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Micro-scale anaerobic digestion of point source components of organic fraction of municipal solid waste

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A R T I C L E I N F O

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A B S T R A C T

The fermentation characteristics of six specific types of the organic fraction of municipal solid waste (OFMSW) were examined, with an emphasis on properties that are needed when designing plug-flow type anaerobic bioreactors. More specifically, the decomposition patterns of a vegetable (cabbage), fruits (banana and citrus peels), fresh leaf litter of bamboo and teak leaves, and paper (newsprint) waste streams as feedstocks were studied. Individual OFMSW components were placed into nylon mesh bags and subjected to various fermentation periods (solids retention time, SRT) within the inlet of a functioning plug-flow biogas fermentor. These were removed at periodic intervals, and their composition was analyzed to monitor decomposition rates and changes in chemical composition. Components like cabbage waste, banana peels, and orange peels fermented rapidly both in a plug-flow biogas reactor (PFBR) as well as under a biological methane potential (BMP) assay, while other OFMSW components (leaf litter from bamboo and teak leaves and newsprint) fermented slowly with poor process stability and moderate biodegradation. For fruit and vegetable wastes (FVW), a rapid and efficient removal of pectins is the main cause of rapid disintegration of these feedstocks, which left behind very little compost forming residues (2–5%). Teak and bamboo leaves and newsprint decomposed only to 25–50% in 30 d. These results confirm the potential for volatile fatty acids accumulation in a PFBR's inlet and suggest a modification of the inlet zone or operation of a PFBR with the above feedstocks.

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1. Introduction

Micro-scale biomethanation (0.1–1.0 ton per day, tpd) is increasingly being tried as an alternative to mechanical and forced air composting when dealing with the organic fraction of municipal solid waste (OFMSW) and other wastes (Khandelwal and Mahdi, 1986) in small communities. Current waste management regulations permit conversion of OFMSW only through aerobic composting or biomethanation processes (MoEF, 2000; Ramachandra, 2006). As cities in developing countries grow, small extensions of the city area are created where residents attempt innovative solid waste management (SWM) approaches. In all such cases it is seen that finding suitable techniques at affordable costs for daily collection, transport, and processing of the OFMSW is the major hurdle (Joseph, 2006; Rathi, 2006; Ambulkar and Shekdar, 2004). While many innovations and options have been tried with respect to daily collection mechanisms and related equipment, there have been few options for decentralized stabilization of OFMSW. Biomethanation at a small scale is an ideal option as it minimizes transport costs and provides on-site treatment without aesthetic and sanitation issues (Kurup, 2003; Kale, 2004; Chanakya and Jagadish, 1997; Kalia and Kanwar, 1995).

Under decentralized conditions, the composition and quantity of the OFMSW collected can be highly skewed (Chanakya et al., 1997,2007a,b). Thus, the challenge at the lower (small) end of this scale is the ability to handle large variations in the composition and characteristics of wastes that are received and fed to biomethanation plants on a daily basis. Waste composition varies widely, ranging from predominantly dry leaves (difficult to decompose) to predominantly vegetable wastes or fruit peels, where fermentation is already initiated (Sateesh Kumar et al., 2001). In large biomethanation plants, such variations either even out or are easily managed by process control facilities. In decentralized small plants, rapid changes in the composition of OFMSW as indicated above will rapidly change the volatile fatty acids (VFA) generation pattern. A great deal of VFA overproduction can lead to an accumulation of inhibitory concentrations of VFA, hindering methanogenesis and sometimes even causing a drop in the pH level (Chanakya and Jagadish, 1997; Kurup, 2003; Kale, 2004).

Zhang and Zhang (1999) studied the anaerobic phased solids digester system for the conversion of rice straw to biogas. Lignocellulosic rice straw is difficult to degrade biologically. Hence, different pre-treatment methods such as physical, thermal, and

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chemical treatment on the digestion of rice straw were investigated. Results reveal that these chemical and mechanical pre-treatments significantly affected the digestibility of the straw. Lawn grass (a major fraction of MSW) was chosen and subjected to this digestion (Yu et al., 2002). The digester employed in this study was an 8 m^3 solid phase reactor (harboring 155 kg of feedstock) coupled with a methane phase reactor consisting of inert commercial packing media used to facilitate bacterial attachment and growth. The maximum loading rate in this upflow anaerobic filter (UAF) was determined to be 2.7 kg of COD/m^3 per day.

Biomass-fed plug-flow biogas reactors (PFBR) function like a three-zone fermentor wherein rapid decomposition occurs in the inlet zone, often with a clear VFA overproduction (acidogenic). In the second zone, after simple compounds in the biomass are removed, a balanced acidogenic–methanogenic decomposition occurs even when the biomass is in a floating state. There is a third VFA conversion zone in the digester liquid (Chanakya and Moletta, 2005). In the initial rapid acidogenesis stage, gas bubbles (CO_2) generally nucleate around and adhere to the decomposing biomass particles, rendering them buoyant. The design and role of the inlet zone is to hold this buoyant, decomposing biomass under the digester liquid until most of the VFA flux from easily decomposed materials is removed and methanogens colonize on them (Jagadish et al., 1998; Chanakya and Moletta, 2005). Under normal circumstances, such buoyant biomass particles from the inlet zone soon form a floating mass that accumulates in size and rises above the liquid layer to gradually dry and become an unfermentable "scum". The PFBR attempts to overcome this problem (Kurup, 2003). It places and retains the freshly fed biomass under the digester liquid for a period sufficient for the acidogenic bacteria to initiate decomposition and digest the easily decomposable fractions within the feedstock. As the decomposition rates fall and the slow-growing methanogenic bacteria colonize this biomass in sufficient numbers, the rate of acidogenesis and methanogenesis very quickly becomes balanced enough to conduct a stable and continuous fermentation of the biomass, even when the biomass feedstock begins to float (Chanakya and Moletta, 2005). This design and process modification avoids the energy- and capital-intensive chemical and physical pre-treatment (mentioned above), thereby making small decentralized fermenters viable. In such a scheme of events, it is important to determine the required period of fermentation wherein the rate of acidogenesis matches the potential of the methanogenic flora to capture acetate, to capture H_2, and to reduce CO_2 to methane. Various feedstocks have differing rates at which they achieve this balance between acidogenesis and methanogenesis (Chanakya et al., 1999). When digesting organic fractions of OFMSW are converted to biogas without the accumulation of toxic levels of intermediate VFA in the digester, an equilibrium between acidogens and methanogens is achieved. Obviously, at this stage the gas composition will be ideal, and the methane content will be much higher than CO_2. When designing PFBRs for OFMSW, it thus becomes important to characterize the individual feedstocks to determine the threshold time required for such pre-digestion. In small-scale decentralized plants, in the absence of process control, it becomes important to determine from the individual feedstock's VFA production or initial decomposition pattern how best the individual components can be co-fermented in appropriate blends such that VFA overproduction from one source could be compensated by a more stable cellulose lignin matrix of more lignified constituents. In this study, we attempt to collect data and examine such possibilities. The main objective of this study is to verify the previous hypothesis – that in plug-flow biogas reactor conditions there is a very rapid acidogenesis and total solids (TS)/volatile solids (VS) loss that makes the remaining mass amenable to fermentation even under conditions when the feedstocks remain afloat on the digester liquid (Jagadish et al., 1998; Chanakya and Moletta, 2005) – as well as to determine the duration and extent of decomposition that common MSW feedstocks need to undergo, and their corresponding holding time in this zone.

2. Materials and methods

2.1. Feedstock selection

Biomass feedstocks were collected within and around the IISc Campus in Bangalore, India. Previously recorded zone-wise OFMSW collection data suggested a predominance of fruit and vegetable wastes (FVW), leaf litter, and paper fractions (Sateesh Kumar et al., 2001). Cabbage waste, banana peels, and orange peels have been found to be the most predominant components of FVW in a few zones (Chanakya et al., 2007b). Citrus peels have been reported to cause some form of inhibition of gas production and therefore are required to be fermented separately from other feedstocks (Mandal and Mandal, 1997). Leaf litter constitutes about 35% of the overall waste collected and varies with the season (Sateesh Kumar et al., 2001; Chanakya et al., 2007b). The decomposition of a few leaf biomass feedstocks has been reported earlier (Chanakya et al., 1999). For this study, we chose bamboo and teak leaves, for which there were no fermentability data. Newsprint fermenting in the presence of another biomass was also studied. Thus, a total of six individual feedstocks were studied, as shown in Table 1.

2.2. Fermentation pattern

Freshly collected feedstocks, cut to 10–25 mm pieces, were weighed and placed in nylon mesh bags of size 20 × 15 cm (Table 1). Between 50 and 200 g fresh weight of the substrate was used in each of the bags, so that at the end of the 10–30 d decomposition period, at least 4–5 g of undigested feedstock would remain in the bag for analysis of composition and to determine what fractions were lost. To facilitate easy sampling, the five different feedstocks (other than orange peel) in duplicate were bundled together such that they could all be removed at a time. The nylon mesh bags containing orange peels were subject to fermentation separately (on the other side of the inlet of the same PFBR), in order to avoid possible toxic compounds leached from digesting citrus fruit peels affecting the digestion of other feedstocks. They were kept separately in the digester at a distance of approximately 1 m away from the rest of the feedstocks but still within the PFBR inlet zone where conditions did not significantly vary from the location used for the other samples. This precaution was taken because previous studies suggest that there could potentially be toxic or inhibitory substances produced during the decomposition of citrus peels (Mandal and Mandal, 1997). Eight bunches of the feedstock bags, with each bunch having ten individual bags (five feedstocks in two replicates), were placed in the inlet region and weighted down with granite blocks. After the first day, the PFBR was operated normally with daily feeding composed mainly of garden wastes or tree leaf biomass at about 1 kg TS/m^3/d. The choice of leaf biomass feedstocks and feed rate ensured that, during daily operation, these

Table 1
Weights of samples used to determine the decomposition rates in a PFR.

Substrate	Fresh weight (g)
Cabbage	200
Banana	200
Orange	120
Teak leaves	50
Bamboo leaves	30
Paper	40

feedstocks did not, by themselves, produce inhibitory concentration of VFAs within the inlet zone of the digester. Care was taken to ensure that these samples were not physically damaged during the daily feeding operation. The contents of these bags were allowed to digest within the inlet region for various time intervals, based on previous information regarding the time intervals necessary to record sufficient levels of change (0, 2, 4, 7, 10, 15, 22, and 30 d) (Chanakya et al., 2007a). By using this method, we envisaged that the pattern of decomposition recorded would emulate the rate and pattern of decomposition of individual feedstocks (in the inlet zone) undergoing decomposition in a typical multi-feed operated PFBR that is predominantly fed OFMSW.

The estimation of the level of degradation of subcomponents of each feedstock was carried out by Chesson's (1978) method, for SRT values of 0, 2, 4, 7, 10, 15, 22, and 30 d. Residual feedstock samples removed from the nylon mesh bags at these time intervals were oven dried at 90 °C to prevent breakdown of carbohydrates. The dried samples were powdered in a laboratory grinder, and any fiber remaining was cut and reground to obtain a fine particle size. Two 1 g samples were used in this analysis, involving sequential extraction for various sub-components for each of the decomposition periods studied. During sequential extraction in various extractants (Chesson, 1978), the leachate samples collected were tested for their total carbohydrate (phenol sulphuric acid method) content and for protein (Lowry's method, data not shown) content. In this study, residual biomass was fractionated into six fractions representing increasing difficulty for anaerobic decomposition, namely: hot water extractable pectin and related substances; ammonium oxalate soluble pectin; dilute acid (0.5 M H_2SO_4) extracted hemi-cellulose; 72% acid extracted cellulose; residual lignin; and ash remaining after combustion in the lignin fraction. The procedure used (Chesson, 1978) involved only one modification. The material remaining after extraction with 72% sulphuric acid was extracted from the sintered glass crucible after weighing. The extracted mass was weighed once again and was placed in a muffle furnace at 600 °C for 1 h to determine the presence of salts and minerals.

The loss of TS and VS was also determined for the above time intervals using standard methods.

2.3. Biological methane potential (BMP) assay

BMP has been used as a quick and inexpensive method to determine the gas potential as well as the rate of conversion of feedstocks to methane during digestion, and it is reported in various ways (anaerobic biogasification potential assay (Chynoweth et al., 1982; Gunaseelan 1997)). Methane content of the gas is also a good indicator of process stability. Under normal circumstances, this value is a function of the H/C ratio of the biodegradable fraction, and it is normally in the range of 50–60% for MSW fractions (Owens and Chynoweth, 1993). Since methanogenic activity is the key factor leading to imbalance, a reduction of methane gas content is a key performance parameter and has been employed as an on-line control parameter. The biochemical methane potential assay (Owens and Chynoweth, 1993; Owen et al., 1979; Chynoweth et al., 1991, 1992, 1993) is normally useful for estimating the ultimate methane yield and relative conversion rates of feed samples. This assay may also be used to determine the toxicity of feed components. In this study, the BMP assay provided data on potential inadequacies, imbalances, or toxicities within feedstocks. This test was carried out in 135 mL serum vials with 1.0% (0.5 g/vial) of dried and powdered feedstock to which 49.5 mL of inoculum was added. To protect the inoculum from air, the headspace was first purged very rapidly with biogas to remove traces of air. These vials were crimped tight with aluminum seals. Subsequently, these vials were purged with oxygen-free nitrogen to remove traces of methane and oxygen, if any. Purging with biogas provided the necessary protection for about 1 h – the time required for the last vial to be purged with N_2 from a cylinder. These vials were then labeled and incubated upside down (to identify leaks, if any) in an incubator at 30 °C. At frequent intervals, the biogas quantity produced was determined by downward displacement of water (acidified dichromate) into an inverted burette, and the gas produced was measured off the burette.

A methanogen-enriched inoculum was prepared and used in the following manner. Digested wet biomass removed from a PFBR (3 kg) was shaken well in 10 L of digester liquid collected at the outlet of the PFBR. Digested biomass was allowed to disintegrate into this digester liquid by manual shaking, and allowed to settle down for 1 h. All floating and settled mass was skimmed or decanted. The remaining mass was filtered through cloth, leaving only fine particles in suspension. This was stored in an air-tight polythene can. For the first 7 d, 1 g of sodium acetate was added on a daily basis. The pH was monitored daily. After 7 d, the liquid was fed 1 mL of acetic acid on alternate days until 20 d. The gas production from this liquid was monitored frequently at 3 d intervals in 135 mL vials. Acetic acid feeding was stopped on the 20th day. On the 24th day, after gas production came down to low background levels (<1 mL/50 mL in 3 d), the material was used as inoculum to overcome the low aceticlastic methanogenic activity.

After each estimation of gas production in the inverted burettes, the gas in the headspace of these vials was tested for its CH_4 and CO_2 composition using a gas chromatograph with a Porapak-Q column and a thermal conductivity detector (150 μl sample) with H_2 as a carrier gas. Using the initial and final composition of head space gas and the total volume of gas, the CH_4 and CO_2 produced were calculated for each time interval as shown below. During this assay, the occurrence of low levels of CH_4 in relation to CO_2 in the BMP assay has been considered a diagnostic tool for a stalled methanogenesis process.

$$[(V_{gas} + 84) \times M_{current}] - [84 \times M_{previous}]$$
$$= \text{methane produced in mL during the specified time interval}$$

where M is methane fraction measured by the GC minus the current and immediately previous reading, and 84 is the headspace volume.

The same method was used for estimating the quantity of CO_2 produced during each time interval.

3. Results and discussion

3.1. TS/VS degradation

Six feedstocks were subjected to decomposition under conditions found in the inlet zone of the PFBR. The PFBRs are designed to trap freshly fed biomass feedstocks under previously fed biomass at the inlet zone. This forced submergence initiates rapid decomposition (mostly acidogenesis) among biomass feedstocks, and VFAs produced here are expected to be diffused into the digester liquid and subsequently decomposed to biogas in the liquid zone itself (Chanakya and Moletta, 2005). As rates of acidogenesis slow, methanogens colonize this biomass and some biomass begins to float above the digester liquid, while biomethanation continues due to a balanced rate of VFA production and utilization in such a biomass. Such a model of functioning is only partly explained experimentally (Jagadish et al., 1998; Chynoweth et al., 1992). Among the six feedstocks, banana peel, cabbage waste, and orange peel had similar kinds of decomposition patterns, involving a very rapid initial decay where between 75% and 95% of initial TS fed decomposed within 4 d of residence time (Figs. 1 and 2). TS and VS loss have very similar patterns among these three

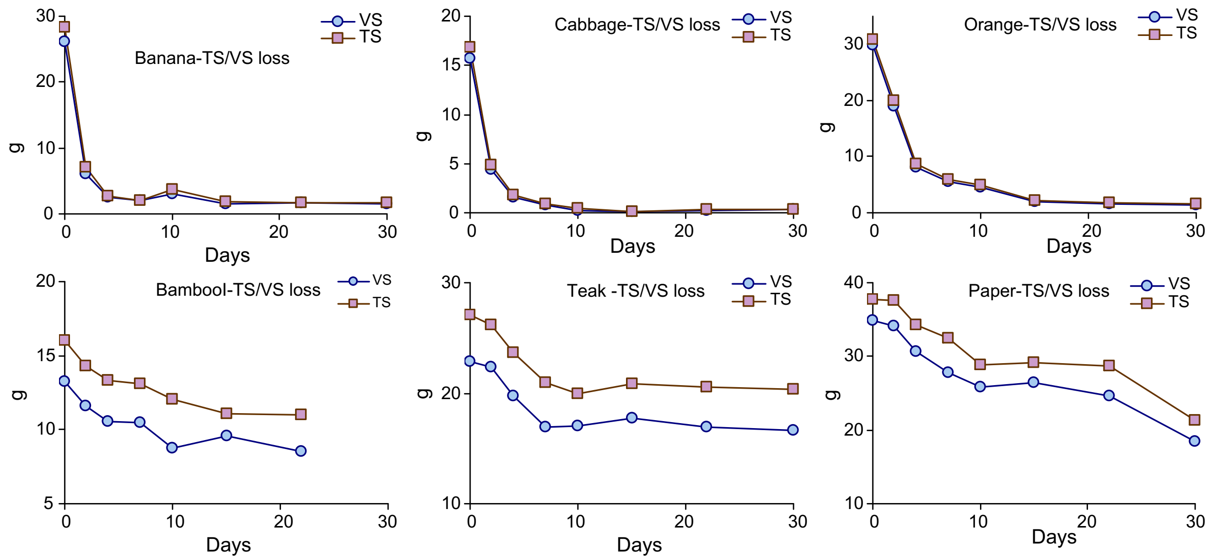

Fig. 1. TS and VS lost among various feedstocks fermented in a typical plug-flow biogas reactor under conditions of complete submergence.

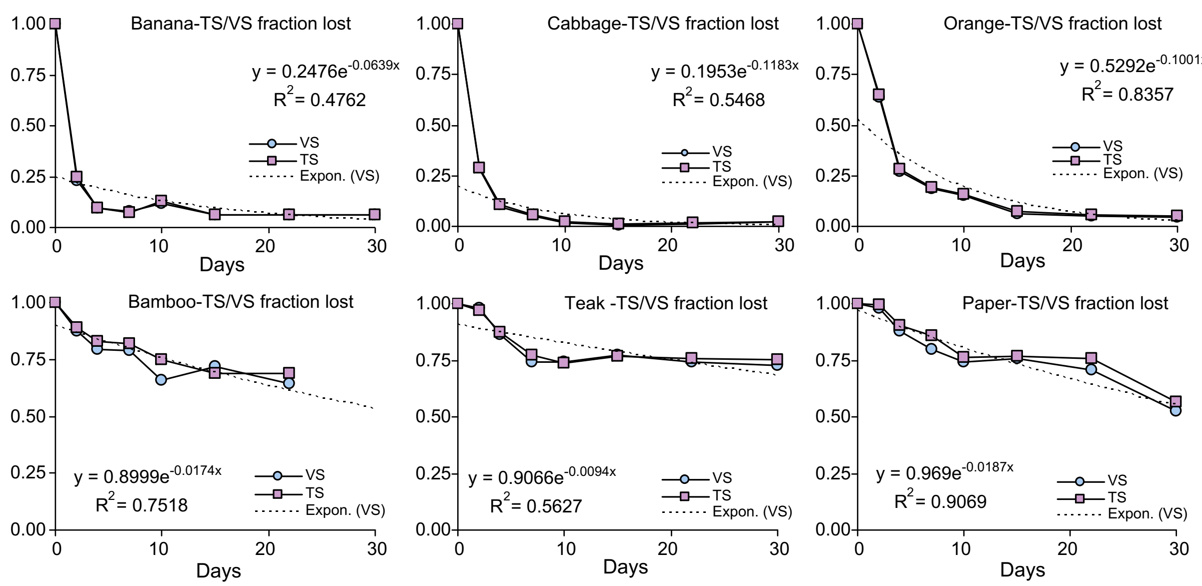

Fig. 2. Fraction of TS and VS lost among various feedstocks fermented at the inlet of a typical plug-flow biogas reactor under conditions of complete submergence.

feedstocks. The decomposition is not adequately explained by an exponential decay pattern (Figs. 1 and 2). The main source of variation arises because of the very rapid initial decomposition. More sampling points are required to understand and model this initial phase for these kinds of feedstocks. These rates are far higher than reported earlier, and are desirable for rapid conversion to biogas (Kalia et al., 2000; Dahiya and Vasudevan, 1987; Kalia and Joshi, 1995; Sharma et al., 1988).

On the other hand, leaf biomass (paper mulberry), mixed fruit wastes, and sugarcane bagasse used as feedstocks in a solid state fermentor have been reported to decompose with an ideal exponential decay pattern (Chanakya et al., 2007a). In comparison, it is clear that total submergence, as in a PFBR, tends to achieve a rapid or even a higher degree of acidogenic decomposition as compared to solid state fermentation (Chanakya et al., 1999). The decomposition pattern has been studied here, and these rates and patterns are compared to similar studies (Chanakya et al., 2007a). However, when each step of MSW digestion has been quantified, it is possible to use Monod kinetics (Nopharatana et al., 2007). The above discussion and Figs. 1 and 2 show that these three feedstocks will decompose rapidly in the initial stages, and thus have the potential to accumulate a large amount of VFA in the inlet zone. To avoid disrupted biogas production, there is a need to convert or disperse these potentially high concentrations of VFA, in order to sustain good biogas production when PFBRs are fed predominantly with these feedstocks.

Bamboo leaves, teak leaves, and newsprint paper feedstocks showed slower decomposition rates, reaching between 25% and 45% TS/VS loss over a 30-d fermentation period (Figs. 1 and 2). Unlike the earlier three feedstocks, there were significant differences between the TS and VS contents of these feedstocks (Fig. 1), indicating the presence of a significant fraction of minerals (ash) in the feedstocks. There were marginal differences between the degradation of TS and VS among these feedstocks (Fig. 2). These three feedstocks decomposed in a pattern resembling exponential decay, with values of paper ($r = 0.948$) and bamboo and teak leaves

($r = 0.866$). Earlier studies indicate similar decomposition rates for leaf biomass with an exponential decay pattern (Chanakya et al., 2007a). Decomposition levels achieved are adequate for use in biogas plants, and potential ways to improve the extent of decomposition need to be examined.

3.2. Breakdown of constituents among feedstocks

Banana peels are largely composed of hot water soluble pectin, cellulose, and hemicelluloses, which together constitute nearly 80% of the mass. Their degradation is very rapid (Fig. 3), and a majority of the mass of banana peels is lost in a residence time of 2 d. There was very little residue left after a 4 d SRT. This rate is much faster than some of the earlier reports where rapid conversion to gas lasts up to 2 weeks (Sharma et al., 1988). The degradation is accompanied by loss of lignin fraction as well. This pattern of degradation suggested that much of this waste will disintegrate within the inlet/pre-treatment chamber of the PFBR with a potential to generate a large flux of VFA. The cellulose content in this study is small compared to that reported earlier (Sharma et al., 1988). PFBRs using this as the predominant feed (fruit juice vendors, fruit processing industries) need to account for the potential for a large VFA flux in the design of the inlet.

Cabbage waste followed a trend similar to banana peels. It contains cellulose, hot water soluble pectin, hemicellulose, and oxalate pectin as the dominant constituents (in that order of abundance). More than 80% of the loss in mass in the nylon mesh bags occurred within a 2 d SRT, and very little residue remained after a 4 d SRT. There was very little lignin content in the feedstock. Also, very little residue remained after 10 d for sampling and determination of the composition. From this data we observe that cabbage waste, just as in the case of banana peels, has a high tendency to release a large VFA flux in the vicinity of the inlet of a PFBR. With cabbage or similar leaves as predominant ingredients in MSW, it is important to disperse VFA pockets near the inlet. Inlet design and digester operation needs to be suitably modified. Furthermore, as a consequence of its greater extent of degradation, very little digested material is expected to emerge from the digester as anaerobic compost. In many parts of India, road-side 'Chinese' food outlets generate wastes dominated by cabbage and cauliflower leaves. In areas populated by such outlets, MSW will have these fermentation characteristics.

Orange (and citrus) peels form a large component of wastes generated from fresh fruit juice vending shops on the road side. Orange peels are composed largely of pectin-1 (hot water soluble), cellulose, and pectin-2 (ammonium oxalate soluble). Decomposition of these constituents is rapid (Figs. 1 and 2), and over 90% of the material is lost in a 4 d SRT. During this rapid decomposition period, a significant loss of lignin and hemicellulose was recorded. Considering that lignin is known to be largely recalcitrant under anaerobic conditions, the disappearance of lignin from the nylon mesh bags could largely be brought about by tissue disintegration and its subsequent escape from the nylon mesh bags into the digester liquid. Further experimentation needs to be carried out to confirm this possibility. This phenomenon of over 90% loss of TS/VS and its constituents suggests that recovery of anaerobic compost from this feedstock is likely to be poor after anaerobic digestion. Reports also indicate that there is some form of toxicity during digestion of citrus peels (Mandal and Mandal, 1997) and, therefore, that the inlets and operation of PFBRs need to be altered in the presence of a large fraction of citrus peels.

Bamboo leaves are found in large quantities both as seasonal leaf litter as well as when bamboo is harvested for paper in other areas. This is a potential source of energy at the point of the bamboo plantations. The pattern of decomposition, as well as its suitability for biogas production, was examined. The pectin fractions are much lower, and the leaves are more lignified, as seen in Fig. 3. Cellulose, hemicellulose, and lignin fractions are higher relative to the earlier three feedstocks. The decomposition rates of all fractions (other than lignin) are gradual. About 30% VS decomposition was achieved. The lignin fraction remained undecomposed up to a 30 d SRT. It is not clear whether the presence of lignin had slowed down the decomposition, and methods to raise the rate of decomposition of these fractions need to be developed. Under existing conditions, a significant part of the feed will end up as digested feed or anaerobic compost.

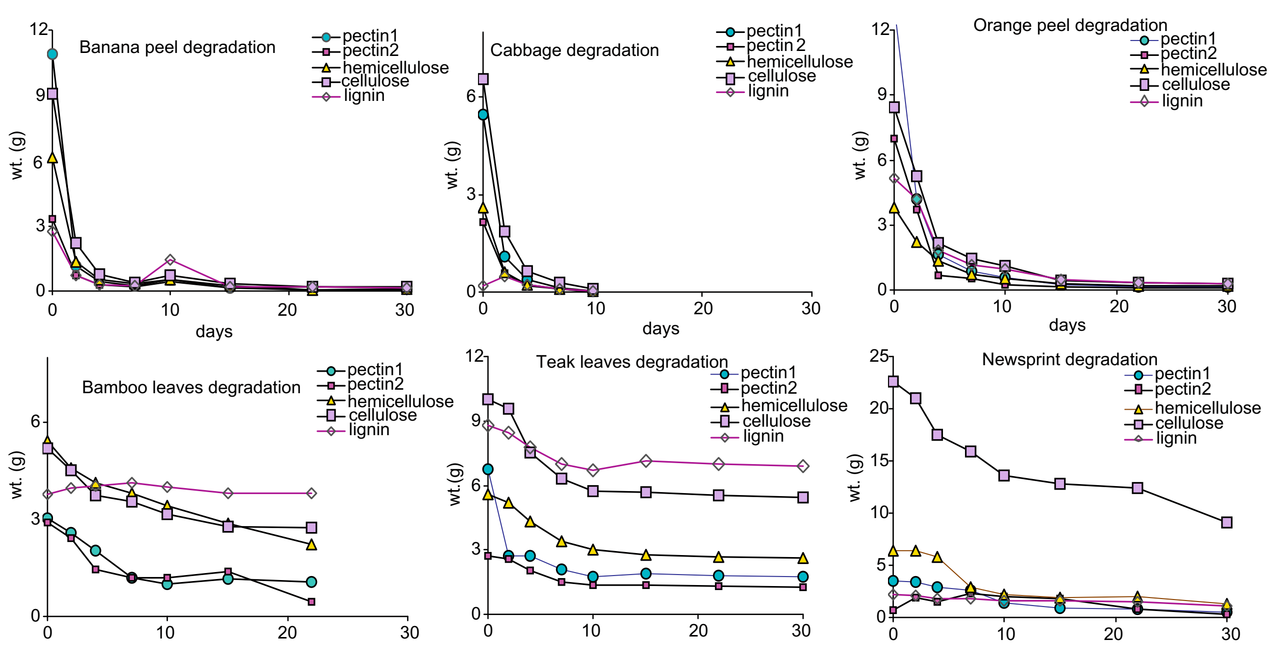

Fig. 3. Main fractions of feedstocks lost during different periods of fermentation [legend –o– pectin 1 (water extract), –□– pectin 2 (hot oxalate extract), –▲– hemicellulose (0.5 M acid extract), –■– cellulose (72% acid extract), –◇– lignin (72% acid ash-less residue)].

A large quantity of teak leaves is available as leaf litter under teak plantations. They are often removed due to their presence being a fire hazard and thus constitute a potential source of biomethanation feedstock. Teak leaves had the highest contents of cellulose and lignin (predominant fractions) among the six feedstocks studied. The pectin fractions were relatively low. Just as in the case of bamboo, teak leaves decomposed slowly, resulting in a 30% decomposition of the cellulose and hemicellulose fractions and 50% of the pectin-1 fraction. The small change in lignin content suggests that only a small component of the whole leaf is disintegrated and lost from the bags. There were very little TS, VS, or subcomponents lost after 10 d, and this result needs to be investigated further. Unlike the first three samples, a significant fraction of the material remained undigested, and thus it is possible to expect a high level of throughput in the form of compost while using this as the main feedstock.

Soiled newsprint occurs as a large single component of OFMSW because it is used both as a packing material of dry merchandise as well as carry bags for many food items. In Bangalore, it is generated in point and non-point sources. Such moist and soiled newsprint cannot be recycled, and hence biomethanation could be a viable option. As expected, the major constituent of newsprint is cellulose, and the major decomposition occurs in the cellulose constituent of the newsprint. It is seen that in the inlet of the PFBR, newsprint decomposes even when used singly as a feedstock. Obviously, nutrients required by microorganisms for decomposing a material like newsprint are available in the digester liquid in the inlet region. This suggests that in the presence of a significant paper/newsprint fraction, decomposition is quite effective. However, a significant content of cellulose is still left undecomposed after a 30 d SRT and further investigations are required to make the decomposition more efficient. The presence of a 50% undecomposed fraction indicates the potential to recover a larger fraction of the input as compost when paper becomes the dominant fraction in the feedstock.

3.3. Biological methane production assay

In this study, we have used the BMP assay both as an estimate of the gas production potential, as well as a diagnostic indicator to determine susceptibility to VFA flux or overproduction, and the related process stability when these individual feedstocks are used in large proportions within the OFMSW. The result of BMP assay at a 1% concentration of feedstock is presented in Fig. 4. In the case of banana peels, in spite of a high rate of degradation, the BMP assay showed a high biogas yield of 400 mL/g TS, and the methane content of the gas very quickly reached high levels. All of these results indicate a potential for balanced methanogenesis at moderate feed rates. In spite of the rapid degradation of banana peels (Figs. 2 and 3), the biogas production extends over a 30 d period. The loss of TS, VS and sub-components shows different trends compared to earlier reports (Sharma et al., 1988). This needs further research to identify which stage of anaerobic digestion is retarded (Nopharatana et al., 2007).

Unlike typical leaf biomass feedstocks, cabbage waste and orange peels showed poor gas production potential even at a 1% concentration. VS, TS, and sub-component loss (Figs. 2 and 3) show evidence of rapid hydrolysis and disintegration of these feedstocks. In the BMP assay, the CO_2 concentration generally exceeded the CH_4 concentration, which suggests that the methanogenesis is arrested. This result shows that with cabbage or citrus peels, there is a tendency for rapid VFA buildup and a stalled methanogenesis. This needs to be verified with additional research on the VFA build-up at the initial stages. Use of PFBRs with these feedstocks then requires operating strategies or design modifications such that rapidly generated VFAs are converted to biogas. In this study, the ultimate BMP could not be determined, apparently due to VFA overload. In spite of using methanogen-enriched inoculum, there is evidence of VFA overload, suggesting that VFA buildup occurs to levels above inhibitory thresholds (5 g/L, Chanakya et al., 1993). From the data recorded, it was not clear whether citrus peels produced other forms of toxicity to normal methanogenesis (Mandal and Mandal, 1997). All of these unknowns need to be investigated in the future.

In the case of bamboo and teak leaves (leaf litter), both produced a BMP level in the range of 250–300 mL/g TS, which is generally low for a leaf biomass feedstock. Decomposition of intact bamboo and teak leaves is low under typical digester conditions, and it is higher under the BMP assay conditions. The BMP assay used powdered feedstock, and this suggests that powdering is an effective way to improve gas production for these two feedstocks, a supposition that needs to be investigated. Bamboo and teak

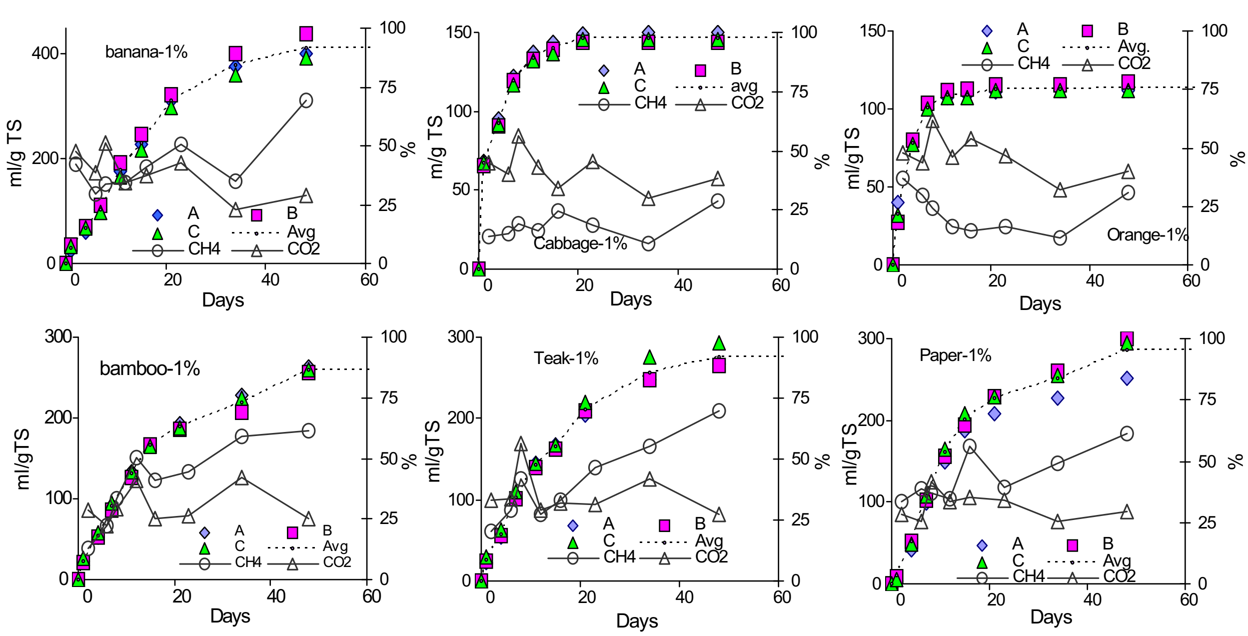

Fig. 4. Biological methane potential (BMP) and head space gas composition measured during various stages of BMP assay for the six feedstocks studied.

plantations show very large levels of leaf litter production, which poses a great fire hazard. Bamboo leaves are also obtained in large quantities during extraction for paper. Conversion to biogas enables recovery of the energy potential of such litter. Considering the high lignin content of both of these feedstocks, it appears that lignin retards and reduces the BMP achievable. Although these two could be used as a potential feedstock, the yields are marginally higher than that of cattle dung and hence could be classified as poor substrates. Similarly, newsprint also decomposed to only a small extent, and the BMP reached 300 mL/g TS. A significant quantity of cellulose was left unused (Fig. 3) even after 15 d. Thus, there appears to be the potential to increase the gas yields even higher when more of the remaining cellulose is made to decompose. Technology alternatives for this option need to be developed.

4. Conclusion

Six hitherto untried OFMSW feedstocks were subject to a fermentation simulating anaerobic digestion in the inlet of the pre-treatment zone of a plug-flow biogas reactor for biomass. The feedstocks used were those that form potential point source feedstocks in Bangalore and the IISc campus. As expected, all of the feedstocks underwent a significant level of degradation. Banana peels, cabbage leaves, and citrus peels underwent rapid decomposition, losing over 80% of their mass in 4 d with a concomitant potential to generate a large VFA flux. This study confirms the potential for such an occurrence. PFBRs fed predominantly with such feedstocks will tend to have a low pH zone in the inlet, and operation techniques need to be developed to overcome this for a stable and trouble-free biomethanation process, especially when small and simple decentralized biogas plants are planned for OFMSW rich in these feedstocks. Feedstocks such as leaf litter (more specifically, bamboo leaves and teak leaves) and soiled newsprint also have a moderate potential to decompose between 30% and 45% of TS, and consequently, a significant amount of the feed will be expected to come out of the digester as digested compost. There was no rapid decomposition phase observed for these feedstocks, and biogas production did not seem to be inhibited by operating conditions.

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References

Ambulkar, A.R., Shekdar, A.V., 2004. Prospects of biomethanation technology in the Indian context: a pragmatic approach. Res. Conserv. Recycl. 40, 111–128.

Chanakya, H.N., Borgaonkar, S., Rajan, M.G.C., Wahi, M., 1993. Two phase fermentation of whole leaf biomass to biogas. Biomass Bioenergy 5, 359–367.

Chanakya, H.N., Jagadish, K.S., 1997. Small-scale biogasification of sorted municipal solid waste. Bioenergy News 3, 11–15.

Chanakya, H.N., Srikumar, K.G., Anand, V., Modak, J., Jagadish, K.S., 1997. Fermentation properties of agro residues, leaf biomass and urban market garbage in a solid phase biogas fermenter. Biomass Bioenergy 16, 417–429.

Chanakya, H.N., Srikumar, K.G., Anand, V., Modak, J., Jagadish, K.S., 1999. Fermentation properties of agro-residues, leaf biomass and urban market garbage in a solid phase biogas fermenter. Biomass Bioenergy 16, 417–429.

Chanakya, H.N., Moletta, R., 2005. Performance and functioning of USW plug-flow reactors in a 3-zone fermentation model. In: Proceedings of Fourth International Symposium on Anaerobic Digestion of Solid Wastes, Copenhagen, vol. 1. pp. 277–284.

Chanakya, H.N., Ramachandra, T.V., Vijayachamundeeswari, M., 2007a. Resource recovery potential from secondary components of segregated municipal solid wastes. Environ. Monit. Assess. 135, 119–127.

Chanakya, H.N., Ramachandra, T.V., Guruprasad, M., Devi, Vinuta, 2007b. Micro-treatment options for components of organic fraction of MSW in residential areas. Environ. Monit. Assess. 135, 129–139.

Chesson, A., 1978. Maceration of linen flax under anaerobic conditions. J. Appl. Bacteriol. 45, 219–230.

Chynoweth, D.P., Dolenc, D.A., Ghose, S., Henry, M.P., Jerger, D.E., Srivastava, V.J., 1982. Kinetics and advanced digester design for anaerobic digestion of water hyacinth and primary sludge. In: Proceedings of Fourth Symposium on Biotechnology in Energy production and Conservation, Gatlinberg, Illinois, pp. 204–212.

Chynoweth, D.P., Bosch, G., Earle, J.F.K., Legrand, R., Liu, K., 1991. A novel process for anaerobic composting of municipal solid waste. Appl. Biochem. Biotechnol. 28, 421–432.

Chynoweth, D.P., Bosch, G., Earle, J.F.K., Owens, J., Legrand, R., 1992. Sequential batch anaerobic composition of the organic fraction of municipal solid waste. Water Sci. Technol. 24, 327–339.

Chynoweth, D.P., Turick, C.E., Owens, J.M., Jerger, D.E., Peck, M.W., 1993. Biochemical methane potential of biomass and waste feedstocks. Biomass Bioenergy 5, 95–111.

Dahiya, A.K., Vasudevan, P., 1987. Farm biomass utilization alternatives. Biol. Wastes 21, 85–91.

Gunaseelan, V.N., 1997. Anaerobic digestion of biomass for methane production: a review. Biomass Bioenergy 13, 83–114.

Jagadish, K.S., Chanakya, H.N., Rajabapaiah, P., Anand, V., 1998. Plug-flow digesters for biogas generation from leaf biomass. Biomass Bioenergy 14, 415–423.

Joseph, K., 2006. Stakeholder participation for sustainable waste management. Habitat Intl. 30, 863–871.

Kale, S.P., 2004. Nisarghruna plant for urban and rural waste management, energy conservation, better environment and restoration of soil fertility. Bioenergy News 8 (1), 1–5.

Kalia, A.K., Kanwar, S.S., 1995. Biogas generation from Ageratum in a semi-continuous plant. SESI J. 5 (2), 61–68.

Kalia, V.C., Joshi, A.P., 1995. Conversion of waste biomass (peas shells) into hydrogen and methane through anaerobic digestion. Biores. Technol. 53, 165–168.

Kalia, V.C., Sonyakya, V., Raizada, N., 2000. Anaerobic digestion of banana stem waste. Biores. Technol. 73, 191–193.

Khandelwal, K.C., Mahdi, S.S., 1986. Biogas Technology – A Practical Technology. Tata McGraw-Hill Publishing Company Limited, New Delhi. p. 128.

Kurup, R., 2003. Performance of a residential scale plug-flow anaerobic reactor for domestic organic waste treatment and biogas generation. In: Proceedings of ORBIT III, Perth, Australia, vol 1. pp. 351–359.

Mandal, T., Mandal, N.K., 1997. Comparative study of biogas production from different waste materials. Energy Conserv. Mgmt. 38, 679–683.

Ministry of Environment and Forests (MoEF), Govt. of India, New Delhi. India, 2000. MSW handling rules-2000.

Nopharatana, A., Pullammanappallil, P.C., Clarke, W.P., 2007. Kinetics and dynamic modelling of batch anaerobic digestion of municipal solid waste in a stirred reactor. Waste Manage. 27, 595–603.

Owen, W.F., Stuckey, D.C., Healy Jr., J.B., Young, L.Y., McCarty, P.L., 1979. Bioassay for monitoring biochemical methane potential and anaerobic toxicity. Water Res. 13, 485–492.

Owens, J.M., Chynoweth, D.P., 1993. Biochemical methane potential of MSW components. Water Sci. Technol. 27, 1–14.

Ramachandra, T.V., 2006. Management of Municipal Solid Wastes, Commonwealth of Learning, Canada. Capital Publishing Company, New Delhi. p. 319.

Rathi, S., 2006. Alternative approaches for better municipal solid waste management in Mumbai, India. Waste Manage. 26, 1192–1200.

Sateesh Kumar, R., Chanakya, H.N., Ramachandra, T.V., 2001. Feasible solid waste management, CES Tech. Report No 86, Centre for Ecological Sciences, Bangalore, p. 145.

Sharma, S.K., Mishra, I.M., Sharma, M.P., Saini, J.S., 1988. Effect of particle size on biogas generation from biomass residues. Biomass 17, 251–263.

Yu, H.W., Samani, Z., Hanson, A., Smith, G., 2002. Energy recovery from grass using two-phase anaerobic digestion. Waste manage. 22, 1–5.

Zhang, Z., Zhang, Z., 1999. Biogasification of rice straw with an anaerobic-phased solids digester system. Biores. Technol. 68, 235–245.