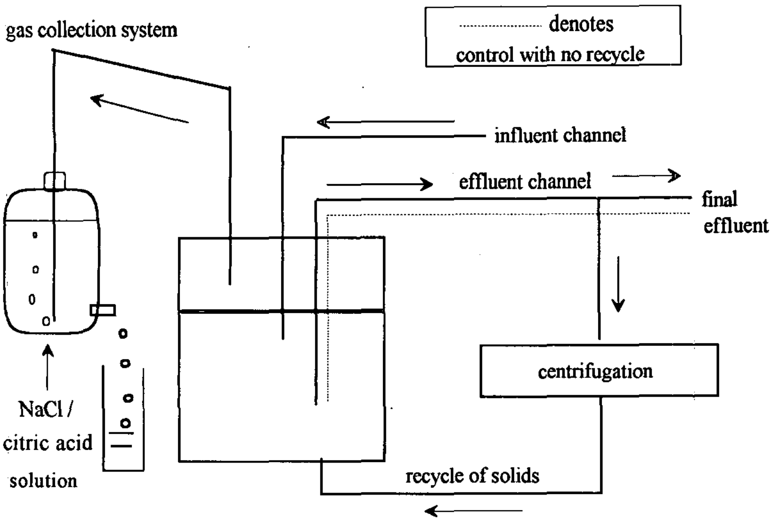

Figure 1

Diagrammatic representation of semi-continuous digester with and without recycle

a concentrated slurry (Bindoff et al., 1988).

Thus, CFMF, with a flexible woven hose, has been suggested as a process which may be used in conjunction with an anaerobic digester for the side-stream concentration and recycle of digester solids (Treffry-Goatley et al., 1986). Ouyang and Lin (1992) for example, reported that digesters operating with a recyle ratio of 0.5, and thus a recycle sludge concentration of about 28 $g\cdot\ell^{-1}$ had higher dehydrogenase concentrations and methane yields. Parkin and Owen (1986) also recorded higher overall methane yields per unit organic matter destroyed but these necessitated protracted solids retention times equivalent to a working volume increase of 570%.

By increasing the mean solids retention time by sludge concentration or recycle, temperature and inefficient mixing perturbations should be reduced. Also, the optimum SRT may facilitate acclimation or metabolism of potential toxicants. Finally, organic material removal efficiency should also increase (Parkin and Owen, 1986). This study was, therefore, made to determine if the efficacy of anaerobic digestion of primary sludge could be improved in the presence of increased solids loadings effected by CFMF.

Experimental procedure

Digester configuration

As experimental tools, semi-continuous systems have the advantage of utilising actively growing and metabolising microbial cells to biodegrade substrates. These systems aim to operate within the exponential phase of bacterial growth thus avoiding the lag, stationary and autolytic phases. Semi-continuous digesters were, therefore, established and were operated simultaneously to determine the efficacy of digestion at different solids concentrations. The total volume of each digester was 2 ℓ, with a working or available volume of 1.5 ℓ, thus giving a headspace volume of about 500 mℓ. These digesters had no mechanical mixing device and were operated with a residence time of 30 d. The digesters were shaken daily during sampling and maintained in a waterbath at a constant temperature of 35°C. Each digester (Fig. 1) was connected to the gas collection system by silicone tubing. An effluent and influent port allowed for waste from the system to be removed and for the substrate (primary sludge) to be added daily, respectively.

Digester operation

Conventional digesters usually operate with solids concentrations of about 2 to 3% (m/v) TS, with 3% TS (m/v) the maximum solids concentration attainable. The four digesters were operated with 2% (Digester 1), 3% (Digester 2), 3.8% (Digester 3) and 4.7 % (m/v) (Digester 4) TS. Digester 1 was the control with no recycle of solids. To maintain concentrations of total solids greater than 2% (m/v), the effluent wasted per day was centrifuged and the solids recycled to the digester. The sludge was concentrated in a Beckman centrifuge at 10 000 $r\cdot min^{-1}$ for 25 min and the concentrate was used to prepare solutions of 3, 3.8 and 4.7% (m/v) TS.

Approximately 50 mℓ of sludge from Digester 1 were removed daily and replaced by 50 ml of primary sludge which contained 5% (m/v) total solids and 78 to 80% volatile solids. Care was taken to maintain a constant concentration. Approximately 150 mℓ of digested sludge were removed daily from Digesters 2, 3 and 4. A volume of 20 to 50 mℓ (depending on type of analysis) digested sludge was stored for analysis while the remainder was centrifuged. A total volume of 150 mℓ was added to the digester i.e., 50 mℓ substrate and 100 mℓ concentrated recycled sludge. Since Digesters 2, 3 and 4 were initially loaded with solids concentrations of 2% (m/v) TS, this procedure of removal and recycling was continued until the solids concentrations within the digesters reached a stable state of operation. Error bars are not drawn since the experimental error during sampling fell within the area of the markers used in Figs. 2 to 5.

Subsequently, the wasted sludge was subjected to various analyses such as volatile solids and total solids concentrations, volatile acid concentration, alkalinity and pH. Gas generated from waste stabilisation was bubbled through a vessel (2 ℓ) which contained a NaCl/citric acid solution (20% w/v NaCl acidified with 0.5% citric acid). This solution prevents CO_2 solubilisation and thus facilitates accurate measurement of the gas generated. The gas produced during anaerobic digestion was measured by displacement of the liquid solution in the gas collection vessel. The displaced liquid was transferred to a 100 mℓ measuring cylinder and measured to the nearest 1 mℓ. With the exception of volatile acids and alkalinity, all of these analyses were conducted according to *Standard Methods* (1985).

Alkalinity

The digested sludge sample was centrifuged with a Beckman centrifuge at 5 000 $r\cdot min^{-1}$ for about 5 min. A 50 mℓ volume of supernatant was transferred to a beaker and the pH was determined with an Orion pH meter. The sample was then titrated to pH 4.0 with 0.1N H_2SO_4. The volume of acid titrated x100 gave the total alkalinity which was reported as mg $CaCO_3\cdot\ell^{-1}$. When the volume of supernatant was insufficient a smaller volume was diluted to give a 50 mℓ sample.

Volatile acid concentration

Once the alkalinity had been determined the pH of the solution was reduced to 3.5 with sulphuric acid (0.1N). The supernatant

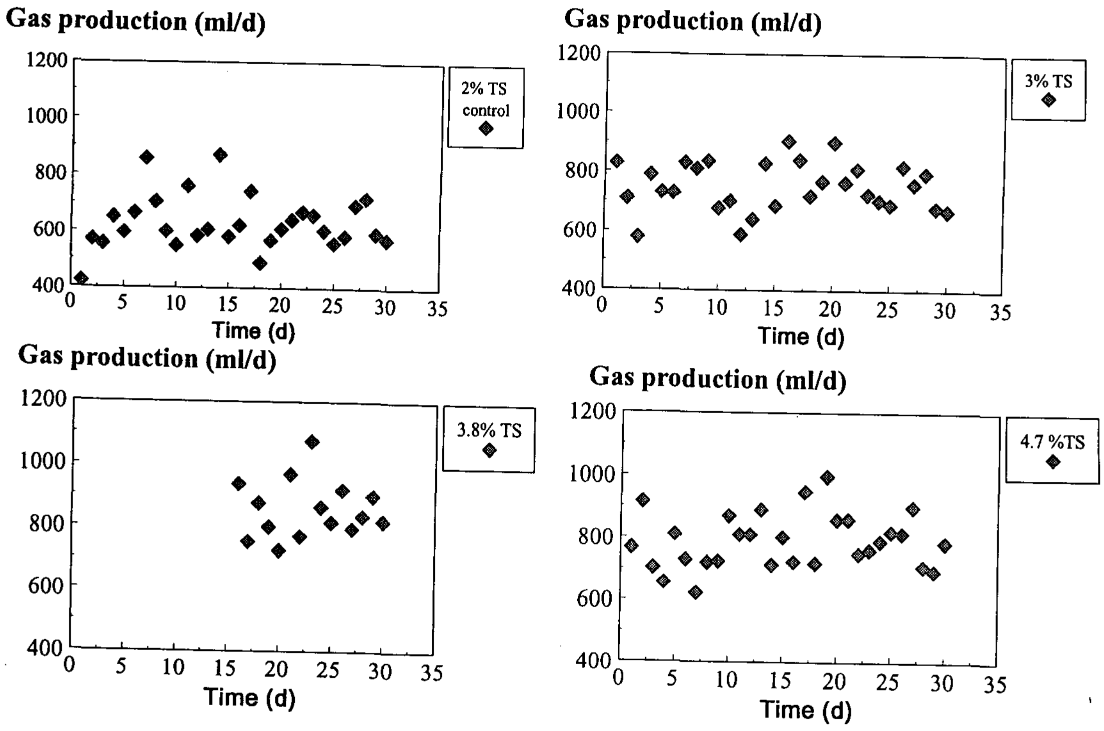

Figure 2
Gas production per day of digesters operating with 2%, 3%, 3.8% and 4.7% TS

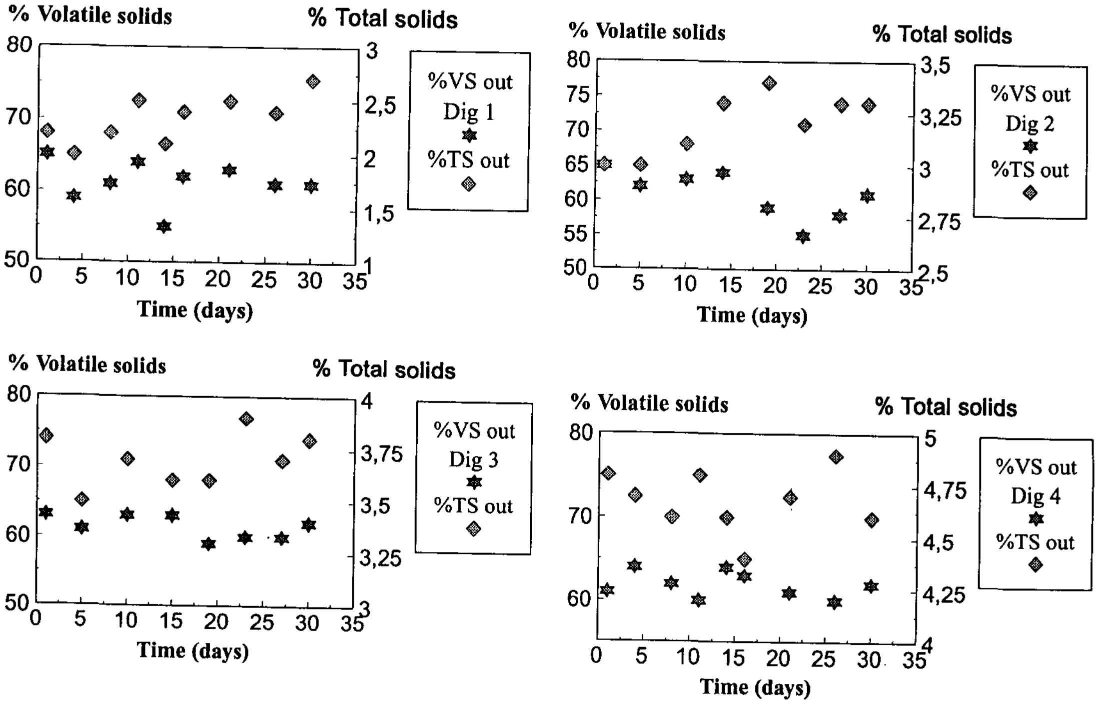

Figure 3
Percentage volatile acids remaining and total solids concentrations recorded in Digesters 1, 2, 3 and 4

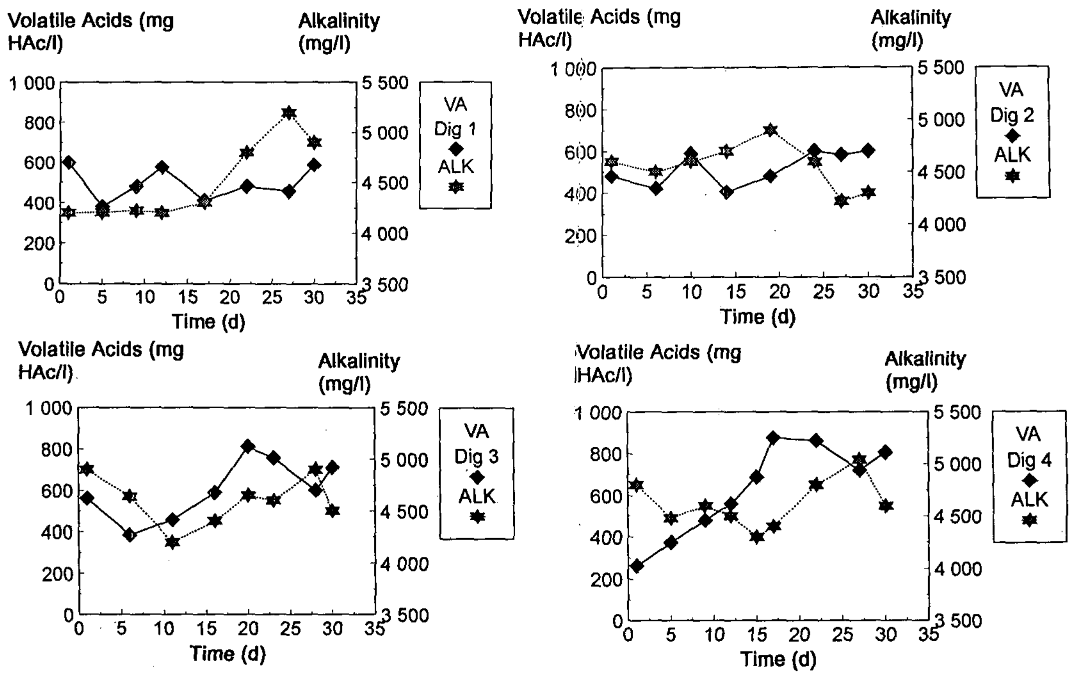

Figure 4

Changes in concentrations of volatile acids and alkalinity of sequencing batch Digesters 1, 2, 3 and 4 with different solids concentrations

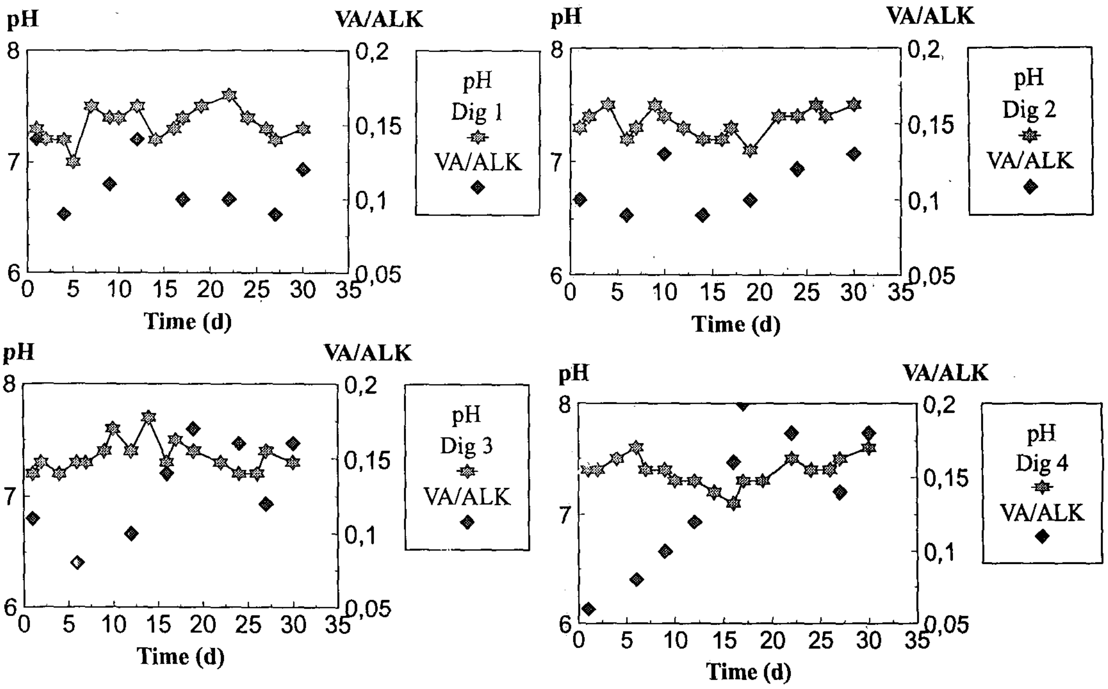

Figure 5

Changes in pH and volatile acids/alkalinity ratios of digesters operating with different solids concentrations

TABLE 1
THE AVERAGE, MINIMUM AND MAXIMUM VOLUMES OF GAS PRODUCED PER DAY BY DIGESTERS LOADED WITH DIFFERENT SOLIDS CONCENTRATIONS

Digester	Concentration %(m/v) TS	Gas produced per day (mℓ·d^{-1}) Average	Minimum	Maximum
1.00	2.00	631.00	422.00	857.00
2.00	3.00	742.00	578.00	904.00
3.00	3.80	856.00	752.00	1 075
4.00	4.70	784.00	622.00	998.00

was then boiled for 3 min and left to cool to room temperature. The volatile acid concentration (VA) was determined by titrating the solution to pH 4.0 (a) and pH 7.0 (b) with 0.1N NaOH. The volatile acid concentration was calculated as follows:

$$VA = (b-a) \times 120 \qquad (1)$$
$$VA = mg\ HAc\ \ell^{-1}$$

Results and discussion

Gas measurements

The gas production per day in each digester was erratic (Fig. 2). Digester 1 (2% (m/v) TS) produced a maximum of 857 mℓ on day 7 and a minimum of 422 mℓ on day 1. Throughout the 30 d sampling and analysis period the gas production in each digester also fluctuated. The initial gas measurements from Digester 3 were disregarded owing to a leak in the silicone tubing of the gas collection system.

Table 1 lists the average comparative gas production volumes of each digester per day and the minimum and maximum values recorded over the 30 d sampling and analysis period. For each of the solids concentrations there was a difference of approximately 300 mℓ between the maximum and minimum values recorded. The rate of gas production increased from 631 mℓ·d^{-1} for 2% (m/v) TS to 856 mℓ·d^{-1} for 3.8% (m/v) TS. Thus, a doubling in solids concentration did not effect a doubling in gas volume production. The digester which was operated with a solids concentration of 4.7% (m/v) produced gas at a lower rate (784 mℓ·d^{-1}) than the one operated with 3.8% (m/v) TS. This discrepancy could possibly indicate either depressed microbial activity or gas trapped in the viscous sludge since the digester contained no efficient mixing mechanism. Inefficient mixing could also have resulted in a non-uniform distribution of substrate to the micro-organisms which could, in turn, have influenced microbial activity. The erratic gas production volumes per day could also be ascribed to the fact that the digesters were only operated for a period of 30 d. This period represents only a single residence time, which may not have been long enough for the digesters to stabilise. Finally, the lack of homogeneity within the digester could have led to the local concentration of inhibitory compounds produced during anaerobic digestion.

Volatile and total solids

Total solids analyses of the digested sludge indicated a relatively stable concentration during the 30 d experimental period (Fig. 3). For Digester 1 (control) the total solids fluctuated from 2 to 2.5% (m/v), with a maximum of 2.7% (m/v) recorded only once on day 30. For each digester the volatile solids concentration of the digested sludge ranged between 60 and 65%, and fell below 60% only twice. The total solids concentration of Digester 2 (3% (m/v)) remained relatively stable for the first 15 d but then increased to 3.4% (m/v) before levelling at 3.25 % (m/v). The initial total solids concentration of Digester 3 of 3.8% (m/v) decreased to 3.6% (m/v) before rising again to 3.8%(m/v). For Digester 4 the total solids ranged between 4.8 and 4.6% (m/v). These fluctuations in total solids concentrations could be attributed to incomplete mixing of the digester contents.

Volatile acids, alkalinity, pH and volatile acids/alkalinity ratio

During the continuous or semi-continuous operation of anaerobic digesters there is always, potentially, a threat of toxic, organic or volumetric overload. Overloading is manifested in various ways such as pH, volatile acids and alkalinity changes. Thus, stress and impending digester failure or "souring" can be anticipated by monitoring the changes within the chemical environment of the digester.

Figure 4 illustrates the changes in volatile acid and alkalinity concentrations. In Digesters 1 and 2, the volatile acid concentrations fluctuated between 400 and 600 mg·ℓ$^{-1}$. Higher concentrations were measured in Digester 3 when the initial volatile acid concentration of 600 mg·ℓ$^{-1}$, decreased to 400 mg·ℓ$^{-1}$ but, subsequently, increased to >800 mg·ℓ$^{-1}$. With Digester 4, the initial volatile acid concentration of 264 mg·ℓ$^{-1}$, increased to about 870 mg·ℓ$^{-1}$, although subsequent analyses revealed concentrations of between 700 and 800 mg·ℓ$^{-1}$. Thus, the digesters operated under increased solids concentrations produced higher volatile acid concentrations.

Figure 5 shows the pH and volatile acids/alkalinity (VA/ALK) ratio results of all four digesters. The pH of each digester remained stable throughout the experimental sampling period although increases in volatile acid concentrations for Digesters 3 and 4 were recorded. High accumulations of acids within the digesters are required to effect pH changes. Thus, pH measurements do not provide a rapid warning of imminent stress or failure. Therefore, reliance on pH alone as a tool for process control of continuous and semi-continuous systems is inadequate.

The VA/ALK ratio is an important analytical criterion for monitoring digester behaviour owing to its sensitivity to changes in the volatile acid concentration and buffering capacity. The VA/ALK ratios for Digesters 1 and 2 ranged between 0.1 and 0.14. Digester monitoring revealed higher VA/ALK ratios (> 0.15) in Digesters 3 and 4 towards the end of the experimental period. These values were, however, still below the maximum permissible limit of 0.3.

Digested sludge observations

The digested sludge wasted daily from the four digesters varied in character. For Digester 1 the sludge can be described as a free-flowing slurry which could be removed from the digester and measured with little difficulty. Digesters 2, 3 and 4 produced sludges which were black and relatively odourless. The sludge removed from Digester 4 was highly viscous and was difficult to sample and recycle to the digester. Shaking of the digesters operating with solids concentrations of 3.8% (m/v) was problematic because of the sticky nature of the sludges.

Summary

The production rates of Digesters 1, 2 and 3 increased as the solids concentration of the digester increased. Digester 4 (4.7% (m/v) TS), however, produced gas at a lower rate than Digester 3 which could be attributed to gas being trapped within the viscous mixture and incomplete mixing. All four digesters produced digested sludge with a volatile solids concentration ranging between 60 and 65%. The volatile acids concentrations recorded for Digesters 1 and 2 fluctuated between 400 and 600 mg·ℓ^{-1}, while Digesters 3 and 4 produced volatile acids concentrations > 800 mg·ℓ^{-1}. The alkalinity of all four digesters was > 4 000 mg·ℓ^{-1} and there were no downward trends in the buffering capacities of the digesters. The pH measurements taken were not sensitive indicators of changes in the volatile acid concentrations, especially for Digesters 3 and 4. The volatile acid/alkalinity ratios changed as the volatile acid concentrations changed and, thus, provided useful information when the volatile acid concentrations were becoming critically high. The results suggest that digesters operating at higher solids concentrations are slightly more efficient with regard to gas production but the changes in volatile solids destruction are not significant. Further research needs to be conducted on the effects of shock loads to such a system.

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