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Micro-treatment options for components of organic fraction of MSW in residential areas

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Abstract There is a growing interest in management of MSW through micro-treatment of organic fraction of municipal solid wastes (OFMSW) in many cities of India. The OFMSW fraction is high (>80%) in many pockets within South Indian cities like Bangalore, Chikkamagalur, etc. and is largely represented by vegetable, fruit, packing and garden wastes. Among these, the last three have shown problems for easy decomposition. Fruit wastes are characterized by a large pectin supported fraction that decomposes quickly to organic acids (becomes pulpy) that eventually slow down anaerobic and aerobic decomposition processes. Paper fraction (newsprint and photocopying paper) as well as paddy straw (packing), bagasse (from cane juice stalls) and tree leaf litter (typical garden waste and street sweepings) are found in reasonably large proportions in MSW. These decompose slowly due to poor nutrients or physical state. We have examined the suitability of these substrates for micro-composting in plastic bins by tracking decomposition pattern and physical changes. It was found that fruit wastes decompose rapidly to produce organic acids and large leachate fraction such that it may need to be mixed with leachate absorbing materials (dry wastes) for good composting. Leaf litter, paddy straw and bagasse decompose to the tune of 90, 68 and 60% VS and are suitable for composting micro-treatment. Paper fractions even when augmented with 10% leaf compost failed to show appreciable decomposition in 50 days. All these feedstocks were found to have good biological methane potential (BMP) and showed promise for conversion to biogas under a mixed feed operation. Suitability of this approach was verified by operating a plug-flow type anaerobic digester where only leaf litter gathered nearby (as street sweepings) was used as feedstock. Here only a third of the BMP was realized at this scale (0.18 m^3 biogas/kg VS 0.55 m^3/kg in BMP). We conclude that anaerobic digestion in plug-flow like digesters appear a more suitable micro-treatment option (2–10 kg VS/day) because in addition to compost it also produces biogas for domestic use nearby.

Keywords Micro-treatment · MSW · OFMSW · Biogas · BMP · Micro-composting

Introduction

Cities in South India have demarcated pockets such as residential, educational, commercial etc. areas created and protected by city regulations that prevent very drastic changes in urban land use and changes occur only slowly. This being the case it is possible to collect solid wastes of specific composition within these demarcated areas of the city based on the type

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of major land usage. Many South Indian cities are characterized by having a high degree of fermentable component in municipal solid wastes (MSW) from residential areas. The fermentable components of MSW consist predominantly vegetable and fruit wastes that can range between 65 and 90% (Rajabapaiah 1988; TIDE 2000; Aus-AID 2002; Hui et al. 2006; Ramachandra 2006). As and when all these cities begin source segregation into fermentables, recyclables and that to be inertized, as specified by new laws (MSW handling rules 2000), it is expected that a significant component of fermentable fraction will be produced and needs to be picked up on a daily basis.

Today the collection and transportation costs of MSW in such cities range between Rs. 500–1,500 (US$12–36) per ton and is often accompanied by uncertainties in frequency and quality of collection and transport (Yedla and Parikh 2002). These have emerged as a source of concern. In response to such uncertainties in daily collection, there have been a large number of decentralized individual and community based collection, processing and reuse efforts (Yedla and Parikh 2002). In such a case the type of treatment option varies according to two inherent factors namely the daily MSW production size and its typical composition. Individual house based treatment units of the organic fraction of MSW use various types of aerobic or anaerobic composting (Chanakya and Jagadish 1997), vermicomposting and insect larvae based composting processes (black soldier fly larva). Amongst these only aerobic composting and vermicomposting techniques have been tried in South Indian cities.

Earlier efforts show that in source segregated solid wastes (henceforth called organic fraction of municipal solid wastes, OFMSW) coupled to door-to-door collection systems are reasonably efficient and have nearly 97–98% OFMSW and only a small content of non-fermentable material (Chanakya and Jagadish 1997). Such segregation and collection efficiency provides potential for this OFMSW to be directly composted aerobically, aerobically composted followed by vermicomposting or anaerobically composted to biogas and compost. As the daily per capita OFMSW production varies between 0.2–0.5 kg in Karnataka state, depending upon lifestyles in the cities (indicated by city population (KUIDFC 2003; CST 2005). Thus, due to the small size of the total fermentable MSW generated at the household scale only composting and vermicomposting seem feasible at the household level. Many commercial and non-commercial devices for household composting and vermicomposting have been tried in Bangalore (Aus-AID 2002). Most of these have run into difficulties either due to excessive malodours due to the generation of large volumes of leachates and organic acids in case of household composters and worm predation or worm migration in household vermicomposting devices (Chanakya et al. 2006; TIDE 2000, 2003; Rajabapaiah 1995).

Area or community scale options indicated above have been more successful in Bangalore and in various places in India. Area or zone wise collection has been shown to simplify collection systems and enables collection of MSW of similar composition (Sathishkumar et al. 2001). Leaf litter and garden wastes, vegetable and fruit wastes, domestic and kitchen wastes, etc. thus are manually carted and treated at scales between 0.050 and 0.250 tpd scale (TIDE 2003). Such efforts have survived long periods of operation with much fewer technical problems. The influence of using such feedstocks on the underlying processes has been poorly documented with regards to technical process parameters, yields, costs and operational difficulties. In this study we have carried out micro-composting of some of the typical feedstocks of zone-wise collected OFMSW and studied the process as typically carried out in the field and attempted to determine the process parameters and yields. Zone wise handling has been considered before (Daskalopoulos et al. 1997). Street sweepings and leaf litter generation in residential localities of the city form a significant year round component of MSW (Sathishkumar et al. 2001). The potential for distributed biogas plants for collected leaf litter component of OFMSW was studied using a plug flow bioreactor concept (Chanakya and Jagadish 1997; Chanakya and Moletta 2005) as a representative of decentralized operation with simple machinery (Garcia et al. 2005). The biological methane potential (BMP) of these individual feedstocks needs to be determined to indicate their suitability for anaerobic digestion in distributed biogas plants.

Composting is the biological oxidative decomposition of organic constituents in wastes under controlled conditions. It thus requires special conditions, temperature, moisture, aeration, pH and C/N ratio, to enable optimum biological activity in the different stages of the process (Barrington et al. 2002, 2003). The main products of aerobic composting are CO_2, H_2O, mineral ions and stabilized organic matter, often called humus. The process is accomplished through different phases (Bari and Koenig 2001) i.e. initial phase during which readily degradable components are decomposed. During a thermophilic phase cellulosic materials are oxidatively degraded rapidly by microbes. This is followed by maturation and stabilisation phases. The process may also be discussed in terms of two well-defined phases mineralisation and humification (Sharma et al. 1997). The degradation is followed by intensive microbial activities producing heat. This high temperature is important to kill pathogenic organisms sometimes present even in MSW components. After this, when the assimilable organic fraction is exhausted, most cells undergo decay by auto-oxidation. This transformation occurs in the second phase and leads to the formation more stable humic substances. The humification leads to tri-dimensional polymers also that provide energy for future microbial activities (Sharma et al. 1997). While composting of agro-residues has been in existence for long, composting of municipal (urban solid wastes is of recent origin, more so when attempts are being made to carry this out at micro-scale (up to 10 kg/day). Many locally evolved processes have been optimized over time (Gotaas 1956). A well-known method is the Bangalore method adapted to ensure >90% nitrogen conservation in N-starved semi arid soils. An important modification has been the frequent turning of compost pile to maintain aerobic conditions. This provided rapid degradation and shortened composting time. None of these early process addressed MSW. de Bertoldi et al. (1983) provides a detailed review of transformation processes of the organic fraction of solid urban waste into compost including processes used when the waste is mixed with sewage sludge. The Vuilafvoer Maatschappij (VAM) process adapted the Indore process to municipal refuse at a large scale (Slater et al. 2001) and has been in operation in Bangalore since 1978 (SANDEC 2002). Zurbrugg et al. (2005) developed a low-cost technique using the "Indonesian windrow technique" for MSW. For micro-composting attempted in this study we try to determine whether there are adequate thermophilic stages, adequate stabilization and physico-chemical changes. Finally we characterize the predominant components of the OFMSW for their suitability to micro-composting or small anaerobic digestion which are considered as ideal decentralized process options.

Materials and methods

Aerobic composting was carried out in rectangular polythene containers of volume 25 l and provided with perforations on the lid as well as on the sides to help aeration. The material to be composted was mixed with biogas digester liquid and 5% previously generated compost to help start the compost process. The overall process was carried out similar to the decentralized micro-composting methods normally adopted that are similar to turned windrows. No temperature control was exercised. The composting material was wrapped in nylon mesh and was placed in the rectangular polythene container to prevent interference by insects and vectors. Once a week these nylon mesh wrapping were opened, contents mixed and replaced in the wrapping. Feedstocks such as fruit waste, paddy straw and leaf litter were used without size reduction. Newsprint and photocopier paper were hand shredded to 3–4 cms, while sugarcane bagasse was chopped to 3–5 cm length prior to placing in the compost bins. Packing density (kg/dm^3) of these materials vary from 0.17 (for fruit waste), 0.12 (leaf litter), 0.12 (photocopier paper), 0.11 (newspaper), 0.07 (paddy straw) to 0.07 (sugarcane bagasse).

Decomposition rate and change in decomposition indicators were determined by subjecting each type of feedstock sample to varying decomposition duration within a pile. Ten nylon mesh bags containing 50 or 100 g

Table 1 Source of OFMSW components used for micro-composting

Feedstock	Place of collection	Dry weight (kg)
1.Fruit waste	Fruit Juice Shop (Yeswanthpur)	12[a]
2.Leaf litter	IISc campus (CST area)	1.75
3.Used copier paper	IISc photocopying center	1.7
4.Soiled Newsprint	CES Library	1.6
5.Sugarcane bagasse	Cane Juice vendors, Yeshwanthpur	1
6.Paddy straw	Yeshwanthpur market	1

[a] Fresh weight per container

portions of the feedstock were placed within the composting material and removed at specific intervals. At the time of weekly mixing or when required, one bag of each of these six feedstocks was removed from the composting pile and subject to physico-chemical analyses. Sampling was carried out on 0, 3, 6, 9, 12, 17, 22, 30, 37, 44 and 51 days. These represent intervals where appreciable weight change was expected to occur. For each of the container, prior to weekly mixing, leachate collected was drained, its volume measured and its COD, BOD, TS, VS were determined by standard methods. The loss in VS, measured as a fraction of the original VS mass added, was plotted for each of the feedstock along with an exponential fit calculated by spread-sheet software.

Six different location specific (representative) OFMSW constituents were studied. Fruit waste, soiled newsprint, leaf litter and photocopier paper represent wastes from areas with fruit juice stalls, service and catering area, gardens and walkways and photo-copier service areas respectively (Sathishkumar et al. 2001). Leaf litter studied here represents a wide

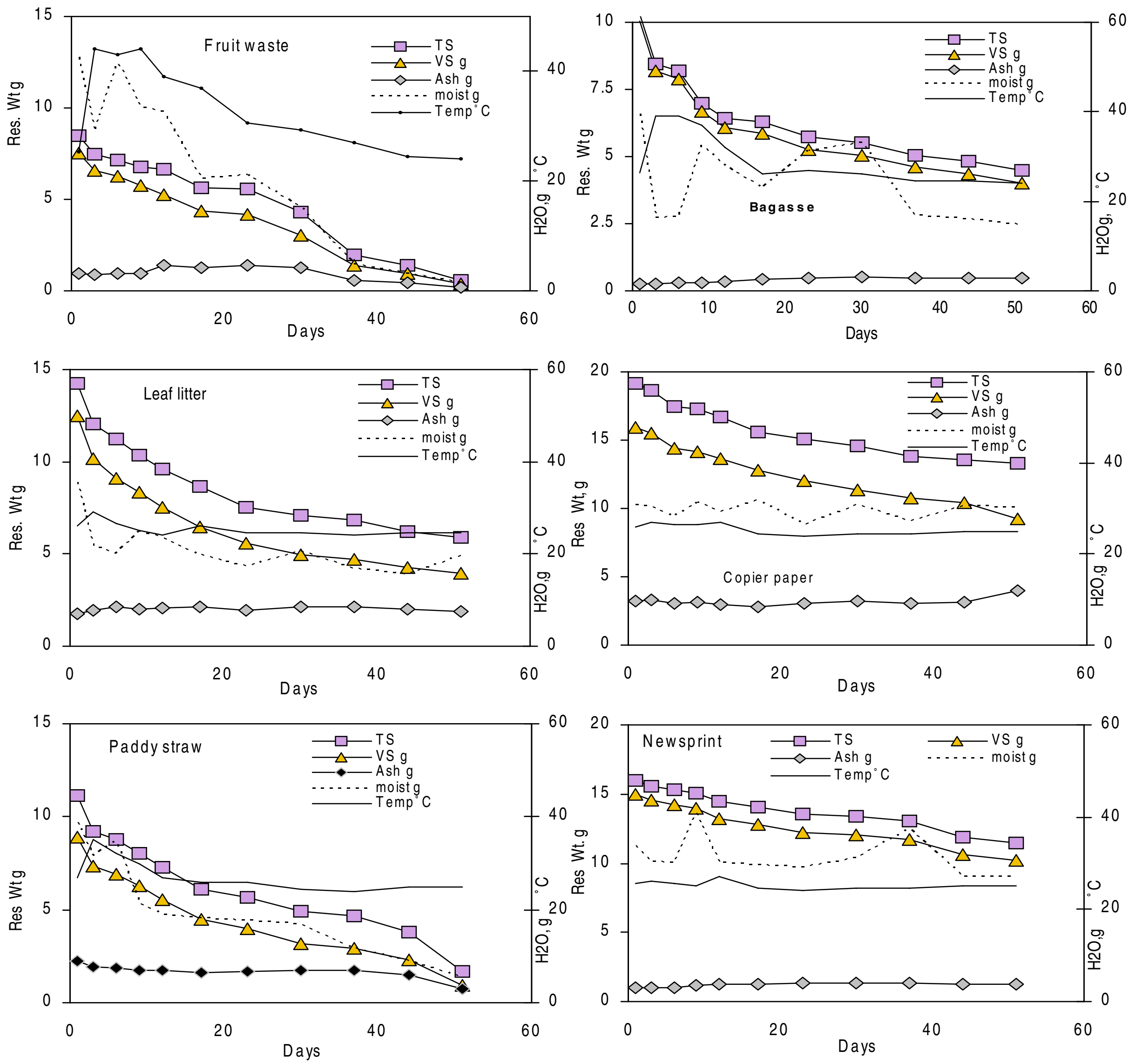

Fig. 1 Mass of various fractions remaining with in feedstocks while being subject to aerobic composting. Each single feedstock was packed in ten nylon mesh bags and composted along with the rest of the same material. One bag was removed at specific intervals and residual properties as shown above were determined to measure the rates of decomposition

range of fallen tree leaves with an age on the ground ranging from 1 to 10 days. This suggests that leaves will be in various stages of decomposition and do not represent green leaves harvested from trees and subsequently dried. Paddy straw (packing material) and sugarcane bagasse (waste collected after juice is pressed out and this differs from sugar industry bagasse in many ways) are found in locations

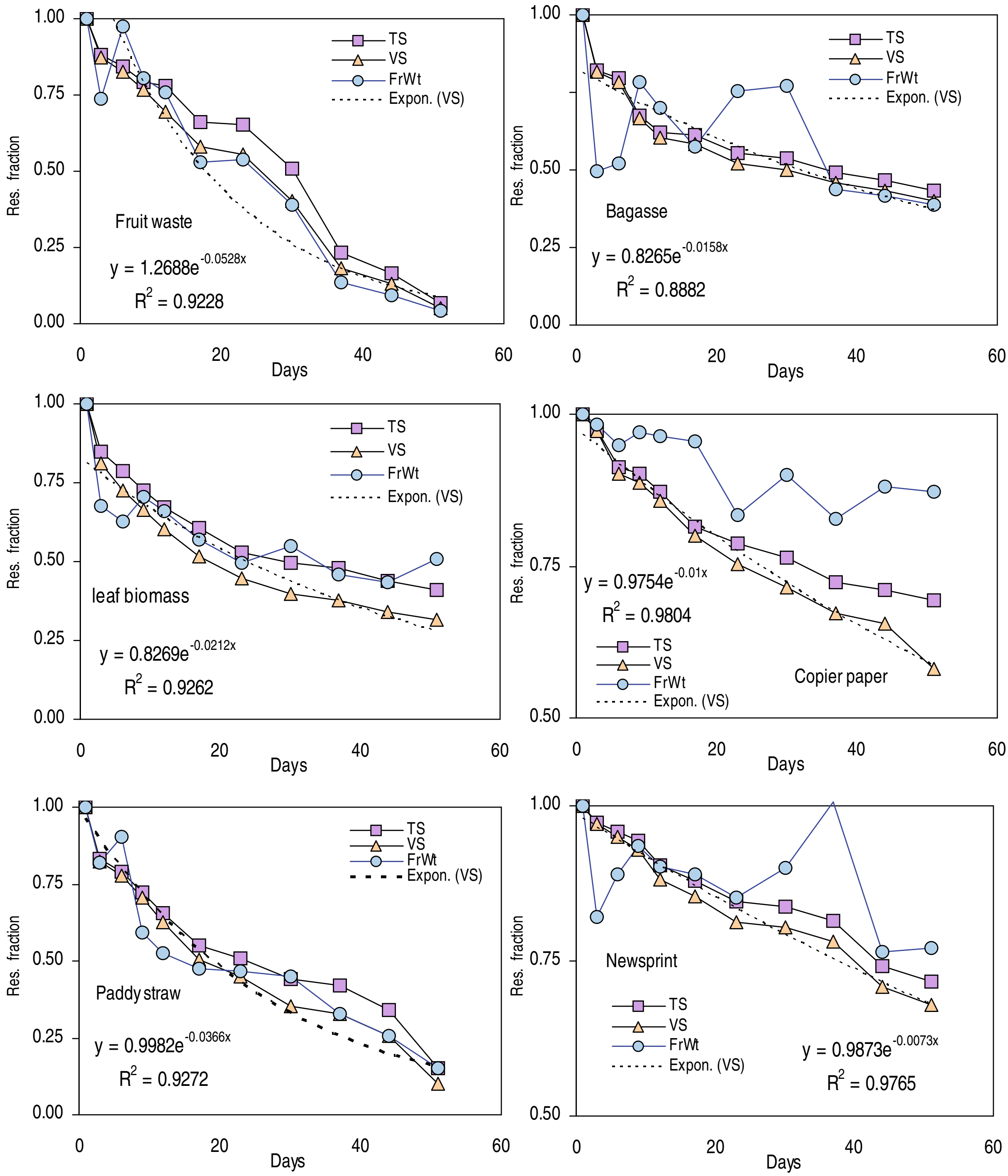

Fig. 2 Rate of change of TS, VS and fresh weight of the six feedstocks subject to micro-composting. The moisture content was adjusted in all feedstocks other than fruit waste. An exponential fit was attempted for VS lost and is shown in *dotted lines*

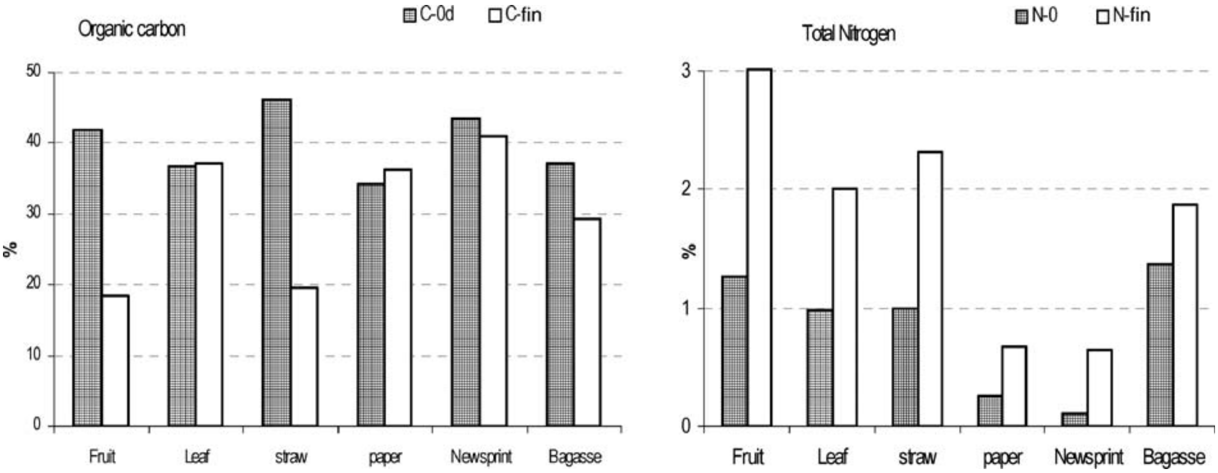

Fig. 3 Changes in percent organic carbon and total nitrogen prior to and after composting process

specialized in metal furniture making (or bulk fruit packing) and sugarcane juice stalls on streets respectively. Anaerobic digestion of bagasse to biogas using a stratified-bed fermentation technique has been studied previously (Chanakya et al. 1999). Paddy straw and bagasse served as internal standards for the study with respect to anaerobic digestion and biogas potential. Food and vegetable wastes have been studied intensively and were not considered for study here. The sources and the quantity of each of the six feedstock composted in plastic bins are presented in Table 1.

Biological methane potential (BMP) was determined by fermenting powdered dry feedstocks at 1 and 2% TS in 133 ml serum vials. The required quantity of dried and powdered feedstock (0.5 and 1.0 g) feedstock was placed in serum vials. Fifty milliliters of biogas digester liquid previously enriched with methanogens was added to these vials (five replications) and the air in the headspace was immediately displaced with biogas from a biomass fed biogas plant, the bottles capped, crimped and incubated upside down. Within a few minutes, the biogas in the headspaces of the vials was replaced by oxygen-free nitrogen. Nitrogen was bubbled into the fermenting liquid with a long hypodermic needle and the headspace gas was vented with a short needle to keep it at atmospheric pressure. The head space gas composition was determined immediately for all the vials in a gas chromatograph with a Porapak-Q column connected to a thermal conductivity detector. These vials were subsequently incubated upside down at 35°C in an incubator. The gas production in these vials was determined by releasing the headspace gas through a hypodermic needle into an inverted burette filled with water. Any gas production accumulating in the head-space of the vials would thus result in it being released into the burette and its volume is read directly in the burette. The composition of gas in the head space was determined each time the gas was released into the inverted burette. In this way the volume and composi-

Table 2 Changes in the carbon to nitrogen ratios (C: N) following the microcomposting process adopted

Feedstock	C:N, before	C: N, after	Decomposition rates		
			Constant	Exponent	R^2 of fit
Fruit waste	33.21	6.1	1.2688	0.0528	0.9228
Leaf biomass	37.5	18.43	0.8269	0.0212	0.9262
Paddy straw	46.2	8.4	0.9982	0.0366	0.9272
Copier paper	136.8	53.95	0.9754.	0.01	0.9804
Newsprint	103.6	64.21	0.9873	0.0073	0.9765
Bagasse	27.04	15.64	0.8265	0.0158	0.8882

Paper based feedstocks show that they are still poor material for reuse as compost.

tion of the gas produced was recorded for a period of 90 days. The interval for gas measurement was chosen from past experience to ensure that significant volume could be recorded each time and also the volume of gas production did not exceed the capacity of the burette. From this data it was possible to estimate the volumes of methane and carbon dioxide produced at various periods. The production of a continuously high fraction of methane is expected to indicate a healthy anaerobic decomposition process. The cumulative gas production was recorded and their average was used for arriving at conclusions on suitability for anaerobic digestion and biogas recovery.

Results and discussion

In this study we sought micro-scale anaerobic or aerobic composting as a solution to irregular removal of decomposable solid wastes that are generated at specialized locations such as street side fruit and fruit juice vendors, food vendors using decomposable paper and agro-residues in packing, as also large gardens and parks, etc. Rapid decomposition by composting or biomethanation processes for such specialized wastes is a potential decentralized solution to maintaining good sanitation with cost recovery. In addition, it is important that the process is amenable for operation at micro-scale of 1–30 kg VS/day. We characterize feedstocks for this potential.

The changes in temperature of digesting mass and moisture held as well as the mass of decomposable components are presented in Fig. 1. Fruit waste, paddy straw and bagasse showed an initial rise in temperature that may be attributed to the initiation of rapid aerobic decomposing bacteria as well as the presence of required components to achieve this. The temperature rise is rapid reaching between levels between 10 and 22°). There is thus a potential to achieve high temperatures needed to sanitize the waste by arranging the shape of microcomposters to have low heat loss. This strategy is not possible with leaf litter, copier paper and newsprint. While leaf litter and copier paper waste do not attract insect vectors, newsprint associated with fruit wastes or food wastes (often practiced by street vendors) will require a different strategy. The moisture held or that needs to be maintained by visual methods showed interesting results. Visual methods for moisture regulation appeared difficult for non-paper feeds. All these feedstocks lost moisture content rapidly during the early stages of composting. Fruit wastes lost moisture in the form of leachates while leaf litter, paddy straw and bagasse appear to lose moisture by evaporation only. For these three feedstocks moisture regulation by visual methods did not permit precise control as seen by highly fluctuating values for moisture content. In microcomposting, alternative strategies may be required to regulate moisture. Newsprint and copier paper did not show too much variation in moisture content. The pattern of degradation of TS, VS and a potential fit for the degradation of VS is presented in Fig. 2. In all feedstocks other than copier paper, the TS and VS degradation pattern followed each other. This suggests that bulk of the TS degraded

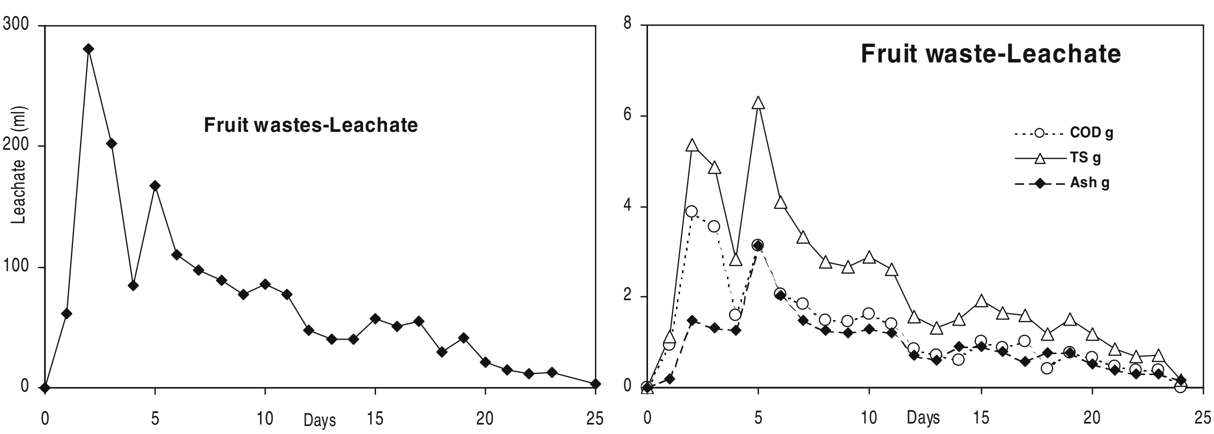

Fig. 4 The volume and properties of leachate collected from composting fruit wastes. A total of 4.5 g VS /kg feed is released and needs to be treated separately

is a result of VS degradation. Only paddy straw provided a perfect fit for exponential decay ($y=e^{-kt}$. R^2=0.93). Fruit wastes and leaf litter could reach decomposition levels >75%. In comparison to these bagasse, copier paper and newsprint decomposed to a lower extent. The decay among the all feedstocks followed a general pattern of exponential decay (Lopes et al. 2004). However, most deviations from a typical exponential fit arose at the point of initiation. Either the initiation of the decay was delayed or the initial decomposition was very rapid compared to the rest of the material. Thereby the fit did not begin at the point of origin. In the case of fruit waste, there is clearly a delay in the initiation of rapid decomposition. It is expected that much of initial decomposition leads to the generation of volatile fatty acids (VFA) and

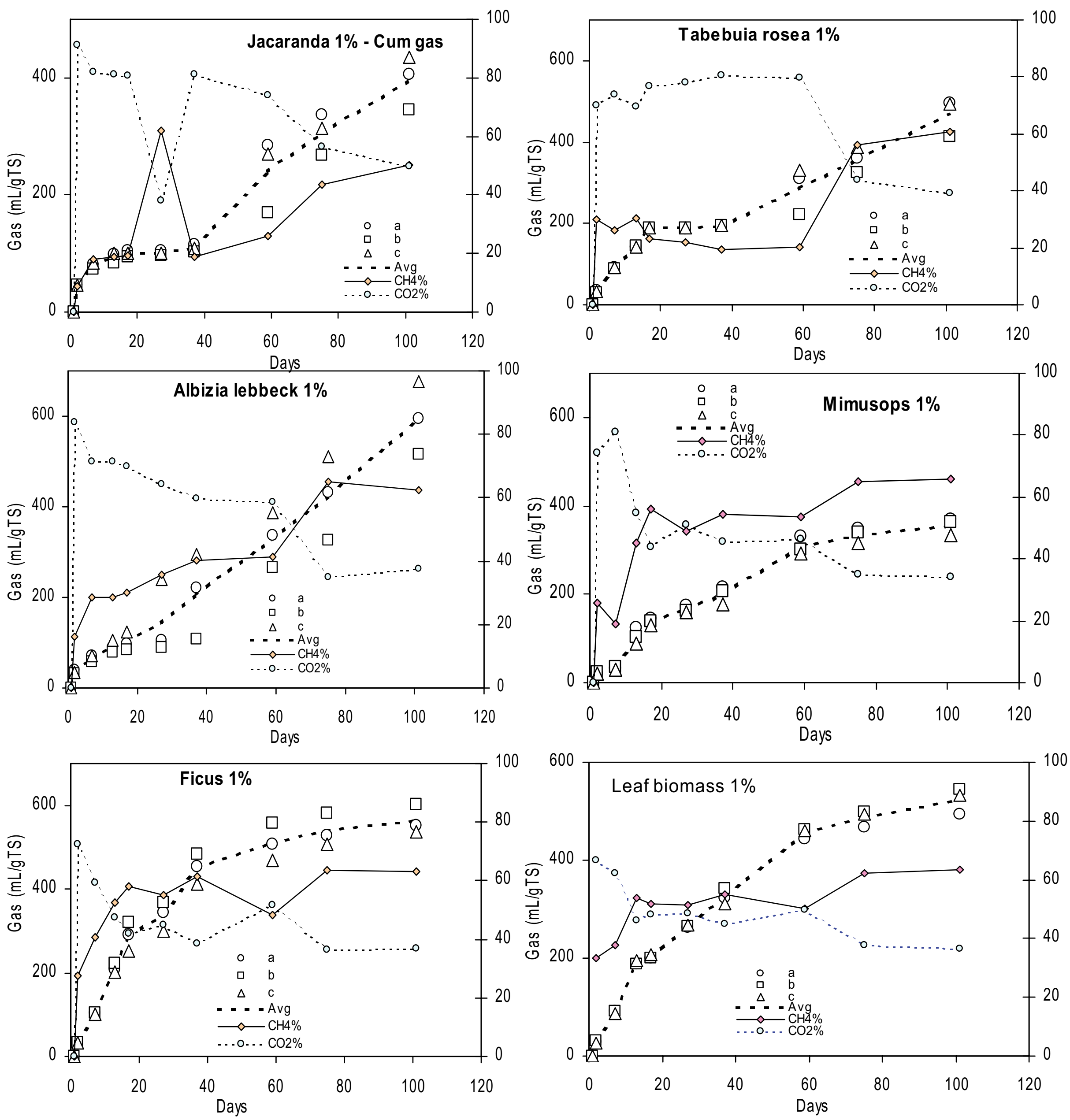

Fig. 5 The biological methane potential of typical leaf biomass feedstock collected and fed to the plug flow biogas plant. The *dotted line* shows the average gas production for three replicates (a, b, c) at 1% TS concentration in the fermenting mass

concomitant reduction in the pH levels of the fermenting mass. A similar pattern is also seen in the case of leaf litter decomposition. A rapid initial decomposition in the case of bagasse (VS loss) accompanied by a rapid rise in temperature at initial stages show that bagasse contains a significant fraction of easy to decompose substances. This accounts for the rapid initial decomposition and is possibly caused by inefficient extraction of sugars during the juice expulsion process. Juice extraction from fruit wastes is also expected to be less efficient leaving behind a significant portion of simple to decompose components in the waste. While bagasse is reasonably porous, decomposition of sugar not extracted occurs without concomitant accumulation of volatile fatty acids (VFA). In the case of paper residues the initiation of decomposition is slow and proceeds only up to an extent of around 50% or less. Thus it may be seen that recovery of compost or residues is the least in the case of fruit waste while newsprint and copier paper are expected to provide a larger fraction of compost like material.

The changes in the carbon and nitrogen proportion before and after the composting process are presented in Fig. 3. Only fruit waste and paddy straw showed significant reduction in the carbon content. This observation suggests that along with decomposition there is a translocation of mineral content which is lost from the composting mass. It is believed that this is either lost in leachate as recorded in the case of fruit waste or gone unrecorded in paddy straw and needs further investigations. Bagasse showed a small reduction in C content in the residual matter. In the other three feedstocks newsprint, copier paper and leaf litter there was only a very small change in the organic carbon fraction. Similarly the change in nitrogen content of the feedstock is presented in Fig. 3. All feedstocks other than bagasse showed a doubling of the N content. This phenomenon is attributable to firstly the break down of carbon fractions without concomitant volatilization of N as ammonia. Fruit wastes, straw and leaf litter made compost that is rich in nitrogen and is thus saleable. Bagasse produced compost that is only marginally useful. Supplementing newsprint and copier paper with N in the form of digested leaf material did not appreciably raise the measurable nitrogen content. The resulting compost also had a low N content. From this we suggest that the proportion of digested compost that needs to be mixed with paper wastes needs to be much higher than used in this study in case the decomposition needs to be hastened and the compost produced is to be sold (Table 2).

Only fruit wastes produced significant quantities of leachate such that it would be considered necessary to provide leachate treatment along with composting (Fig. 4). These values indicate that a total of 1,749 ml leachate in 20 days (c.150 ml/kg), 31.5 g COD (2.6 g COD/kg feed), 54 g TS=4.5 g TS/kg feed) for wet waste needs to be managed. The total solids measured in the leachate are much higher than the COD measured. This suggests the presence a large mineral content in the feedstock as visible from the ash content that accounts for nearly half the total solids measured in the leachate. The COD and BOD in the leachate rose to high levels and gradually fell after a 10-day period. However, this period is much smaller than recorded for landfills (Fan et al. 2006). There is thus a significant loss of COD/BOD lost in leachate. This explains to some extent the large change in organic C and nitrogen in digested fruit waste. It is clear from the above that in the case of fruit wastes the conventional windrow composting needs to be accompanied by treatment options for the leachate. A significant proportion of the leachate was released within 10 days after the initiation of composting process.

It was observed that only fruit wastes and leaf litter were found in proportions and quantities that suit its use on at-site for biogas generation. The BMP of fruit and vegetable wastes have been studied extensively and hence only BMP of leaf litter was determined and reported. The biological methane potential of collect-

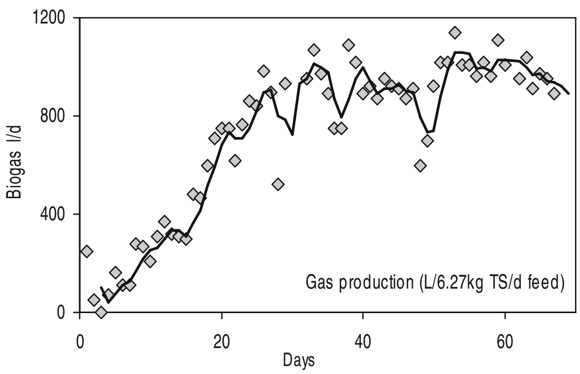

Fig. 6 Biogas production pattern from dry leaf litter collected and fed to a 6 m^3 total volume plug flow biomass based biogas plant designed to produce about 3 m^3/day biogas. The *line* connecting is the moving average determined to show the pattern

ed leaf litter has not been determined extensively. The fallen leaves undergo decomposition almost immediately. The biogas potential residual is therefore quite uncertain. Understanding the BMP of such material is tackled in the following way. Firstly the BMP of the major tree leaves contributing to the leaf litter has been determined in the laboratory for leaves harvested fresh and dried. Second the leaf litter collected was fed to a 6 m^3 total volume plug flow biomass biogas plant (Jagadish et al. 1998) and the biogas production rates from this was determined by measuring the gas collected in an inverted drum. The BMP of leaf material is presented in Fig. 5. All freshly harvested leaves (except Mimusops) showed a BMP level >400 ml/g TS fed. Leaves of Ficus species and mixed leaf biomass showed a rapid conversion to gas and had high methane content. This suggested good decomposition pattern that is usually not inhibited by VFA accumulation within. The other four species showed a short period of reduced gas production between 15–40 days and subsequently the gas production picked up along with increased methane content. These two suggest the potential for VFA flux induced inhibition of methanogenesis at higher feed rates and the need to ensure appropriate solutions to overcome these fluxes. The daily biogas production rate from an average daily feed rate of 6.27 kg of leaf litter is presented in Fig. 6. This showed that such operations required a start up time of about 30 days after which steady state was achieved. However, in place of about 1.8 m^3 gas/day about 1.05 m^3/day was recovered resulting in an average gas production of about 170 l/kg TS fed. From this it is observed that allowing leaf litter to accumulate on the ground for long and then subjecting them to anaerobic digestion loses about 50% of the gas production potential and nearly 60% of the BMP is not recoverable. To ensure higher recovery alternative management techniques need to be developed. Thus biogas from dried leaf litter collected and stored in open spaces could enable operation of anaerobic digesters for biogas and compost and is an attractive idea for managing garden wastes in many urban areas.

Conclusions

Micro-composting or micro-scale processing of organic fraction of municipal solid wastes (and its components separately) have become attractive or necessary in many locations where there is poor access to a SWM involving source segregation as well as a daily collection and transport of fermentable components of MSW. There are locations within urban areas where single components of OFMSW can be collected in appreciable quantities to evolve micro-treatment processes. In this manner, bagasse (from sugarcane juice vendors), paddy straw, leaf litter and paper wastes can be subject to microcomposting using an aerobic process. However, fruit wastes and leaf litter permit anaerobic digestion to biogas and compost. This latter option can easily prevent spread of insect vectors and makes the effort sanitary and safe. Most tree species contributing to leaf litter are found to have the potential to be converted to biogas. However, methods need to be improved firstly in their collection and storage without suffering extensive decomposition and second to convert such a floating mass in conventional biogas reactors. Leaf litter that has been collected intermittently decompose slowly and show lower biological methane potential and biogas plant using them needs to be operated at higher feed rates. During micro-composting fruit wastes produce a large quantity of leachate and corresponding COD/BOD that attract insect vectors. Alternatives such as leachate conversion etc. need to be developed. An effective alternative is to use anaerobic digestion and convert it to biogas.

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References

Aus-AID (2002). *Overview report on environmental sanitation vol 1. Solid waste*. Bangalore, India: Australia-India Development Cooperation.

Bari, Q. H., & Koenig, A. (2001). Effect of air recirculation and reuse on composting of organic solid waste. *Resources, Conservation and Recycling, 33*, 93–111.

Barrington, S., Choiniere, D., Trigui, M., & Knight, W. (2002). Effect of carbon source on compost nitrogen and carbon losses. *Bioresource Technology, 83*, 189–194.

Barrington, S., Choiniere, D., Trigui, M., & Knight, W. (2003). Compost convective airflow under passive aeration. *Bioresource Technology, 86*, 259–266.

Centre for Sustainable Technologies (2005). *Report on processing facility for Chikkamagalur city, Karnataka*. TIDE-CST, Indian Institute of Science, Technical report, July 2005, p5.

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

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.), *Proceedings of the 4th international symposium on anaerobic digestion of solid wastes. DTU, Copenhagen Aug 31–Sep 02, 2004, vol. 1* (pp. 277–284). International Water Association.

Chanakya, H. N., Ramachandra, T. V., & Vijayachamundeeswari, M. (2006). *Anaerobic digestion and reuse of digested products of selected components of urban solid waste*. CES Technical report No 114, Centre for Ecological Sciences, Bangalore.

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.

Daskalopoulos, E., Badr, E., & Probert, S. D. (1997). Economic and environmental evaluations of waste treatment and disposal technologies for municipal solid waste. *Applied Energy, 58*, 209–255.

de Bertoldi, M., Vallini, G., & Pera, A. (1983). The biology of composting: A review. *Waste Management & Research, 1*, 157–176.

Fan, H.-j., Shu, H. T., Yang, H. S., & Chen, W. C. (2006). Characteristics of landfill leachates in central Taiwan. *Science of the Total Environment, 361*, 25–37.

Garcia, A. J., Esteban, M. B., Marquez, M. C., & Ramos, P. (2005). Biodegradable municipal solid waste: Characterization and potential use as animal feedstuffs. *Waste Management, 25*, 780–787.

Gotaas, H. B. (1956). *Composting – Sanitary disposal and reclamation of organic wastes*. Geneva: World Health Organization.

Hui, Y., Liao, W., Su, F., & Gang, H. (2006). Urban solid waste management in Chongqing: Challenges and opportunities. *Waste Management*.

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.

Karnataka Urban Infrastructure Development Finance Corporation, KUIDFC (2003). Detailed project report for solid waste management in Chikkamagalur city (Report in conjunction with MDPC, DHVC and Communities Group International USA, p. 31).

Lopes, W. S., Leite, V. D., & Prasad, S. (2004). Influence of inoculum on performance of anaerobic reactors for treating municipal solid waste. *Bioresource Technology, 94*, 261–266.

Rajabapaiah, P. (1988). *Energy from Bangalore garbage – A preliminary study. ASTRA Technical Report*. Centre for Application of Science and Technology to Rural Areas, Indian Institute of Science, Banagalore 560 012.

Rajabapaiah, P. (1995). Waste management for IISc. *ASTRA Technical Report*. Centre for Application of Science and Technology to Rural Areas, Indian Institute of Science, Banagalore 560 012.

Ramachandra, T. V. (2006). *Management of municipal solid wastes, commonwealth of learning, Canada*. New Delhi: Capital Publishing Company.

Sandec (2002). Composting as source of income for the urban poor. *SANDEC News, 5,* 7–8.

Sathishkumar, R., Chanakya, H. N., & Ramachandra, T. V. (2001). *Feasible solid waste management*. CES Technical Report No 86, Centre for Ecological Sciences, Bangalore.

Sharma, V. K., Canditelli, M., Fortuna, F., & Cornacchia, G. (1997). Processing of urban and agro-industrial residues by aerobic composting: Review. *Energy conservation and management, 38*, 457–478.

Slater, R. A., & Frederickson, J. (2001). Composting municipal waste in the UK: Some lessons from Europe. *Resources, Conservation and Recycling, 32*, 359–374.

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

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

Yedla, S., & Parikh, J. K. (2002). Development of a purpose built landfill system for the control of methane emissions from municipal solid waste. *Waste Management, 22*, 501–506.

Zurbrugg, C., Drescher, S., Rytz, I., Sinha, A. H. M. M., & Enayetullah, I. (2005). Decentralised composting in Bangladesh, a win–win situation for all stakeholders, Resources. *Conservation and Recycling, 43*, 281–292.