Environ Monit Assess
DOI 10.1007/s10661-007-9712-4

Resource recovery potential from secondary components of segregated municipal solid wastes

H. N. Chanakya · T. V. Ramachandra · M. Vijayachamundeeswari

Received: 23 June 2006 / Accepted: 14 November 2006

Abstract Fermentable components of municipal solid wastes (MSW) such as fruit and vegetable wastes (FVW), leaf litter, paddy straw, cane bagasse, cane trash and paper are generated in large quantities at various pockets of the city. These form potential feedstocks for decentralized biogas plants to be operated in the vicinity. We characterized the fermentation potential of six of the above MSW fractions for their suitability to be converted to biogas and anaerobic compost using the solid-state stratified bed (SSB) process in a laboratory study. FVW and leaf litter (paper mulberry leaves) decomposed almost completely while paddy straw, sugarcane trash, sugarcane bagasse and photocopying paper decomposed to a lower extent. In the SSB process between 50–60% of the biological methane potential (BMP) could be realized. Observations revealed that the SSB process needs to be adapted differently for each of the feedstocks to obtain a higher gas recovery. Bagasse produced the largest fraction of anaerobic compost (fermentation residue) and has the potential for reuse in many ways.

H. N. Chanakya (✉) · T. V. Ramachandra · M. Vijayachamundeeswari
Centre for Sustainable Technologies and Centre for Ecological Sciences, Indian Institute of Science, Bangalore 560 012, India
e-mail: cestvr@ces.iisc.ernet.in, chanakya@astra.iisc.ernet.in

Keywords Municipal solid wastes (MSW) · Fermentation wastes · Solid-state stratified bed (SSB) · BMP

Introduction

India is building up its city level solid waste management in an extensive manner. It has framed necessary rules and guidelines (MSW handling rules 2000). Within the state of Karnataka over 200 cities (urban local bodies) will attempt to set up necessary infrastructure for the collection, transport, processing and disposal sub-systems. The existing centralized collection and open landfill systems are gradually becoming expensive and will need to be closed for fermentable wastes (MSW handling rules 2000). Compliance to the new rules will enhance the current costs (Rs.700/t collection for Bangalore 2004, US$= Rs.45 and Euro=Rs.56) even further. Sustainable and economic alternatives are being developed within India to lower the cost burden and increase the marketable outputs from centralized and decentralized processing of MSW (Chanakya and Moletta 2005). In this scenario, alternatives that reduce the need for daily collection and transport will greatly bring down the overall costs. Most cities in Karnataka have determined characteristics of wastes (TIDE 2000, 2003) where fermentable components mainly fruit and vegetable wastes (FVW) dominate.

The generation of these wastes is localized in different parts of the city. Buenrostro et al. (2001) conceptualized on the solid waste generated within the territorial limits of a municipality independently of its source of generation. This aided in a hierarchical source classification of MSW based on the economic activity that generates a solid waste with distinct physical and chemical characteristics. This enabled the assessment of the volume of MSW generated and provided an overview of the types of residues expected to be generated in a municipality, region or state. By choosing proper processing options a significant component of the organic fractions in the wastes can be utilized (sometimes utilized many times over). Most countries are heading towards a zero landfill approach which then necessitates that wastes be characterized such that they be re-used or converted to reusable products.

It is possible to collect wastes zone, sector and time-wise such that different types of wastes can be collected separately and consigned to various types of processing and treatment (TIDE 2000; Aus-AID 2002) such that the end products accrue better value. The MSW collected in Bangalore, especially in residential and restaurant areas, consists of a large fermentable fraction (c.80% – mainly vegetable and fruit wastes, Rajabapaiah 1988; Sathishkumar et al. 2001; Aus-AID 2002; Ramachandra 2006). Such a large wet and fermentable component requires daily removal from places of generation because the high ambient temperatures are conducive to rapid initiation of fermentation and emanation of malodours. Models involving primary collection by handcarts and immediate composting /vermicomposting within the locality have been tried with mixed levels of success (CEE, TIDE personal communication). On the one side the processes have not sustained for long due to inadequate attention to economics and revenue collection. On the other side the composting techniques themselves have not been satisfactory and consistent quality end-products have not emerged. Some of the causes are examined.

Composition of MSW listed in Table 1 clearly shows the predominance of fermentable materials at all locations in the process of generation to its reaching the dump site. In residential areas, parks and vegetable markets, the presence of a large fraction of fruit and vegetable wastes (Fermentable fraction, 70–90%) increases the moisture content of MSW to about 70–80% (TIDE 2000). When composting of such high moisture feedstock is attempted by the standard windrow method there is excessive generation of leachates and its fermentation results in malodours (TIDE personal communication). High levels of such wastes arise even in business districts where there is a concentration of fresh fruit juice vending shops in the area. Citrus fruit skins, pineapple cores, sugarcane bagasse (from sugarcane juice), other fruit wastes, etc. are thus generated in large quantities in certain pockets of the city. These form nearly 80% of the waste collected in the area (Sathishkumar et al. 2001). It is therefore important that such wastes are treated rapidly in decentralized units. Two options available are aerobic composting and biomethanation (MSW handling rules 2000).

In many residential or quasi-residential areas of Bangalore a variety of slow to decompose biomass wastes such as paddy straw, sugarcane trash, photocopier paper, tree leaf litter, etc. also enter organic fraction of municipal solid waste (OFMSW) streams in the form of micro-point source discharge. Paddy straw is used as a packaging material and it is also found to occur in significant proportion in some parts of MSW – especially fruit and furniture packing. Today it has been increasingly found in and around fruit stalls. Paddy straw is a bulky material with a low packing density (Chanakya et al. 1997) has large particle size and has a medium level of ligno-cellulosics. Zhang and Zhang (1999) studied the anaerobic phased solids digester system for the conversion of rice straw to biogas. Ligno-cellulosic

Table 1 Composition of MSW at all locations in the process of generation to its reaching the dump site

Sub components (%)	Street bin, before rag picking, Rajabapaiah 1988	Street bin, after rag picking, Rajabapaiah 1988	Dump site, TIDE 2000	Bangalore overall, TIDE 2000
Fermentables	65	78	70	72
Paper	8	4	11.4	11
Miscellaneous	12	15	8.7	1.9
Glass	6	1	0.5	1.4
Polythene/ plastics	6	1.9	9.1	6.2
Metals	3	0.1	0.3	1
Dust and sweepings	NA	NA	NA	6.5

rice straw is difficult to degrade biologically. Hence different pre-treatment methods such as physical, thermal and chemical treatment on the digestion of rice straw have been investigated. Results depict that the pre-treatment has some significant role on the digestibility of the straw. Lawn grass-major fraction of MSW was chosen and subjected to this digestion by Yu et al. (2002). The digester employed in this study was 8 m^3 solid phase reactor (harbouring 155 kg of feedstock) coupled with methane phase reactor consisting of inert commercial packing media used to facilitate the bacterial attachment and growth. Maximum loading rate of this UAF digester was determined to be 2.7 kg of COD/m^3 per day. Yu et al. (2002) also studied the effects of temperature on the biomethanation efficiency by using heated upflow anaerobic filter (UAF) in one of the reactor. Higher gas production reported in the heated UAF was due to the higher COD conversion. This COD conversion contributes 0.344 m^3 and 0.339 m^3 of CH_4/kg of COD removed. Hence it suggests that 1 kg of grass gave a yield of 0.15 m^3 of methane.

These components of OFMSW, when in excess of a threshold value, cause a different type of the problem for decentralized composting and vermicomposting facilities. All vegetable and fruit wastes tend to decompose within a span of 15–20 d. However, the slow to decompose components remain nearly intact. Therefore the resultant compost at this stage cannot be sieved and bagged for sale and subsequent use. This prolongs the composting process to nearly 75 d. It then requires that such types of wastes are processed singly and the composts are mixed later on to achieve a balanced product. Such problems of decentralized composting/vermicomposting may also be avoided if the primary treatment involves anaerobic digestion in simple biogas digesters. In this study we characterize how such problematic single feedstock dominant OFMSW decompose in a solid-state stratified bed (SSB) reactor. We also examined the digested feedstock for its suitability for subsequent use as a biofilm support in wastewater treatment (Chanakya et al. 1998) i.e. an additional use other than compost. We expect that in doing so, in addition to biogas generated in the process, the biofilm support will also provide a high value byproduct. We believe that the price paid to biogas as well as for digested biomass for use in biofilm support together will offset the rising prices of MSW collection and processing. (Yang et al. 2004)

Materials and methods

The feedstocks used in this study came from various points within the city of Bangalore. Several individual types of fruits wastes were collected within 4–5 h of generation from nearby fresh fruit juice vendors who stored these fruit wastes separately for our study. Feedstocks were collected fresh once a week at the generation site and fed in the fresh state. For studies on biological methane potential (BMP) assay, individual types of fruit wastes were collected separately and subject to assay and physico-chemical analyses. Paddy straw and cane trash are major packing materials for fruits and furniture in urban areas. They are normally recycled as cattle feed but are also found in large quantities in OFMSW of areas manufacturing or trading with steel furniture, glass, etc. Paddy straw and cane trash were picked up from such locations. Tree leaf litter is an important component of avenues where fallen litter of the nearby gardens or roads is swept frequently. It occurs in large quantities during months of peak litter fall. Bangalore has a very large diversity of trees and litter collected is usually mixed (Jagadish et al. 1998; Sathishkumar et al. 2001). In this study we have used mature leaves of one tree species *Brousenetia papyrifera* (paper mulberry) that is found in large numbers in the vicinity of the laboratory – it was thus a convenient feedstock of the SSB as well as BMP studies.

Solid-state stratified bed (SSB) reactor (Fig. 1) made of opaque PVC pipes (Chanakya et al. 1998) were used to characterize decomposition of various feedstocks. These reactors consist of 0.6 m tall, 0.15 m dia PVC pipes placed in a pool of recycled digester liquid. The top of the pipes was modified to hold a water jacket such that the top cover could be opened out to put in the feed. Under this cover was placed a perforated plate that enabled the recycled liquid to be spread and sprinkled over the bed of decomposing biomass below. Once a week, the top hatch was lifted and a nylon mesh was placed over the existing bed of decomposing biomass and then a pre-determined quantity of waste was fed to them by placing it on the existing bed and closing the hatch. No preprocessing was adopted for any of the feedstocks. This operation lasted about 5 min in a week. We adopted a weekly fed operation to minimize interference by air inadvertently entering the reactor during the feeding operation. A total of six such

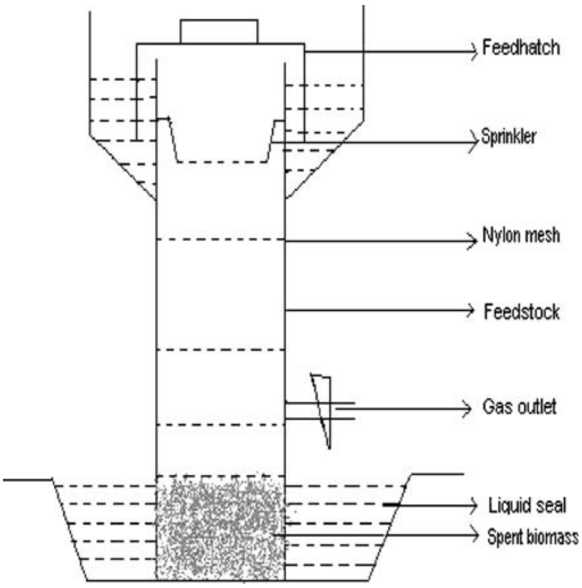

Fig. 1 Solid-state stratified bed (SSB) reactor made of opaque PVC pipes

reactors were operated for 70 d. The process was initiated by placing a 0.15 m depth of digested biomass in each digester. Digested biomass was taken from a 6 m^3/d SSB reactor and it served as a methanogen rich bed to initiate the process. A total of 3 l of digester liquid from the large biomass reactor was used as the recycling liquid in each reactor. The liquid in lower reservoir (1.5 l) was manually recycled twice daily at 0900 and 1630 h. The gas produced in this reactor was led to a 0.6 m tall, 100 mm diameter PVC pipe and collected by downward displacement of air. When required, a sample of the gas was drawn with a micro litre syringe and analyzed for gas composition. The gas production was recorded twice daily. The feedstocks were initially fed at 0.5 g TS/l/d and feed rates were gradually raised. An attempt was made to reach pseudo steady state operation at 2 gTS/l/d (14 g TS fed once a week). In a few feedstocks however, this could not be achieved and hence were continued at 0.5 g TS/l/d feed rates.

After a digestion period of 70 d the fermenting mass was removed in the form of layers of decomposing mass subject to increasing solids retention time (SRT). Each layer was characterized for its residual TS/VS, moisture, mainly to determine the extent of decomposition it had suffered. Biomass such as fruit waste, paper mulberry, were extremely decomposed and/or pulpy and considered unsuitable for further re-use as biofilm support. Only fermented bagasse was recovered in adequate quantities and form after SSB digestion. We operated a reactor with bagasse+20% leaf biomass as biofilm support. Biofilm biomass was packed at 200 g fresh weight/l. This downflow reactor was operated by feeding synthetic feed (rice flour dispersed in hot water, cooled and diluted to required strength). The gas produced was connected to downward displacement type storage and measured on a daily basis. The COD of wastewater at inlet and outlet was determined and used to indicate the satisfactory functioning of the biofilm support. The composition of biogas collected was monitored at frequent intervals to determine the health of the reactor. This was tried to determine the possibility of co-fermentation of solid and liquid wastes in a single fermentor configuration (Chanakya et al. 1998).

The BMP assay was carried out in 133 ml serum vials with 3–6 replicates and fermented at 35±1°C in an incubator. Each vial contained 49.5 or 49 ml of methanogen enriched digester liquid and 0.5 or 1.0 g TS equivalent of specific feedstock. This gave a final concentration of 1 or 2% TS in the fermenting liquid. All vials containing 2%TS showed stalled fermentation and were subsequently not reported in this study. The gas production was measured by downward displacement of water in an inverted burette at progressively increasing intervals of time e.g. on days 1, 3, 6, 9, 12, 16, 20, 27, 35, 49, 63, 79, 100, etc. These intervals were standardized from previous experience with leaf biomass feedstocks. On all days when gas production volume was estimated, the gas composition was also measured using gas chromatograph connected to a thermal conductivity detector with H_2 as carrier gas. From the volume and composition we estimated the total CH_4 and CO_2 produced. BMP assay was carried out as a reference to determine the potential of the SSB reactor to extract maximum biogas potential of the feedstock.

The total solids (TS) and volatile solids (VS) was determined for the feedstock mass residual in the SSB reactors which was removed after the 70 d fermentation period by simply lifting the reactor out of the digester liquid and gently pushing out the fermenting mass (bed) within. This mass was lifted out layer by layer (separated by nylon mesh) and individual layers representing various solid retention times (SRT) were weighed and sampled for TS/VS estimation. The ratio of the residual mass was expressed as per cent of original fed in order to overcome varying feed rates and attempts were made to fit an exponential decay pattern for each of the feedstock tried.

Results and discussion

The potential to carry out decentralized processing of OFMSW using only door to door collection greatly averts the high cost and need for daily fossil fuel based MSW collection as is stipulated in national and state level MSW rules and guidelines in India. The OFMSW component in Bangalore's MSW is reasonably high necessitating its rapid removal and processing. Here we consider that anaerobic digestion (AD) has the potential to provide two saleable byproducts biogas and anaerobic compost to make it more economic. Further using a simplified 2-stage system, as in SSB, will be a potential solution to decentralized AD where feedstocks vary widely both in mass and composition (Chanakya and Moletta 2005). It is thus important to establish and characterize that each of these subcomponents of MSW with respect to their amenability to be fermented under SSB conditions.

Decomposition under SSB conditions Mixed fruit wastes could be fed at high feed rates (2 g TS/l/d) without significantly affecting operation (Fig. 2). Fruit wastes rapidly underwent decomposition and only a small fraction was left behind after a fermentation period (Fig. 3). However, such a feed rate and >90% TS reduction did not commensurate with gas production. We noticed that pH levels in the digester were generally low and long-term operation gave rise to fungal growth in exposed digester liquid. This low pH (<5.5) implicates high VFA in digester liquid (VFA not measured) and thus incomplete conversion to gas. For this extent of TS loss in the reactor, the expected gas production rates need to be above 1.0 l/l/d. Over 75% decomposition occurred in 14 d. This high rate of decomposition and VFA accumulation suggests that SSB reactors for mixed fruit wastes need to be operated with a much deeper biomass bed to ensure complete conversion to biogas, efficient operation and high biogas recovery. It is clear that compost recovered from such reactors is going to extremely low and will be less than 10% of the original weight of mixed fruit waste added.

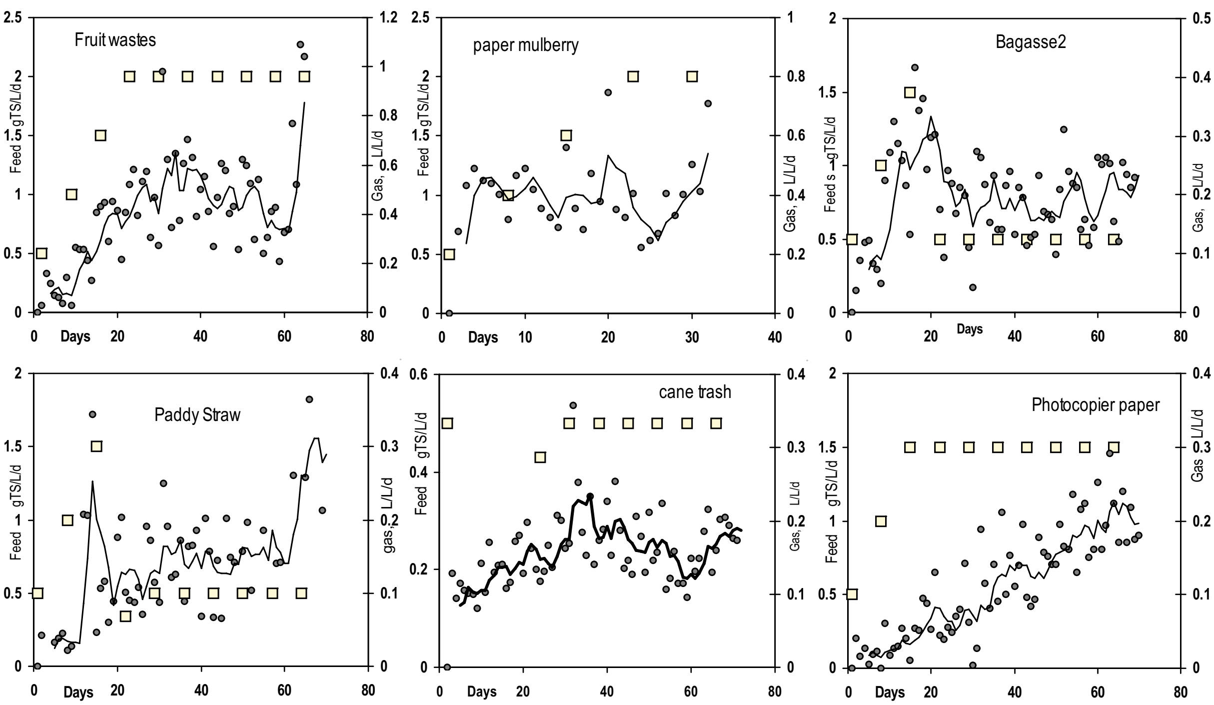

Fig. 2 Average daily feed rates used in laboratory SSB reactors (*empty square*=gTS/l/d) and gas production response to such feed rates measured in terms of l gas/l reactor volume /day (•). Fruit waste, tree leaf litter (paper mulberry) and photocopier paper supported high feed rates where as bulky dry feedstocks such as paddy straw, bagasse and cane trash did not permit high feed rates (>0.5 g TS/l/d)

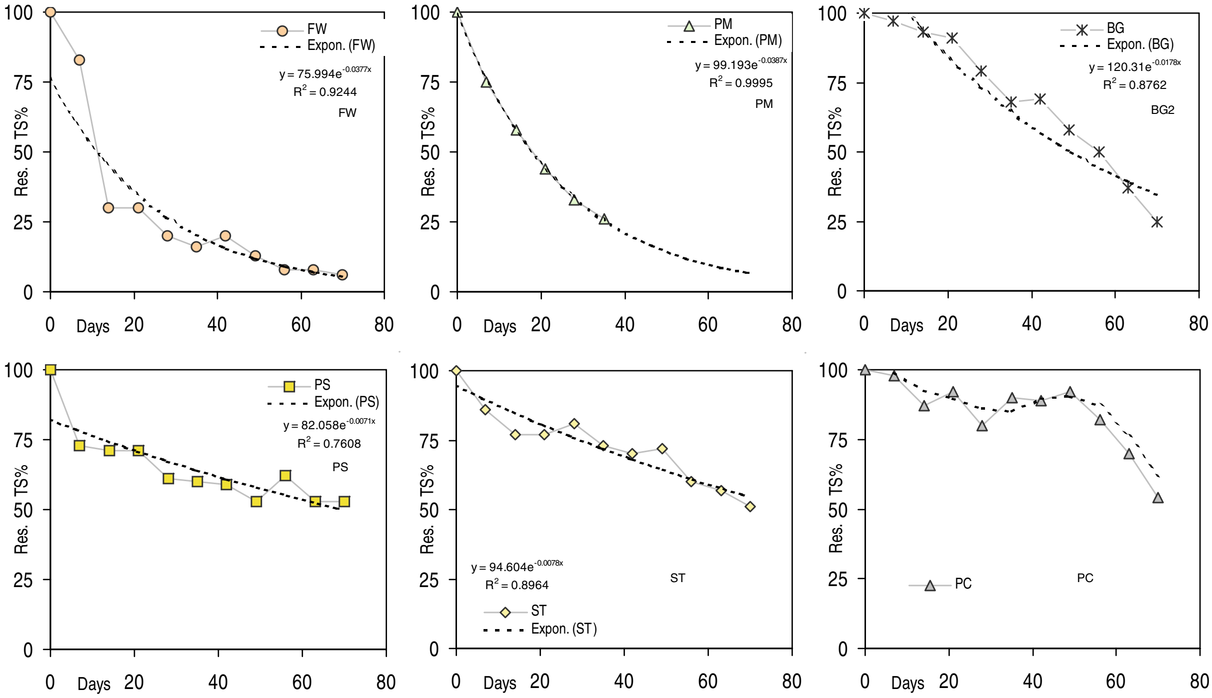

Fig. 3 Decay rates of feedstocks in laboratory SSB reactors. Most feedstocks showed reasonably good fit to an exponential decay approach but requiring some correction to incorporate delayed initiation of decomposition or due to very rapid initial decay. Decay constants are provided in Table 2

It appears possible to support high feed rates for paper mulberry (leaf litter) based SSB (2 g/l/d) but gas production pattern seen, like in the case of mixed fruit waste, did not commensurate with the feed rate (Fig. 2) or TS removed. The high TS removal suggests that just as in the case of fruit waste the generation of required methanogenic bed and its subsequent conversion to biogas is poor. SSB digesters designed for large fraction soft leaf feedstock (paper mulberry) require longer SRT such that the active methanogenic bed height is adequate to decompose the VFA during its downward passage. It is seen that 75% decomposition took 35 d. Here the rates of decomposition are as reported before (Chanakya et al. 1997, 1999) however, it is important to ensure that TS to gas conversion efficiency is improved. Just as in the case of mixed fruit waste the quantity of compost generated is expected to be low. Table 2 lists the decay pattern for five of the six feedstocks and the decay pattern is exponential ($y=me^{-kt}$). In the case of bagasse, it was found that by not using the 7 d value of decomposition, the fit is much better and suggests that the delay in onset of decay if overcome, the decay process would be truly exponential.

Owing to the bulky nature of bagasse (BG), sugarcane trash (ST) and paddy straw (PS) the lab scale SSB bioreactors used here could not be fed beyond the 0.5 g TS/l/d. The conversion to gas is however good reaching values between 0.2–0.25 l/l/d volume efficiency in all these feedstocks. There is a gradual increase in gas production rates during the initial period but the gas production data is highly scattered and reasons for scatter are not clear at this stage. PS and ST decompose to the tune of 50% of TS and may be considered suitable feedstocks for this approach. Although exponential decay pattern is visible, the current fit does not adequately explain for the initial rapid

Table 2 Decay pattern of feedstocks

Feedstock	Constant	Exponent (e^{-})	R^2
Fruit Waste	0.76	−0.0377	0.93
Paper Mulberry	0.99	−0.0387	1.00
Bagasse	1.20	−0.0178	0.88
Bagasse*	0.99	−0.024	0.91
Paddy Straw	0.82	−0.0071	0.76
Sugarcane Trash	0.95	−0.0078	0.90

*not using the 7 d value of decomposition, the fit is much better decomposition stage in these two feedstocks. Similarly in the case of bagasse while there is a reasonably good fit with exponential decay pattern and yet it does not explain for the delay in the initiation of decomposition and TS loss. The causes for these deviations need further investigation and necessary corrections need to be made to use these decay rates in future. We expect that in larger reactors where the mass of feedstock will be higher, the compaction rates of feed would be high and it in turn would permit higher feed rates making SSB reactors acceptable for these feeds as well as economic and viable.

The case of photocopying paper is unusual. The gas production has gradually built up to reach a rate of 0.25 l/l/d after 50 d period. A feed rate of 1.5 gTS/l/d could be sustained without running out of digester space as was the case with the dry feedstocks or high VFA build up as in case of FW mentioned above. From this gradual build up of biogas production rate it is clear that the decomposition rate under present conditions is low (Fig. 2). This has happened in spite of adding 10% digested leaf biomass to compensate for low nutrient status of paper. This suggested that the current level of nutrition supplement is either inadequate or is not the right approach to handle photocopier (PC) paper decomposition to biogas.

Biological methane potential and realizing BMP under SSB conditions The BMP of the six feedstocks along with the gas composition is presented in Fig. 4. All the BMP assay vials using 2% feedstock exhibited low biogas production with low CH_4 content. It was clear that the methanogen populations were inadequate to handle the various inhibitory intermediates generated especially in the case of FW where the pH was low (5.2, data not shown). We therefore draw inferences only from BMP assay carried out at 1% substrate concentration. The BMP of fruit waste was similar to what was achieved under SSB conditions. Under SSB conditions it was possible to obtain a specific gas production of about 0.5 l/l/d at a 2 g/l/d feed rate. At nearly 90% VS/TS degradation as found in Fig. 3 it would result in ≥1.5 l/l/d at the above feed rate. While a large fraction of TS/VS was degraded it did not translate into gas, it was seen that the digester liquid contained a significant extent of fungal growth indicating among others, the presence of VFA that has flowed through the methanogenic bed without being converted to biogas. From this it is inferred that fruit waste based SSB biogas fermentors need to start with a deeper and more active methanogenic bed compared to what is used for other materials. The BMP was low, arrested by inadequate conversion of feedstock to methane and corresponding low methane content in the ensuing gas (Fig. 4).

Paper mulberry (leaf litter), bagasse, paddy straw and cane trash showed a BMP level of nearly 600 ml/gTS with gas production rates tapering off between 40 and 80 d of fermentation. The methane content of the gas reached ≥50% within a reasonable fermentation time (c.5–20 d). All these indicate that these feedstocks have the potential of being converted to biogas with reasonable gas yields and a stable process not easily afflicted by VFA overproduction is possible under SSB conditions. However, the efficiency of conversion under SSB conditions (Fig. 3) has not been commensurate with results of the BMP assay (Fig. 4). The average gas production at pseudo-steady state operation (Chanakya et al. 1999) works out to be 200, 380, 380 and 360 ml/g TS for paper mulberry, bagasse, paddy straw and cane trash respectively. This accounts for realization of 60% of BMP of dry feedstocks and only 30% of the BMP of paper mulberry. Dry feedstocks decompose slowly (Figs. 3 and 4) and therefore are not easily subject to VFA flux induced methanogen toxicity. Thus they can produce reasonable quantities of biogas with high methane content compared to paper mulberry (leaf litter) under the current set up of SSB reactors. This evidence suggests that as found in the case of fruit waste, the methanogenic bed at the lower part of the SSB reactor did not function adequately to convert VFA leaching downwards to biogas. Thus good VS destruction achieved did not result in good gas production. In solid waste management (SWM) terms when SSB reactors are operated with such feedstocks, it is necessary to ensure that the start-up methanogenic bed is acclimatized to high VFA flux before being operated at full loading rates. Photocopier paper when augmented with 10% digested biomass does not stabilize and reach pseudo-steady state (Fig. 2). The highest gas production is also poor (c.140 ml/g TS) nor did the decomposition follow a predictable pattern. In BMP assay the gas production tapered off at around 40 d and reached a little above 400 ml/g TS. The reasons for such low conversion and gas production rate for a feedstock that is expected to be largely cellulose is not clear from available data and needs to be investigated.

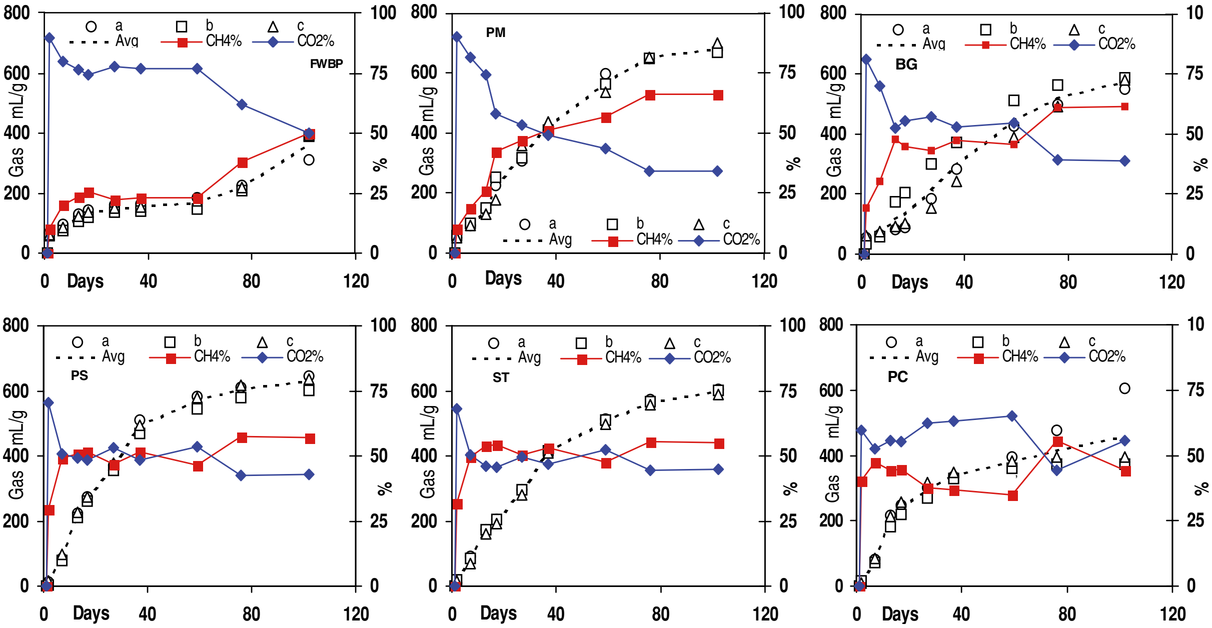

Fig. 4 The biological methane potential assay is shown for the six feedstocks studied. Fruit waste (banana peel) showed reasonable arrested methanogenesis (low methane) where as all others feedstocks showed reasonably high methane content in the head space gas indicating normal methanogenic process

At longer SRT, greater methanization takes place in the hydrolyser reactors than in methanizer, because VFA are at a lower concentration, not inhibitory to methanogens and thus phase separation is not very effective. At low organic loads, VFA concentrations are poor, because they are immediately converted and the yields (l/g VS) are high. Thus in order to enhance yield in a two-phase system, many more investigations are needed with respect to the system set-up, the control of pH in both reactor, etc. Only then it is possible to optimize conditions in the hydrolyser and methanizer. Thus a single phase system would be the appropriate choice as it is simpler, can be applied successfully to the treatment of this type of waste without any type of process control while simultaneously using the concepts of co-digestion (Callaghan et al. 2002). It also permits mesophilic operation at 25°C (Castillo et al. 1995) to avail of steady yield and economic operation (low heating needs).

Reuse of digested feedstock as methanogen biofilm for wastewater treatment Chanakya et al. 1998, 2004, showed that digested herbaceous biomass forms a pre-colonized biofilm support for carrying out high rate wastewater treatment. Green leaf biomass however had a short half life of 120 d as support after which it would disintegrate and was lost in the effluent. This suggests that fibrous biomass feedstocks, such as bagasse, paddy straw, leaf litter, cane trash, paper, etc. can be first digested for their energy recovery through SSB mode of biomethanation in decentralized MSW biogas plants. Later the spent residue removed from these digesters could be sold as ready to use biofilm support for anaerobic digestion of wastewater. It was found that only bagasse fed SSB reactors had adequate digested biomass for further trials as biofilm support. Bagasse with 25% digested leaf biomass was used as biofilm support in a down flow reactor. Bagasse with biomass showed good performance measured as the difference between inlet and outlet COD. At feed rates up to 1,000 mg/l it has shown around 50% conversion (data not shown). This reuse potential leading to zero discharge needs to be examined further.

Conclusions

Urban India has niches where single type biodegradable materials are discharged in appreciable quantities what one could indicate as micro-scale point sources. Typical biodegradable packing materials used in urban India such as paddy straw, cane trash and shredded paper as well as residue from street-side fruit juice vendors (mixed fruit waste and sugarcane bagasse) have potential to be used as sole feedstocks for decentralized processing of such MSW to biogas and compost. Setting up decentralized anaerobic digesters within urban locations in India captures and processes these fermentable wastes near the site of generation and has the potential to obviate daily MSW collection and transport. This approach reduces costs of solid waste management and has the potential to make the overall process sustainable. There is potential for the re-use of digested residue as pre-colonized methanogen support and increase local value addition to biogas.

Acknowledgements A part of the research effort was carried out with infrastructure created at CST under the Indo-Norwegian Environment Program (INEP) of Govt. of Karnataka. Ms Vijayachamundeeswari worked as visiting student with financial assistance from the annual grant to CES from the Ministry of Environment and Forests, Government of India. The authors gratefully acknowledge this help.

References

Aus-AID (2002). *Overview report on environmental sanitation-Vol.1-solid waste. Bangalore water supply and environmental sanitation master plan project*. Bangalore, India: Aus-AID.

Buenrostro, O., Bocco, G., & Silke, C. (2001). Classification of sources of municipal solid wastes in developing countries. *Resources, Conservation and Recycling, 32*, 29–41.

Callaghan, F. J., Wase, D. A. J., Thyanithy, K., & Forster, C. F. (2002). Continuous co-digestion of cattle slurry with fruit and vegetable wastes and chicken manure. *Biomass and Bioenergy, 27*, 71–77.

Castillo, T. R., Luengo, L. P., & Mata-Alvarez, J. (1995). Temperature effect on anaerobic digestion of bedding straw in a one-phase system at different inoculum concentration. *Agriculture, Ecosystems and Environment, 54*, 55–66.

Chanakya, H. N., & Moletta, R. (2005). Performance and functioning of USW plug-flow reactors in a 3-zone fermentation model. In B. K. Ahring, & H. Hartmann (Eds.), *Proc. 4th intl. symp. on anaerobic digestion of solid wastes, Vol.-1*, (pp. 277–284). Copenhagen: International Water Association, Aug 31–Sep02, 2004.

Chanakya, H. N., Ramamurthy, N., Shanmukhappa, V., Vinutha, D., & Deepa, G. B. (2004). Biomass-biofilm bioreactors for liquid and solid wastes of agro-processing-field performance studies. In *Proc. Int. conf. adv. Ind.*, (p. 441–450). Chennai, India: Wastewater treatment, Anna Univ.

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 and Bioenergy, 16,* 417–429.

Chanakya, H. N., Srivastav, G. P., & Abraham, A. A. (1998). High rate biomethanation using spent biomass as a bacterial support. *Current Science, 74*, 1054–1059.

Chanakya, H. N., Venkatasubramaniyam, R., & Modak, J. (1997). Fermentation and methanogenic characteristics of biomass feed stocks in a solid phase biogas fermenter. *Bioresource Technology, 162*, 71–78.

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

MSW handling rules (2000). *Ministry of environment, Govt. of India*. New Delhi, India.

Rajabapaiah, P. (1988). *Energy from Bangalore garbage – A preliminary study. ASTRA technical report, centre for sustainable technologies*. Bangalore, India: Indian Institute of Science.

Ramachandra, T. V. (2006). *Management of municipal solid wastes*. New Delhi: Capital.

Sathishkumar, R., Chanakya, H. N., & Ramachandra, T. V. (2001). *Feasible solid waste management, CES technical report no 85, centre for ecological sciences*. Bangalore 560 012, India: Indian Institute of Science.

TIDE (Technology Informatics Design Endeavour) (2000). Energy recovery from municipal solid wastes in around Bangalore. Technical report. Bangalore 560 003, India: TIDE, Malleshwaram.

TIDE (2003). Municipal solid waste in small towns. Technical report. Bangalore 560003, India: TIDE, Malleshwarm.

Yang, Y., Tada, C., Miah, S., Tsukahara, K., Yagishita, T., & Sawayama, S. (2004). Influence of bed materials on methanogenic characteristics and immobilized microbes in anaerobic digester. *Materials Science and Engineering, 24*, 413–419.

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

Zhang, Z., & Zhang, Z. (1999). Biogasification of rice straw with an anaerobic-phased solids digester system. *Bioresource Technology, 68*, 235–245.