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Techno-economic Potential for Value Added Products from Digestion of Urban Solid Wastes and Rural Residues

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ABSTRACT

India is urbanizing rapidly accompanied by a gradually increasing rate of municipal solid waste (MSW) production that ranges from 200-500 g/cap/day. The domestic, restaurant, garden and community eatery wastes constitute nearly 90% of the total MSW produced in a city and comprises of >85% decomposable or fermentable components. Decentralized anaerobic digesters are an attractive option that reduces transportation costs and C-footprint but is impeded by difficult to digest components such as banana leaves, stems etc – about 15-20% of the total fermentables of USW. This situation requires simultaneous fermentation of banana leaf/stem along with food wastes. Plug flow approaches allow multi-feed digestion without preprocessing and such an option has been tried out for banana leaf. The feasibility and techno-economic potential of multi-product anaerobic digesters using banana leaf is examined. The operation and function of a 50 kg/d plant (equivalent to a large household plant) is described here. The study quantifies recovery of four value-added products (VAP) sensible to this option and describes the processes required, estimates their value and projects commercial viability – to finally make a case for decentralized, commercially run zero waste option for this type of waste – predominant in south India.

Keywords: anaerobic digestion, biogas, banana leaf biomass, banana leaf fibre

Abbreviations: BMP, biological methane potential; **GC**, gas chromatography; **GHG**, green house gas; **MSW**, municipal solid waste; **N**, nitrogen; **OC**, total organic carbon; **PFR**, plug flow reactor; **SRT**, solid retention time; **TKN**, total Kjeldahl nitrogen; **TP**, total phosphorus; **TS**, total solids; **VAP**, value-added product

INTRODUCTION

Most metros in India produce over 200-500 g/cap/d of municipal solid waste (MSW). A major constituent of this is organic waste (72%; Chanakya and Saratchandra 2008) of which banana leaf 10%. The domestic, restaurant, market, garden and community eatery wastes constitute over 90% of the total MSW produced in a city and comprise of >85% decomposable components (Chanakya *et al*. 2010). Banana leaf is also used daily at homes, in temples, at community eateries (*choultries*), restaurants, etc. as a traditionally used disposable plate and also to pack cooked food and other perishables such as fruits, flowers, etc. As a result a lot of banana leaf is found in urban solid wastes. In rural areas, when banana is harvested and the land is cleared for starting the next crop, between 25-100 t/ha/year of leaf, rachis and pseudostem is discarded (Lee *et al*. 2010). These discarded banana residues degrade slowly, both in the agricultural field and as a significant component of MSW being composted or when subject to open dumping (Shah *et al*. 2005). The magnitude of this problem is only expected to rise higher and manifest to a larger extent in popular places of pilgrimage like Tirupati, Kollur, Trichy, etc. where banana leaf is used as disposable plates. It is therefore sensible to set up decentralized treatment plants such that these wastes need not be transported over great distances as it is done today – greatly avoiding the need for transportation or large landfills. This potentially lowers fossil fuel C-footprint, methane emissions and operation costs in poorly turned windrows or open dumps (uncontrolled landfills; Chanakya 2011).

Under normal conditions of disposal of domestic and hotel wastes, banana leaves decompose slowly and therefore poses a problem for which a sustainable and environment friendly solution needs to be found (Shah *et al.* 2005). In a situation where fibre, biogas, pest repellant and compost can be extracted from such discarded leaves, it serves as an incentive to avoid banana leaves entering waste-streams and significantly reduce the problem of poorly decomposed MSW. In rural India too, this product would make the overall farming more remunerative and a lot more environment friendly through multiple stages of reuse/recycling.

MSW disposed in open dumps and landfills tend to produce appreciable quantities of methane, a green house gas (GHG; Banik *et al.* 1993). All over the world efforts are underway to reverse the trend of decomposable wastes entering landfills (Mshandete *et al.* 2008). Aerobic composting of banana leaves along with food waste at the source level has also posed appreciable problems. Food wastes are rapidly converted to volatile organic acids and such piles of wastes become odoriferous, unaesthetic and attractive to insect vectors and pose health risks (Chanakya *et al.* 2010). On the other hand, anaerobic digestion has a potential to provide four products from the processing of banana residues namely fibre (commercial product), compost (recycling for sustainability), biogas (local uses as well as a commercial product) and digester liquid (recycling for fish production or as a pest repellent; Chanakya *et al.* 2009).

Leaf biomass from typical herbaceous plants contains 30-40% lignocellulosic material that digests slowly under anaerobic conditions. Most leaf biomass feedstocks are known to produce tiny biogas bubbles that adhere to the digesting leaf during anaerobic digestion. This phenomenon makes them to float on the digester liquid and to quickly become dry and bring down the decomposition rates to near zero (Chanakya *et al.* 1997). Efforts to digest large quantities of banana leaves (and other biomass) in typical animal dung fed anaerobic digester designs have not been successful in the field because banana leaves and similar feedstocks

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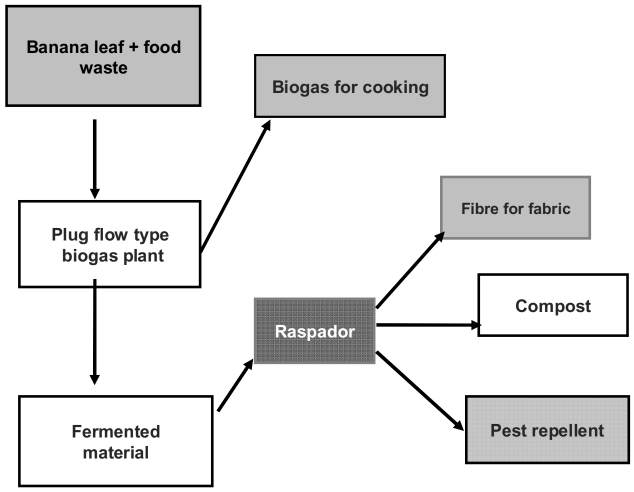

Fig. 1 Material flow and recovery using a banana leaf-fed PFR biogas plant.

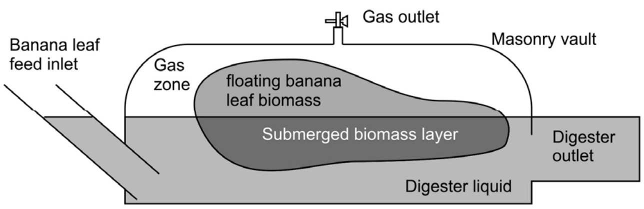

Fig. 2 Longitudinal section of a plug flow bioreactor.

float, tend to dry, form a scum and make recovery of digested feed not possible just as predicted above (Chanakya *et al.* 1997). This therefore requires novel method of anaerobic digestion that would firstly allow uninterrupted fermentation as well as digest the leaves to yield fibre, biogas, pest repellent and compost – making it economically attractive.

Process

The process includes fermenting of banana leaf along with food waste in a plug flow type biogas plant for a specific retention time set for optimum fibre recovery (**Fig. 1**). Biogas recovered is used for cooking purpose or as liquefied petroleum gas (LPG) substitute. Fermented banana leaf is removed from the digesters and fed into a raspador in order to remove the loosely adhering tissue material form the fibre (**Fig. 1**). The leaf tissue that separates from the fibre is later used as compost. The fibre extracted is dried and can be used for making fabric after some processing. The liquid extracts of anaerobically digested leafy material are popular as a nutrient liquid and as a pest repellent (Zhang *et al.* 2002; Chanakya *et al.* 2004).

This study attempted to determine the fermentation properties of banana leaf so as to determine the ideal fermentation conditions required to extract fiber, biogas and compost from a plug-flow biogas plant and thereby get the best outputs to make the overall process sustainable.

MATERIALS AND METHODS

Banana leaves along with food waste were fermented in a typical biomass fed plug flow type biogas plant developed by CST-ASTRA (**Fig. 2**). Banana leaf samples packed in nylon bags were fermented in the outlet of the PFR (plug flow reactor) reactor to ensure controlled recovery of the fermenting leaf at specific retention time in the digester. The outlet chamber is wide and rich in microflora and therefore it permitted reasonably uniform fermentation conditions that could be standardized.

Fermentation procedure

Fifty grams of banana leaves with plastic tags were fermented in nylon mesh bags placed in fermentor outlet in order to obtain at least 8-10 g residue for analysis after a 30 d SRT (solid retention time). Thirty six such bags (9 time periods, 4 replicates) were used in all. The plug flow reactor was operated normally with daily leaf based feeding (1 kg TS/m^3/day). The temperature of the liquid in the outlet of biogas plant varied between 18 and 24°C. The time intervals chosen for sampling were based on a pilot study conducted to record sufficient levels of change (0, 3, 6, 10, 14, 17, 20, 24, 27 and 30 days). The original fresh weight and wet weight of each retted bag in a unit was recorded. From one retted unit of four replicates, contents of 2 replicates were taken for fibre extraction and the contents of the other 2 replicates were oven dried at 90°C for 24 h to analyze total solid contents and composition. These oven dried samples were powdered fine in order to carry out various analytical procedures and determination of composition. At different stages of fermentation, the samples extracted were monitored for total organic carbon (TOC), total Kjeldahl nitrogen (TKN) and total phosphorus (TP) were measured using standard procedures (APHA 1975). The overall mass distribution in the process was thus monitored.

Fibre extraction

The fermented leaf samples were blended for 2 min at low speed in a laboratory blender along with 100 ml of water. The water remaining after blending containing the residual matter (compost residue) was dried in an oven at 90°C for 24 h for the water to evaporate and the residue was analyzed later for its constituents. The wet weight of fibre was recorded first. The fibres were then oven dried at 90°C for 24 h and their dry weight was recorded.

Physico-chemical analysis

Gas production potential was determined by biological methane potential (BMP) assay (Chanakya *et al.* 2009). Gas composition was determined using a gas chromatograph (GC) using a Porapak-Q column (Mayura Analytical, Bangalore) at 40°C.

RESULTS AND DISCUSSION

Efficiency of the process

This decomposition process was studied for a period of 30 days based on the extractability of fibre from banana leaves in a pilot study. Mass distribution at various time intervals of fermentation expressed in terms of fibre, total dry matter, residue after fibre extraction (compost residue), etc. are shown in **Fig. 3**. The decomposition of banana leaves showed an initial lag phase of 3d for the retting to start during which no measurable loss in mass of feedstock was found or biogas production observed (discussed later). This pattern of degradation exhibited by banana leaf in anaerobic digester was different from most other leaf biomass feedstocks such as cabbage (*Brassica oleracea* var. *capitata*), paper mulberry (*Broussonetia papyrifera*), jackfruit (*Artocarpus integrifolia*), etc. wherein maximum degradation occurred in 3-10 days of digestion (Chanakya *et al.* 1997, 2009). While these traditional feedstocks such as vegetable and fruit wastes turned into pulpy mass within 3-10 days of digestion, this phenomenon was not observed in banana leaf. This is one of the key differences observed in the pattern of decomposition and is important in the design of the digesters. The rate of decomposition was found to be high from 3-17 days wherein about 59% of the TS were lost from the digesting mass during this period (**Fig. 3**). From 6-17 days, there was an increase in fibre recovery (11-18%). However, the quality of fibre recovered during this period was poor and the extracted fiber mass contained a lot of broken fibre and had leaf tissue partially adhering to the extracted fibre thereby making it unsuitable for yarn making or spinning. Between a fermentation time of 20 and 30 days, the residual TS reduction was low (decreasing only by

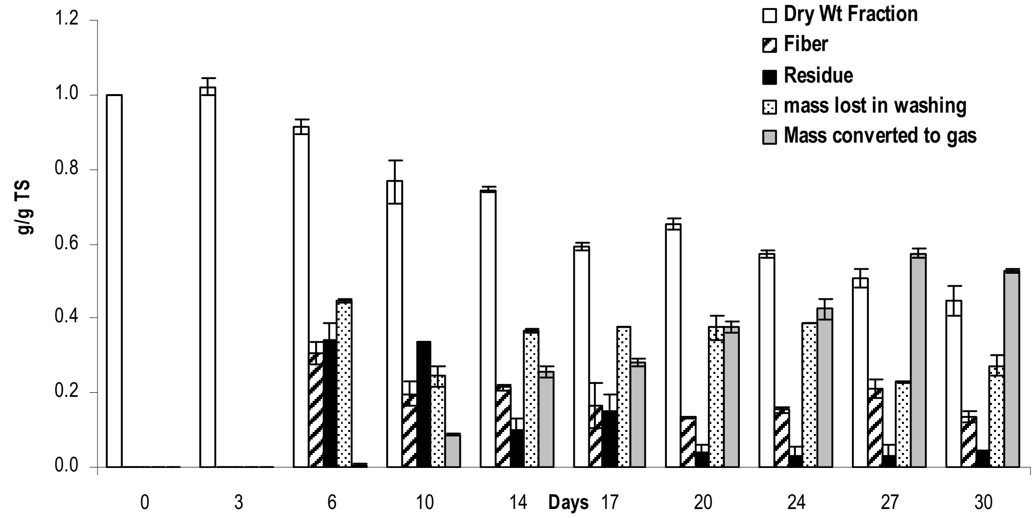

Fig. 3 Mass distribution and recovery of the fibre, biogas and compost (g).

17.6% from 62.7 to 44.1% in 10 days). However, in spite of only a low level of observable TS loss due to fermentation, the quality of the fibre as well as the fiber yield improved significantly. At the 27th day, the quantity and quality as well as the ease with which the fibre was recovered was the highest. At this stage solids recovered as fiber were 20% of the original TS fed to the digester or equivalent to 40% of the TS remaining in the digester.

From this we conclude that under the current conditions of fermentation namely (a) completely submerged in digester liquid (b) undisturbed by daily operation or low digester content mixing conditions (c) temperature regime in the range of 18-24°C, the optimum solid retention time for highest fibre recovery is 27 days. Digesters designed for banana leaf feedstock with fibre recovery option need a SRT of 27 days. The compost obtained on 27 days of fermentation accounted for 5% of the original TS added (**Fig. 3**). This latter observation suggests that the compost recovery by this method would be low (*c*. 5% of the original TS fed) and is unlikely to be an economic and attractive byproduct as is the case for other feedstocks.

TOC distribution

The overall carbon balance was carried out to understand the distribution of organic carbon in the process (**Fig. 4**). The organic carbon fraction breaking down and leaching out from the fermenting banana leaf into the digester liquid or being converted to biogas was low from 0-14 days. During this period less than 20% of the original TOC was used up by the anaerobic bacteria for biogas production. Between 14-17 days there was a spurt in digestion that was found to be repeatable over many replications and repetitions. And in this period of digestion around 41% of the original TOC was used up suggesting the occurrence of a rapid fermentation around 14-17 days (**Fig. 4**). This period showed rapid removal of hemicellulose (12% loss) and a small fraction of lignin (10%, unpublished data). Again from 17-24 days the digestion process slowed showing marginal loss of TOC. The major constituent lost during this period is hemicellulose, cellulose and a small fraction of lignin (unpublished data). The level fermentation achieved at 27th day corresponds to 56% TOC removal – largely as gas.

On 27 days of fermentation when the fibre recovery was optimum the TOC present in the fibre fraction was 14% of the original TOC (**Fig. 4**). The fibre fraction showed relatively high TOC from 6-14 days as the fibre extracted on these days has a lot of leaf tissue adhering to the fibre. The fibre extracted between 17-30 days of digestion had 10-14% of the original TOC. The TOC in fibre remained consistent between 17-30 days of digestion. The level of pith adhering to the fiber gradually fell and remained low after 17 days.

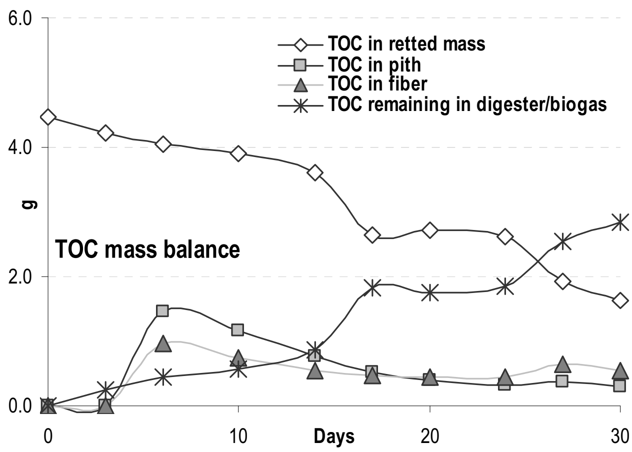

Fig. 4 TOC distribution into 4 fractions during the digestion process.

The TOC in the compost fraction obtained on 6 days of fermentation had 32% of original TOC and showed a decreasing trend till 17 days of fermentation (**Fig. 4**). From 20-30 days of fermentation the TOC content of compost ranged between 6.8-8.7% of the original TOC. On 27 days the period for the best fibre recovery, the TOC present in the compost was 8.3% of the original TOC. For most of the biomass feedstocks it is seen that the optimal SRT or degradation time coincide with the time corresponding to the best recovery of N and organic manure. In this study we see that the optimal digestion time corresponds to recovery of the highest level of fibre and biogas.

TKN distribution

The utility of biogas plant technology is mainly determined by the quantity (and efficiency) of N rich compost produced as well as the gas yields. Therefore TKN balance of the overall process was studied in order to understand the distribution of nitrogen among various components such as fibre, digester liquid and compost and to estimate the efficiency of the overall process in conserving N. TKN content of the fresh undigested banana leaf was 0.7%. The nitrogen content of the fermenting banana leaf biomass showed three rapid removal stages and was seen at specific intervals namely 0-6, 14-17 and 24-27 days. On other sampling dates

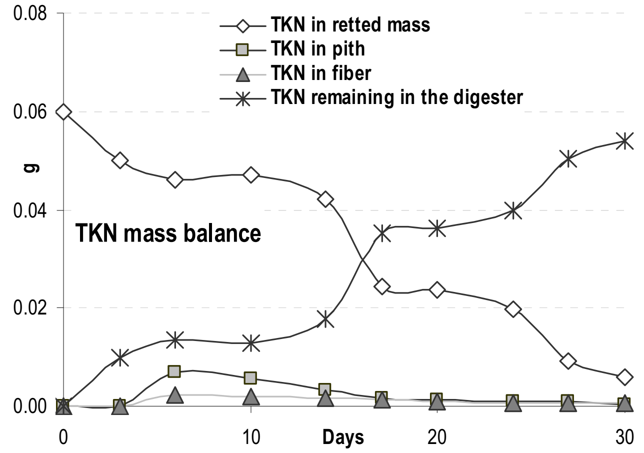

Fig. 5 TKN distribution in the process.

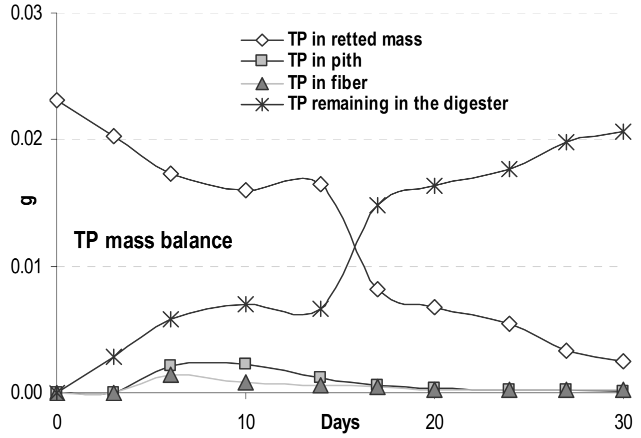

Fig. 6 TP distribution in the process.

N content remained generally constant (**Fig. 5**). The maximum N removal occurred from 14-17 days of fermentation (30% removal in 14d and 60% removal in 17 days). On 27th day of fermentation the TKN present in the fermenting mass was only 15.8% of the original TKN.

The TKN fraction in the extracted fibre was low and decreased from 4 to 1% in 30 days of fermentation (**Fig. 5**). The fibre extracted on 27 days of fermentation had 1.16% of the original TKN. The fibre, one of the main outputs in this process, is a poor reservoir of N and commercial fiber recovery would therefore not reduce recycling of N in the process.

TKN in the compost fraction was also low and ranged from 11% to 0.5% of the original in 30 days (**Fig. 5**). The TKN leaching from the fermenting material was found in the digester liquid. The digester liquid had 84% of the initial TKN on 27 days of the process. This suggests that the compost fraction along with the digester liquid obtained on 27 days needs to be used as fertilizer conserving 90% of the nitrogen. This pattern is unlike most other leaf biomass feedstocks reported so far (Molnar *et al.* 1988). In cattle dung digesters a large part of the N is in the digester residue and only about 15% is found as ammoniacal N in the digester liquid that is potentially lost soon after the digester liquid is allowed to dry. It is observed that 90% of the recoverable N in this feedstock and fermentation pattern is in the digester liquid. This being the case it is potentially a very useful material for fertigation or leaf sprays that have been reported to boost good crop yields (Gunnarsson *et al.* 2006).

TP distribution

Distribution of phosphorus in fermenting mass, digester liquid, fibre and compost was determined (**Fig. 6**). Phosphorus found in the fermenting mass showed a similar pattern to that of TKN. Rapid removal of phosphorus from the fermenting mass happened in three periods corresponding to 0-6, 14-17 and 24-27 days of fermentation (**Fig. 6**). TP content of banana leaf was 0.27%. There was 90% removal of TP from the fermenting mass in 30d. Rapid removal occurred within 17d where 64%% of the original TP. On 27th day, the TP remaining in the fermented banana leaf was 14% of the original TP.

TP content of the fibre fraction was low and reduced from 0.08-0.02% (in fermented mass) in 30 days of fermentation (**Fig. 6**). Fibre extracted on 27 days had 1% of the original TP. Compost fraction also contained low TP and most of it was recovered in the digester liquid. Extraction of fibre therefore does not reduce the recoverable and reusable phosphorus content of the feedstock and most of the original P is extracted into the digester liquid. Digester liquid has 85% of the original TP in 27 days of fermentation (**Fig. 6**). It is therefore important to reuse the digester liquid in order to recover most of the P in the feedstock. It may be noted that the total P, unlike other feedstocks is recovered in the digester liquid fraction. In the case of cattle dung slurries, the maximum P is locked into the undigested solids and very little is found in the digester liquid.

Fibre recovery and biogas production

The efficiency of the process to recover biogas as well as the fraction recoverable as fibre and compost was monitored by measuring the TS lost during fermentation process (**Fig. 3**). A recovery of 20% of original TS fed in the form of fibre (**Table 1**) and 5% as residue suggest 55-60% conversion efficiency. Fibre recovered on 27d has been found to be the best in terms of quantity and quality. The length of the fibre was found to be between 20-30 cm and quite flexible. Some degree of added chemical treatment has the potential to improve the color and luster making it attractive for fabric purposes. Other mechanical proprieties need to be determined in subsequent research. Fibre recovery did not improve between 14 and 24 days of fermentation. The recovery then increased to its maximum on 27 days (**Table 1**). The increase in fiber recovery coincides with the removal of the hemicellulose and lignin fraction of the banana leaf (unpublished on-going studies). The quality of fibre gradually improved from 14 to 24 days of fermentation and the extent of pith and leaf tissue adhering to the fibre gradually reduced. These fibres extracted before 27d SRT were thus considered unacceptable for further use for yarn or fabric. Extractable fibre on 27th day of fermentation was about 20% of the original TS and 40% of the material remaining in the fermentor.

In this study, the decomposition was carried out in an undisturbed part of daily fed biomass based biogas plant (Chanakya and Moletta 2005). Biogas production during this process could not be measured simultaneously. We could therefore assume that in such a continuous process a 55-60% conversion to gas is possible. The digested mass remaining in the digester, although has very low TS is high in moisture content and could sometimes weigh 70% of the original wet mass. This paves way for a need to dewater the digested feedstock prior to further use in order to extract the maximum level of nutrients locked in the digester liquid. This in turn suggests a need for a net daily addition of water as some moisture is picked up by the digested mass. Once again this is unlike other green feedstocks where following their fermentation in a biogas digester there is a net moisture surplus that needs to be removed from the digester (Chanakya and Jagadish 1998; Chanakya and Moletta 2005).

In this study we have used BMP to estimate the gas production potential of banana leaf. The result of BMP assay at 1% TS concentration is presented in **Table 1**. In the case of banana leaf biogas production was 450 ml/g TS. The biogas production potential of banana leaf till 30 days SRT was

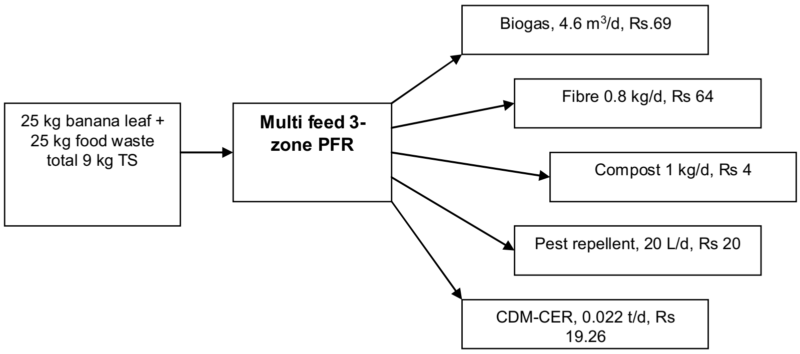

Fig. 7 Economic analysis of the process. Total benefit (Rs 276/d) = [cost of transportation + costs of benefits listed above] – [costs of added Opex].

Table 1 Biogas production, composition and fibre recovery.

Days	Biogas (ml)	Methane %	Carbon dioxide%	Fibre fraction of residue dry wt	Fibre fraction of original dry wt
0	0	0	0	0	0
3	18	9	17	0.39	0.39
6	17.2	27	26	0.25	0.23
10	25.2	53	39	0.23	0.17
14	29	57	40	0.27	0.2
17	33	60	42	0.28	0.16
20	25	60	42	0.27	0.17
24	18	60	42	0.3	0.15
27	10.4	60	42	0.4	0.2
30	12	57	30	0.32	0.14

350 ml/g TS when fermentation was sufficient for fibre extraction. A biogas production potential of 350 ml/g TS, as seen above, has been found with a wide variety of leafy biomass feedstocks e.g. grass, *Artocarpus* (Chanakya *et al.* 2008), rice straw, sugarcane trash, *Parthenium*, surgarcane bagasse, etc. (Chanakya *et al.* 1997). However, it is known that continuously operated biomass biogas plants produce biogas at a rate that is more rapid than determined in a batch mode by BMP assay for any particular fermentation period. There is therefore a potential to extract a higher than the equivalent BMP rate of 350 ml/g TS (35 days SRT) could be achieved in continuous fermentation. The biogas composition from banana leaf on 27d was 60% methane and 40% carbon dioxide (**Table 1**).

Economic analysis

The economic analysis of a 50 kg/day (equivalent to a large household plant) feeding biomass based biogas plant is shown in **Fig. 7**. The cost of construction of a 50 kg/day feeding plant is INR 35,000 (2011) which could be recovered within four months of continuous operation. A 50 kg/day plant (25 kg food waste and 25 kg banana leaf) would yield 4.6 m^3 biogas of value INR 69, 0.8 kg of fibre of value INR 64, 1 kg anaerobic compost of value INR 4, 20 l of pest repellent and plant nutrient liquid of (notional) value Rs 20 and carbon emission reduction of 0.022 t of value INR 19.26. Therefore the total cost benefit of operating such a plant would be INR 276/day.

CONCLUSIONS

Banana leaf along with food waste, a major part MSW from hotels and eateries, was subject to anaerobic conditions in a plug flow biogas plant for simultaneous production of fibre, biogas, pest repellent and compost. A 50 kg/day biomass biogas plant gave a total benefit over cost of Rs 276/day where in 20% of the TS was recovered as fibre, 60% as biogas and 20% as compost while the major nutrient recovery occurred in the digester liquid and not the digested solids as is normally found

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