PERFORMANCE OF A SISAL FIBRE FIXED-BED ANAEROBIC DIGESTER FOR BIOGAS PRODUCTION FROM SISAL PULP WASTE

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ABSTRACT

A single stage anaerobic digester employing a sisal fibre waste fixed bed was studied for biogas production from sisal pulp waste. The fibre was colonized by microorganisms involved in biogas production. The sisal pulp waste to be digested was fed from the top and was sprinkled intermittently with recirculating leachate from the material. Organic loading rates of 0.1-10 kg volatile solids (VS) $m^{-3}d^{-1}$ could be applied and methane yields in the range of 0.13-0.48 m^3 CH_4 kg^{-1} VS added were obtained. The average methane content in the biogas produced from sisal pulp waste was 55%, and the biogas production rate was 0.15-0.54 $m^3m^{-3}d^{-1}$. The methane yield obtained and the highest organic loading rate that could be sustained by this simple, fixed-bed digester are indications of an attractive system in terms of performance and reliability. It is concluded that the sisal fibre waste fixed bed is a promising carrier for microbes and can be employed for long-term operation without changing the bed.

INTRODUCTION

The sisal industry traditionally utilises only 5% of the total weight of the leaf in sisal fibre production, and the remaining 95% is being regarded as waste. Fifty-two sisal factories in Tanzania produce about 444,000 tons of waste pulp and 148,000 tons of waste fibre annually, which is often dumped on land or near rivers where it is degraded by microorganisms under uncontrolled conditions. This leads to land, water and air pollution. Sisal waste, however, constitutes a major potential source of clean energy if digested anaerobically under controlled conditions to generate methane. Assuming a standard yield of biogas from biomass wastes of 0.3 m^3 biogas kg^{-1}volatile solids (VS), 16×10^6 m^3 biogas could be obtained from sisal pulp waste with a total solids (TS) content of 14.3% (82.3% of this being VS) and 37×10^6 m^3 biogas from sisal fibre waste (TS 91.6% of which 92% is VS). The amount of biogas produced (assuming 50% CH_4 content and complete conversion without losses) would be equivalent to 77 GWh and 183 GWh of electricity from sisal pulp and sisal fibre waste, respectively. To produce one ton of sisal fibre 200-300 kWh are required (Lock 1969). Thus, for the production of 24,000 tons of commercial sisal fibre in the year 2001, 7.2 GWh of electricity were used (Ronarco 2001). The possibility of using sisal waste for the production of methane could be a cost-effective option at sisal factory level, while at the same time reducing environmental pollution.

Anaerobic digestion involves the biological degradation of almost all organic material into biogas. The biogas produced contains methane with contents typically around 60%, which can replace conventional fuels (Chynoweth 2001). It is however, a complex process realised through the combined action of consortia of anaerobic microorganisms (Pavlostathis & Giraldo-Gomez 1991). The digestion of solid biowaste involves a delicate balance between the rate of hydrolysis and the rate of methanogenesis, as the methanogens are far more sensitive to the accumulation of volatile fatty acids (VFAs) and the corresponding pH drop, than acidogenic and fermentative bacteria. If the

rate of hydrolysis is higher than the methanogenic rate, the accumulation of VFAs and hydrogen may lead to irreversible acidification of the digester. Such an effect can lead to cessation of methane production and ultimately process failure (Pavlostathis and Giraldo-Gomez 1991). To alleviate this problem, the application of two-stage systems has been suggested for the digestion of easily hydrolysed organic material in which liquefaction and acidification take place in the first bioreactor and methanogenesis in the second bioreactor. Also two-stage system is beneficial for lignocellulosic material since there will be pretreatment in the acidogenic stage which improves the solubilisation of the organic compounds (Ghosh 1991).

Two-stage bioreactor systems are efficient, but expensive due to high investment and operational cost. They also suffer from problems of clogging or channel formation in the percolated bioreactor (Lettinga and Hulshoff 1991). In the case of lignocellulosic material normally hydrolysis is the rate-limiting step. Therefore acidification of the digester normally does not occur and a two-stage system could not be necessary (Weiland 1993).

Single stage fixed film (bed) is an emerging, attractive, cost-effective simple technology for high solid anaerobic digestion implementation, in which acidogenesis and methanogenesis are partially separated within a single vessel. Hydrolysis and acid formation take place preferentially in the fresh biomass/humid waste fraction at the top of the digester, while gas formation occurs to some extent in the fixed bed bacterial support at the bottom of the digester (Chanakya *et al.* 1999). Digesters are fed directly with the solid waste instead of first processing the waste into a slurry as is done in conventional digesters. Apart from saving processing time and cost, such digesters often enable handling of higher concentrations of VS per unit digester volume than if the same solids were fed as a

slurry (Ramasamy & Abbasi 2000). Increasing the solid content in anaerobic digestion greatly enhances the economy of the technology due to increased methane production per unit volume of the reactor.

In developing countries such as Tanzania, low-cost systems for biogas production have considerable potential for application and acceptance in rural areas and peri-urban regions where the inhabitants may have no other option for sustainable energy production. Organic support materials such as plant biomass can be used for immobilization of the microorganisms leading to increased population of the microbes, thus enhancing the performance of the fixed bed anaerobic digester. At the same time rigid plant biomass can constitute a humidity reservoir, mechanical support and provide structural stability to the bed. In addition, plant biomass is inexpensive and easily available compared to traditional support materials (Guitonas *et al.* 1994; Chanakya *et al.* 1997; Chanakya *et al.* 1998, Sene *et al.* 2002, Andersson and Björnsson 2002). Being a solid, lignocellulosic material with 88-90 %TS, sisal fibre waste is relatively resistant to biodegradation. Furthermore, it is coarse and has a rough surface (Lock 1969). The possibility of utilizing it as a biofilm carrier in a fixed bed digester for converting sisal pulp waste to methane is thus worth investigating.

The objective of this study was therefore to investigate the performance of a single-stage anaerobic digester with sisal fibre waste as the fixed bed when digesting sisal pulp waste, in terms of biogas volume, biogas yield and sustainable organic loading rate.

MATERIALS AND METHODS
Experimental set-up
The digester was made of Plexiglass with a total volume of 2 L and a 0.9 L reservoir placed at the bottom of the reactor where leachate was collected and recycled, by means of a peristaltic pump to the top of the

reactor. The biofilm support, which consisted of sisal fibre waste (SFW), was placed at the lower part of the reactor. During operation, sisal pulp waste (SPW) was added in a batch wise manner and accumulated at the top of the digester. Leachate recycled from the reservoir transported soluble organics from the green biomass down to the methanogenic culture in the SFW bed. Biogas produced was collected into a gas-tight bag at the top of the reactor. The digester was operated at an ambient temperature of $(24 \pm 2^\circ C)$, without heating the whole reactor because ambient temperatures in East Africa where sisal residues are generated are higher and will permit the utilization of the digesters without heating.

Inoculum and start-up procedure
In order to obtain quick start-up, pre-digested SFW was used. Digested slurry (inoculum) used was obtained from a pilot-scale wheat straw fixed-bed digester, fed with sugar beet tops, operated for 120 days (Agrigas Research Station, Annerberg, Sweden). SFW and SPW were obtained from a sisal processing factory at Ubena Zomozi in Tanzania. The initial packing density was 30 kg m^{-3}, (based on a combination of 78% pre-digested SFW and 22% of spent wheat straw). The bed materials were thoroughly mixed with 500 mL of the inoculum and quickly packed in

the digester. The volume occupied by the bed was 1 L with a bed height of 0.15 m. During start-up of the digester, a continuous leachate flow rate of 0.14 L day^{-1} was applied. A low leachate flow rate was applied to prevent the possibility of irreversible acidification of methanogenic pockets. The start-up time took 32 days. The criteria used to determine this start-up period were attainment of pH above 7.2, partial alkalinity (PA) above 3500 mg CaCO$_3$ L^{-1}, chemical oxygen demand (COD) below 2000 mg L^{-1} and total volatile fatty acids below (1000 mg L^{-1}) in the recycled leachate. Further criteria were constant methane content around (60%) and insignificant biogas production in last two weeks. During this period no SPW was fed to the system. Following completion of the start-up period SPW was fed to the digester at varying organic loading rates (OLRs). The continuous leachate recirculation during the start-up period was changed to intermittent pumping every 6 hours with a flow rate of 1.0 L day^{-1} during experimental operation.

Feedstock and organic loading rates
The SPW had a TS of 14.3%; 82.3% of which was VS. The SPW was not diluted. Feeding was achieved by removing a rubber stopper from the feeding port admitting the pre-weighed SPW and replacing the rubber stopper immediately. No compaction of the feed was employed.

Table 1:   Feed rates adopted with sisal pulp feed stock

Weeks	Fresh weight (g)	VS added gVS 2L^{-1}	LC gVS L^{-1}	OLR kgVS m^{-3}d^{-1}
1	17	2	1	0.14
2	34	4	2	0.28
3	51	6	3	0.42
4	68	8	4	0.57
5	85	10	5	0.71
6	102	12	6	0.85
7	119	14	7	1
8	136	16	8	1.14
9	153	18	9	1.28
10	170	20	10	1.42
11	187	22	11	1.57
12	204	24	12	1.71

Table 1:	Cont.			
13	221	26	13	1.85
14	238	28	14	2
15	255	30	15	2.14
16	306	36	18	2.57
18	374	44	22	3.14
19	459	54	27	3.85
20	1224	144	72	10.4

The digester was fed at weekly intervals and the organic loading rate (OLR) was gradually increased (Table 1). The OLR, expressed as kg VS $m^{-3}d^{-1}$, started at low rates ranging from 0.1 to 2.1 from week 1 to week 15. Feeding was then increased to moderately high OLRs of 2.5-3.8 kg VS $m^{-3}d^{-1}$ during weeks 16–19. At week 17 feeding was not done to allow the system to recover after feeding 2.57 kg VS $m^{-3}d^{-1}$ during week 16.

Stability of the system to overload
High substrate additions were made in week 20 to test the stability of the system to overload. The reactor was fed three times during this week instead of once and each batch load consisted of 408 g (2.19 kg VSm^{-3}) of sisal pulp waste. The organic loading rate, expressed in kg VS $m^{-3}d^{-1}$ was increased from 3.80 to 6.04 (after first batch addition) from 6.04 to 8.23 (after second batch addition), and finally from 8.23 to 10.4 (when third batch load was added). During each addition, the pH, alkalinity, volatile fatty acids (VFAs), biogas compositions were monitored at 4, 8, 20, 24 and 72 hours. Digestion was then allowed to proceed for two weeks, up to week 22 to monitor the system performance.

Continuous operation was limited by the volume of the digester. However, we did not increase the digester volume as this would have lead to an increased cost. Digested SPW was thus removed when the digester was full in order to create space for continued operation. The digested SPW at the top of the digester was removed by opening the digester at the top during weeks 15 and 18. Before emptying, any liquid in the digester was allowed to drain into the reservoir.

Analytical methods
The biogas volume was measured with a wet-type precision gas meter (Schlumberger, Karlsruhe, Germany). Biogas composition, partial alkalinity (PA), total alkalinity (TA), pH and VFAs were measured every 24 hours after feeding SPW using methods previously described by Björnsson *et al.* (2000). The gas composition was determined by gas chromatography (Varian 3350, Walnut Creek, CA, USA). VFAs were monitored with high performance liquid chromatography (Varian 9000 HPLC, Walnut Creek, CA, USA), using a BioRad column (Biorad 125–0115, Hercules, CA, USA), column for fermentation monitoring. UV absorbance at 208 nm was used for peak detection. Samples for VFAs analysis were centrifuged at 3000 x g for 3 min and the supernatant was acidified with concentrated sulphuric acid. The samples were stored at –20°C until analysis. Before analysis, the samples were thawed and filtered through 0.45 μm filters (Minisart, Satorius AG, Göttingen, Germany). The pH and alkalinity were monitored using a TIM titration manager with an ABU 901 Autoburette (Radiometer Copenhagen, Denmark). Samples were centrifuged at 3000 x g for 3 min, and 6 ml of the supernatants were used. TS and VS were analysed according to standard methods (APHA 1985).

RESULTS AND DISCUSSION

Structural stability of the bed and leachate recirculation
The original volume of the SFW bed decreased by 40% after 6 months of operation. Despite the fact that the sisal fibre

waste bed was partially degraded, it still had sufficient structural stability at the end of the experimental run of 6 months. In a full-scale system, exchanging or replenishing bed material on this time scale is feasible. During the 6 months of operation, no clogging, drainage, or foaming problems were encountered, even with high batch loading. It is possible that intermittent pumping allowed for drainage hence preventing free liquid in the digester from causing the biomass to float.

Bed shrinkage has been reported by others using organic materials for bacterial support

in fixed-bed reactors for biogas production from crop residues. However, the extent of shrinkage depends on the organic support used, the packing density and scale, as well as the age of the bed. For example, in their laboratory-scale study of a straw fixed-bed reactor of 105 kg m^{-3} packing density, Svensson *et al.* (2002) observed 80% decrease in the original volume when the straw was 274 days old. The original volume was reduced by a further 6% from day 274 to day 326.
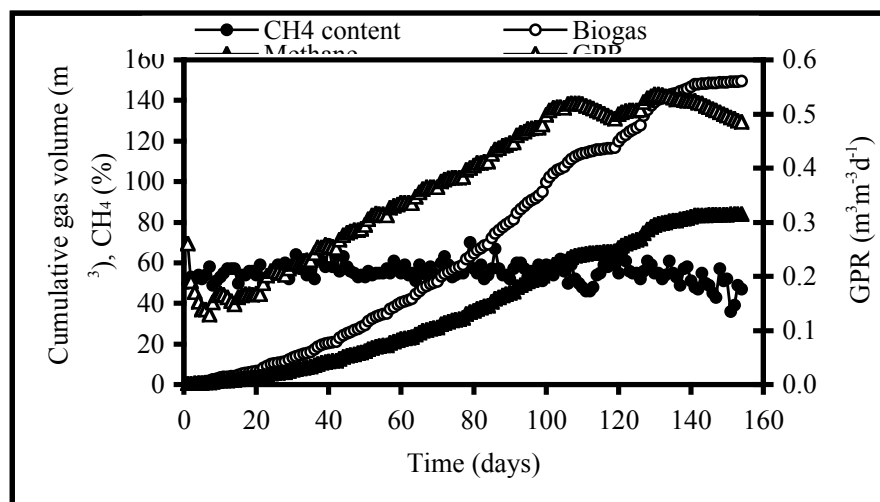

Figure 1:   The cumulative gas volume, gas production rate and biogas composition during anaerobic digestion of sisal pulp waste in the sisal fibres waste fixed-bed digester

Biogas composition, production and methane yield
Although some air was introduced during the addition of SPW, the overall process was not affected. The air introduced may have been consumed by facultative anaerobic fermenting bacteria during the hydrolysis and acidification of SPW loaded in the top of the digester. The methanogens colonized the lower part of the decomposed material of the bed and the oxygen introduced at the top of the bed could not easily reach these lower

layers. The results in Figure 1 show cumulative biogas volume and gas production rate (GPR). The daily observed GPR expressed as m^{3}m^{-3}d^{-1} ranged between 0.15 and 0.54, generally increased with time when fresh biomass was added in the digester. The GPR achieved in this study was comparable to that observed in the digestion of leaf biomass in plug flow digesters (0.5 m^{3}m^{-3}d^{-1}) (Chanakya *et al.* 1997). Chanakya *et al.* (1993) previously reported a GPR range of 0.5-0.6 m^{3}m^{-3}d^{-1}

during solid-phase fermentation of untreated leaf biomass. The average methane content of 55 ± 5% obtained in this study compares well with that (50%) obtained from anaerobic digestion of fresh beet tops and ensiled ley crops (6:1 wet mass ratio) in a single-stage wheat straw fixed-bed digester (Svensson *et al.* 2002). Previously, on digesting leaf biomass and urban market waste in a solid-phase biogas fermenter, Chanakya *et al.* (1999) also obtained 50-60% methane content in the biogas produced. These observations show that the GPR and methane content obtained in this study are typical of a single-stage fixed-bed digester treating plant biomass.

The rate of charging the digester is important; continuous addition of small amounts of the feedstock is best and the most practical compromise is daily addition of uniform amounts. As can be seen in Figure 2, low (0.1-2.1 kg VS $m^{-3}d^{-1}$) to moderately high (2.5-3.8 kg VS $m^{-3}d^{-1}$) organic loading rates were possible and gave methane yields in the range of 0.13-0.48 m^3 CH_4 kg VS^{-1} added which decreased with an increasing OLR. In earlier work, Chanakya *et al.* (1999) reported methane yields in the range of 0.11-0.28 m^3CH_4 kg VS^{-1} * for fermentation of plant biomass digested in a solid-phase biogas fermenter. (*Values calculated from the data reported). Recently, Svensson *et al.* (2002) reported methane yields ranging between 0.30 and 0.40 m^3 CH_4 kg VS^{-1} from crop residues digested in a single-stage wheat straw bed digester. The methane yield data obtained in this work fall within values of literature for digestion of plant biomass in solid-phase bed digesters.
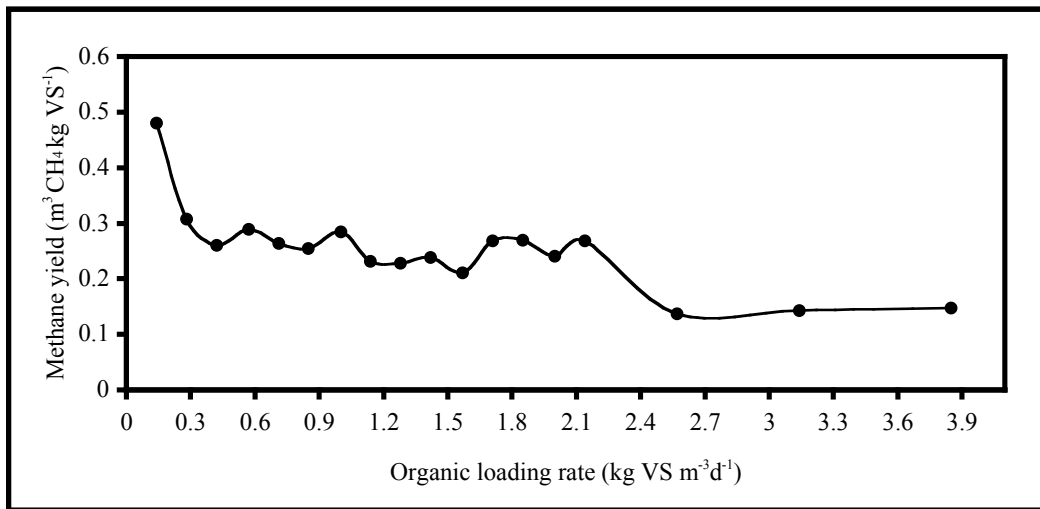

Figure 2:   Methane yield for sisal pulp waste at low (0.1–2.1 kgVSm^{-3}d^{-1}) to moderate high (2.51–3.8 kgVSm^{-3}d^{-1}) organic loading rates in the sisal fibres fixed bed digester

Stability of the system against overload
As seen in Figure 3a, b and c, the addition of three batch loads, each consisting of 2.19 kg VS m^{-3} to a normal load of 3.8 kg VS $m^{-3}d^{-1}$ in a week corresponding to an increase in OLR of 6-10 kg VS $m^{-3}d^{-1}$, did not cause serious imbalance in the digester. Even with

digester liquid VFA concentrations between 1200 and 2600 mg L^{-1}, the process pH and PA were stable at around 7.3 and 3000-3900 mg $CaCO_3$ L^{-1}, respectively. This finding is important, and shows that the bacterial sisal fibre waste support system can withstand the fluctuations in VFAs when high batch loads

are added to the system. The ability of the digester to handle higher OLRs of up to 10 kg VS m^{-3}d^{-1} without serious process stress indicates reliable performance of the single-stage system tested. The highest OLR sustained by the present digester is comparable to the 9-10 kg VS m^{-3}d^{-1} suggested by Chanakya *et al*. (1997) as being optimal and practically attractive for solid-phase biogas fermenter digesting leafy biomass feedstock.

The overall characteristics of the digester liquid
The results in Figure 4 show that the pH was above 7, and the PA ranged between 3000 and 4000 mg CaCO$_3$ L^{-1}. However,

there was an initial decrease in pH and PA at 4, 8 and 20 hours after feeding moderately high OLRs of 2.5-3.8 kg VS m^{-3}d^{-1} (results not shown), which subsequently increased to higher pH and PA levels 24 hours after each batch was added. The tendency towards initial fall in pH and PA upon feeding may have been caused by the degradation of SPW, which produced more organic acids. The increase in PA with time can probably be attributed to the increase in NH$_4^+$ resulting from the feed mineralization. Similar observations have been reported by Svensson *et al.* (2002), when studying laboratory-scale fixed-bed anaerobic digester.
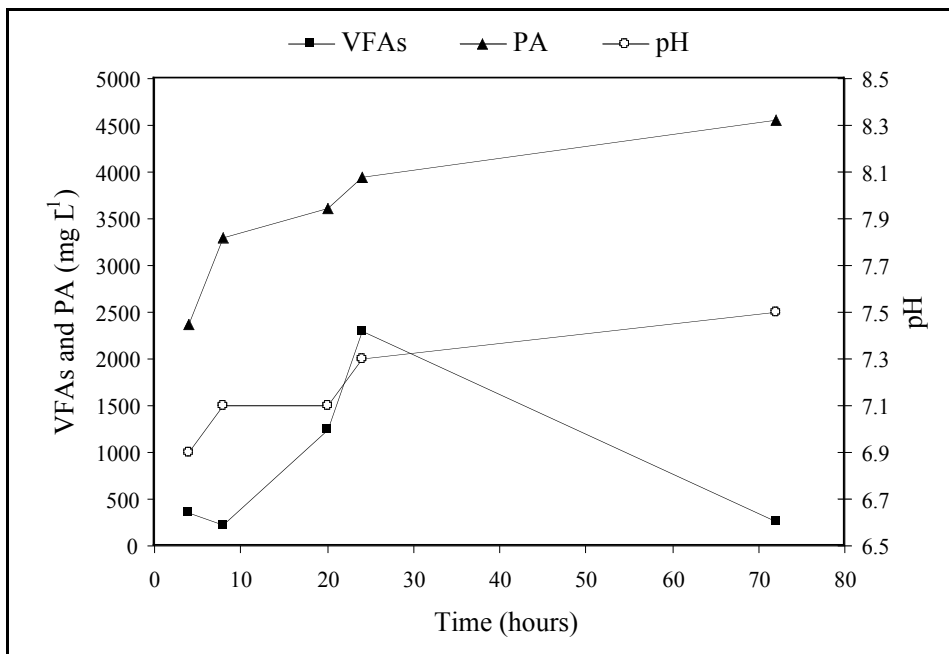

Figure 3a: Composition of the digester liquid after of addition of 2.19 kgVSm^{-3} during stability testing. First pulse 6.04 kgVSm^{-3}d^{-1}
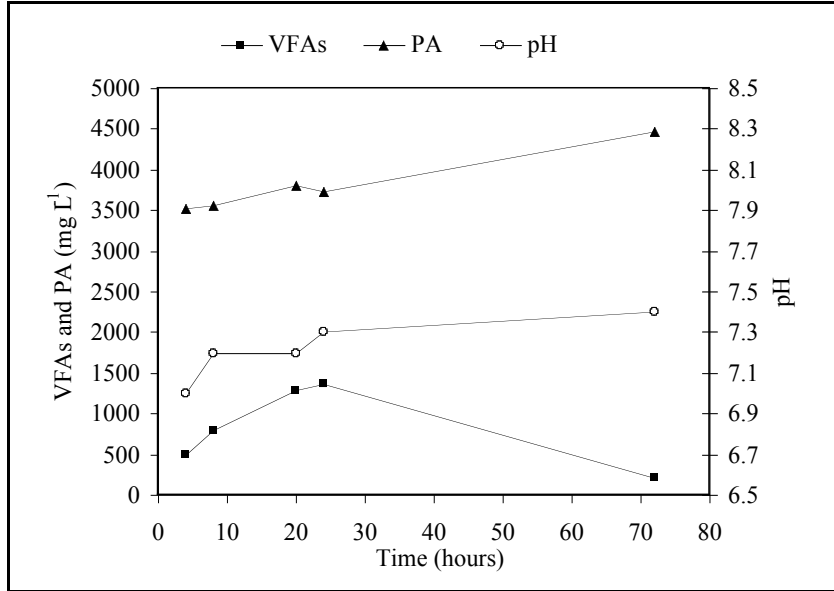
Figure 3b: Composition of the digester liquid after of addition of 2.19 kgVSm^{-3} during stability testing. Second pulse 8.23 kgVSm^{-3}d^{-1}
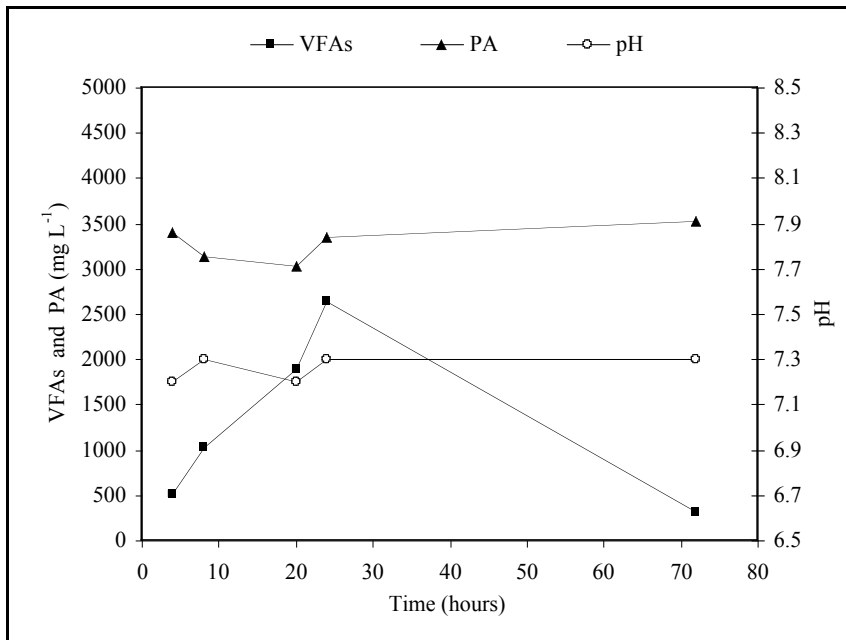

Figure 3c: Composition of the digester liquid after of addition of 2.19 kgVSm^{-3} during stability testing. Third pulse 10.4 kgVSm^{-3}d^{-1}
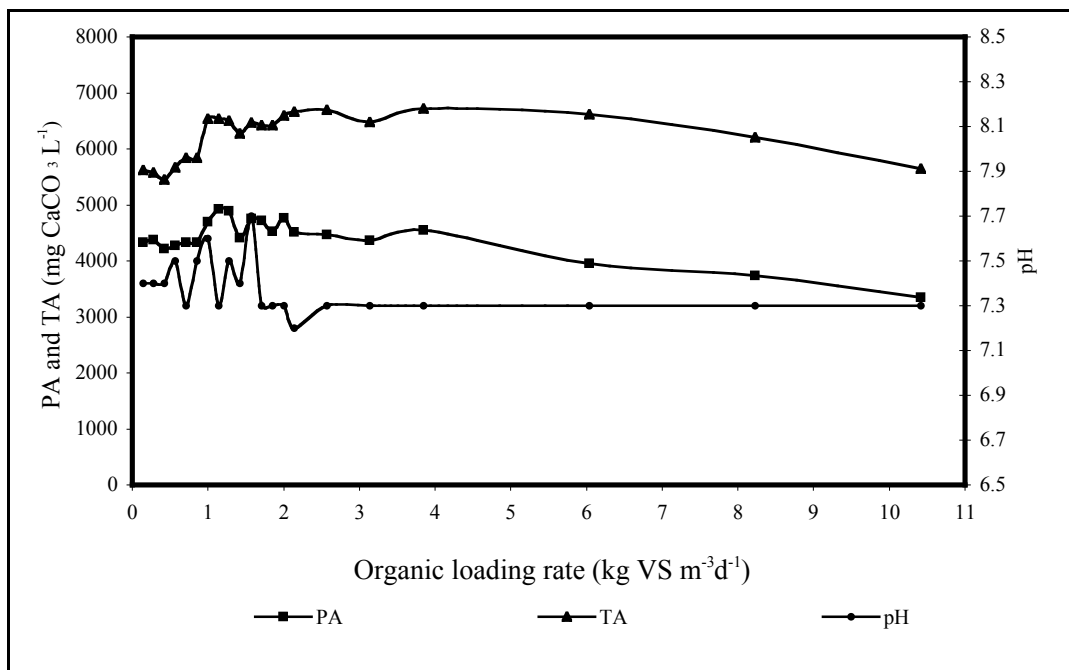
Figure 4:   The pH and partial and total alkalinity profiles of the digester liquid which was determined every 24 hours after feeding the sisal pulp waste in the digester.

The total VFA concentrations at different OLRs, recorded 24 hours after feeding are presented in Figure 5. The total VFAs varied between 3000 and 3900 mg L^{-1} at different OLRs investigated. However, the total VFAs recorded 4, 8 and 20 hours after feeding moderately high OLRs 2.5-3.8 kg VS $m^{-3}d^{-1}$ reached 5000 mg L^{-1} (results not shown). The levels of VFAs accumulation at different OLRs demonstrated an irregular pattern. This shows that it is not feasible to define an absolute VFA level indicating the state of the process under the operating conditions used in this study. However, it is interesting to note that even at VFA concentrations as high as 5,000 mg L^{-1} in the digester liquid no detrimental effect on the process was observed. These results show that the system was well self-buffered,

which enabled the established methanogenic culture to degrade the volatile fatty acids formed in the process. Chanakya *et al.* (1993) observed no suppression of gas production in the biomass bed when the VFA levels in the digester liquid was below 6000 mg L^{-1}, when digesting untreated leaf biomass by solid-phase fermentation. This observation is comparable to that of the present study. Furthermore, the range of the propionic acid: acetic acid ratio of 0.20-1.30 obtained in this study is below the value of 1.4 suggested for unstable process by Hill (1982). Sisal fibre waste has been found to be a promising carrier for the microbes in the SPW digestion since the vulnerable microorganisms under these conditions seem to be able to sustain much larger changes in VFAs concentrations.
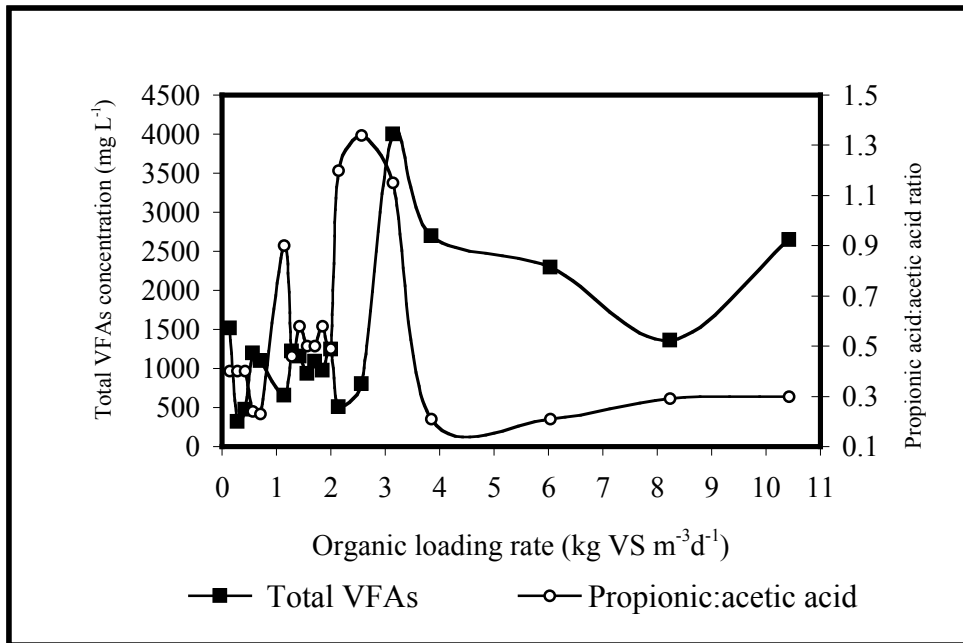
Figure 5: Total concentration of VFA accumulation profiles after 24 hours feeding the green biomass and the propionic acid/acetic acid ratio at different organic loading rates in a waste sisal fibres fixed bed reactor digesting sisal pulp waste.

CONCLUSIONS

The results of this study show that the digestion process can be run at OLR of 10 kg VS $m^{-3}d^{-1}$ without causing instability, indicating that the process can be run cost-efficiently on laboratory-scale. However, it remains to be seen whether this is possible on pilot and larger scale. Methane yields between 0.14 and 48 m^3 CH_4 kg VS^{-1} with 50-60% methane content is promising for energy generation from SPW, which could be used at sisal factory level. One factory in Tanzania with the potential to generate about 8,000 tons of SPW per year (14.3% TS, 82.3% of which is VS) could be capable of generating about 140,000-480,000 m^3 CH_4 per year. This is equivalent to about 1.4 GWh-4.7 GWh of electricity. This is ten times the energy consumption of the factory when producing 460 tons of commercial sisal fibre. The generation of electricity from biogas is thus highly advantageous compared with releasing SPW untreated.

In conclusion, SFW has shown to be a promising biofilm carrier in fixed-bed anaerobic digester for SPW digestion. Besides being abundant and inexpensive, both sisal fibre and sisal pulp are wastes produced in sisal factories, which makes scale-up of a fixed-bed digester at sisal factory level feasible and cost-effective, with respect to handling and transport.

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