ANAEROBIC DIGESTION AND REUSE OF DIGESTED PRODUCTS OF SELECTED COMPONENTS OF URBAN SOLID WASTE

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Contents

Abstract

Urban solid wastes (USW) pose a major threat in terms of disposal in the developing countries. By virtue of having >53% putrescibles, it has been considered as a suitable feedstock for biogas plants for generating renewable energy (Kayhanian, 1995). In this study, 11 feedstocks of USW origin (mixed fruit wastes, waste paper, agro residue used in packaging, aquatic weeds from urban water bodies) were subjected to anaerobic digestion and their decomposition properties were studied. The gas production pattern and potential problems of fermentation were monitored using a modified biological methane potential (BMP) technique. Results showed that most feedstocks studied had a good biogas production potential except water hyacinth roots. They also had high CH_4 content suggesting amongst others, a balanced fermentation. Paddy straw (600mL/gTS), water hyacinth (625L/kgTS) and sugarcane trash (600mL/gTS) were better among the feedstocks tried. Many of these feedstocks with high BMP showed lower daily gas production and volumetric efficiencies under SSB mode of fermentation in laboratory trials. A fed batch approach to anaerobic digestion in solid-state stratified bed reactor (SSB) was followed for a 70d-fermentation period. More than 50% TS degradation has been achieved with green feedstocks compared to the dry feedstocks. In the presence of a rapid VS reduction, lower gas production was often achieved. (i.e. the gas production observed was well below levels of VS destruction). These low gas production rates in all the feedstocks tried appear to be due to inadequate colonization of and acid conversion of older biomass by methanogens. This therefore requires a further study to determine the reasons for such a low gas yield with respect to rapid VS reduction occurring without resulting in gas production. The anaerobically digested residue was used as methanogenic support to digest liquid effluents. The suitability of these anaerobically digested biomass feedstocks as biofilm support for re-use of digested material in wastewater treatment examined in down flow fixed bed reactor (DFFBR) mode. For this part of the study three reactors packed with bagasse, mixture of bagasse and biomass and reticulated PVC spirals were studied for their property to decompose the large quantities of soluble organic matter for a 100-day operation period. Rapid fluctuations in the gas production and VFA build up suggest the requirement of proper start up. In spite of these abnormalities, packed bed reactor with mixture of bagasse and biomass possess 52.8% COD reduction of synthetic wastewater. Bagasse and PVC reticulated spirals showed 49.5% and 49.2% COD reduction levels, respectively.

Chapter 1: Introduction

In general, the term ‘waste’ implies to a substance, which has no longer any economic value. The composition, nature and properties of wastes depend largely on the source from where it is generated. For the purpose of classification, wastes in general can be subdivided on the basis of its physical state /nature (solid, liquid, gaseous) or on sources (urban and rural) or even nature of origin – agro wastes, industrial wastes, trade wastes, domestic wastes, etc. All these classifications are however, interdependent. This study focuses on urban solid wastes. With the progress of civilisation, the solid wastes generated and related problems have become more complex.

Waste disposal and pollution are inextricably linked. The term pollution describes both the act of polluting and the consequences of that act. Waste describes unwanted residues that are usually perceived to be of negative value. Pollution can be defined as “the introduction into the natural environment by humans the substances, materials or energy that cause hazards to human health, harm to living resources and ecological systems, damage to structures and amenities or that interfere with the legitimate uses of the environment” (Braber, 1995). It is implicit in the definition that pollution only describes situations where unwanted effects occur. The majority of waste disposal situations involve pollution of one kind or another. Thus the solid wastes one of the serious problems in developing countries situations need eco-friendly treatment options. This has become a major environmental issue in India. The quantity of waste generated per capita is estimated to increase at a rate of 1-1.33% annually in India (Shekdar, 1999). This is largely because of rapid population growth and economic development in the country. Thus there have been significant increases in USW generation in India during the last few decades. This enormous increase in solid waste generation will have significant impacts in terms of the land required for disposing this waste as well as on methane emissions. The burden that the increase in solid waste generation would impose is evident from the fact that the cumulative requirement of land for disposal of USW in India would amount to around 1400 km^2 by 2047 (Singhal and Pandey, 2001). Solid wastes generation, urbanization and population growth are highly inter-related and will compete in the process of land acquisition. Improper waste disposal practices in the past have created several problems as well as aesthetically unpleasant sites. Two problems are foremost in India and in the other developing countries:

- Absence of adequate dumping sites and
- The absence of appropriate primary treatment of USW.

The sustainable option thus lies in the reuse of these wastes by non-polluting and environmentally benign technologies while simultaneously deriving economic and material benefits in the process. One important option for energy recovery is anaerobic digestion. The organic fraction of USW (OFUSW) may be digested anaerobically to produce methane rich biogas and nitrogen rich compost and these can be used for domestic and commercial purposes.

There have been many attempts to carry out such anaerobic digestion in laboratory, pilot and field scale plants (Mata-Alvarez., 2000, Chanakya, 1998, Gunaseelan,1994, Sharma,2000). In all the cases, the need for a simple technology alternative has been the major concern. Solid waste on account of its organic fraction has a large energy potential (20-25MJ/m^3 - Braber, 1995) and is renewable. The oil crisis came to light in the year 1973 and the consequent energy price rises have brought considerable interest in energy from USW. Biogas production from OFUSW is an attractive option. because,

- It can process dry and moist feeds together.
- It does not require thermal or chemical pretreatment.
- It does not require pure cultures or sterile conditions (contamination with other microbes does not affect the process).
- The product methane is of high quality and is easily recovered from the reactor.
- The product methane is commonly used as an energy form throughout the world.

It is important to note that USW has often fermented in simple fermenters resembling that used for cattle-dung slurries. Digesting OFUSW in such digesters has always posed several technological and operational problems. They may be short-listed as:

- Significant time, energy and machinery wasted in the pretreatment procedures - a pre-requisite to slurry-based conversion to biogas.
- Most biomass feed stocks release a large volatile fatty acids flux (20-30%VS) in the first 3 days of decomposition, which is responsible for methanogenic inhibition.
- Problems of floating and scum formation when using OFUSW as the feedstock.
- The low density and buoyancy of leafy portions of OFUSW causes difficulties in feeding as well as removal of spent material.
- The buoyancy of digesting material pushes the biomass fraction above the liquid level, it dries and gradually ceases to decompose. Biogas bubbles adhering to digesting biomass, which lifts the biomass even more out of the liquid, further enhance the buoyancy.

These above problems have inspired the development of small scale and decentralized OFUSW based biogas plants. In many of the USW biogas plants developed in different parts of the world, slurry based reaction fermentor design and reactor systems are used. USW is often rendered into a thick slurry and fermented to biogas (Chanakya *et al*., 1992, 1993). The solid-state stratified bed reactor (SSB) has been developed and used to treat wide variety of solid wastes to recover the energy. The SSB mode of fermentation is easy to maintain, escapes scum formation, obtains higher gas production rates, etc. The SSB reactor system also works as a "high rate land fill". Such fermenters are expected to obviate the need for stage separation, make the digestion of wastes very simple and can use a large range of feedstocks without the need to change process parameters. The present study deals with the decomposition properties and gas production pattern of different biomass found in USW using SSB fermentation process. The characteristics of digested biomass in terms of TS/VS lost gas production pattern and conversion efficiency was also studied.

1.1. Objectives:

The present work is designed to be carried out at a laboratory level with a view to improve the understanding of the decomposition pattern and fermentation properties of the key components of USW found on the IISc campus as well as in Bangalore. The outcome is meant to confirm some of the earlier findings as well as to verify the gas production rates obtained earlier. Finding another use for digested biomass increases the viability of anaerobic digestion projects. In this context the potential and feasibility of digested USW to serve as a support for methanogenic biofilm in treatment of low strength wastewater is examined. The main objectives are to study:

i.) Feasibility and potential of anaerobic digestion of a few selected components of USW
ii.) The fermentation pattern of selected components of USW in a SSB fermenter.
iii.) Reuse of the anaerobically digested feedstock from a SSB fermentor as a support material for methanogens in the treatment of liquid waste under down-flow fixed bed (bio-film) reactor.

Chapter 2: Review of literature

In this review, the first section focuses on the availability, composition and the utilization of the urban wastes as an alternative feedstock for biogas plants. Second section deals with the principles and process details of anaerobic digestion of these materials to energy (biogas). The third section deals with the technology involved in the biogas production process, namely biogas production from USW. In addition, the re-use of anaerobic digestion products, specifically the new applications for digested biomass namely its use as a bio-film support in anaerobic conversion of liquid wastes to biogas.

2.1. USW – sustainable energy resource for future

Brunce and Ernst (1986) define USW as "*the materials collected by the municipality (or) by authorized organization*". Similarly Cailas *et al*., (1996) classify USW as the residues coming from households, commerce, and institution and finally it represents "*all those generated by the activities of the community*" (Buenrostro *et al*., 2001).

2.1.1. Problems from illegal disposal of USW

2.1.1.1. Emission of toxic gases

For a long time USW components have been burnt in open peri-urban (rural – urban) tracts with a view to make treatment and disposal inexpensive. It is burnt either as roadside heaps or at dump sites to reduce waste volume and/or to recover the recyclable materials (Srinivas *et al*., 2003). Open burning of household wastes is often reported in developing countries (Lemieux *et al*., 2004). Such burning also increases annual emissions of green house gases (Sinha, 1997). Such situations emit many toxic chemicals and gases such as carbonyls in addition to the volatile organic carbonyls, poly aromatic carbonyls (Lemieux *et al*., 2004), which are dangerous to human health. Open burning of many of the plastic components within USW results in carcinogenic substances such as dioxins (Srinivas *et al*., 2003), vinyl-chloride in particular and many other vinyl compounds, CO, CO_2, SO_x, NO_x, tars, chlorinated hydrocarbons, incompletely combusted hydrocarbons and their derivatives, etc. Other than CO_2 and CH_4 in small quantities of other gases are toxic.

2.1.1.2. Proliferation of vectors

Other than open burning, USW is also dumped in shallow layers in unused areas around towns and cities (Chakrabarti, 2003; Hamer, 2003). In India about 90 % of USW is dumped in low-lying areas (TERI, 1998) and only a small fraction (<10%) is intermittently processed in mechanical compost plants (Shekdar, 1999). Shallow open USW dumps are firstly unaesthetic and second create a potential for parasites and pathogen breeding risks. Although USW may not directly carry large pathogen loads they promote the growth, multiplication and establishment of various insect, nematode, annelid, rodent, etc (CPCB, 2000). The example of the city of Surat that had a protracted epidemic of plague as a result of its open USW dumping and in turn supporting a large rodent population is a classic example (Sundaravadivel, 2000, Venkateshwaran, 1994).

2.1.1.3. Green house gases emissions

The problem of haphazard USW dumping (as also burning) has been growing at an alarming rate. Shallow open dumping is implicated very strongly with emissions of CH_4 and CO_2 – where methane is a GHG gas with a large GHG potential – about 23 times larger than that of CO_2 (IEA, 2004). Over a period of time this open dumping is reported to greatly increase the GHG footprint of cities (El fadel., 2001; Garg, 2002; Aitchison, 1996). Such large GHG footprints require large and protracted clean up efforts. The methane emissions are reported to last many years (20-50 years) after the material has been dumped (Aitchison, 1996) and thus the clean up costs are likely to be very high as well (Gupta *et al*., 1998)

2.1.2. Origin of USW components

The type of waste and its nature depends largely on its source. The sources of urban wastes include institutions, commercials, parks and gardens, residential areas, and construction and demolition sites etc., (CPHEEO, 2000; Kumar, 2001). A study of the source of USW plays an important role since the source of generation is often the best place to segregate the waste material for reuse, recycling and treatment (CPHEEO, 2000). Buenrostro *et al*., (2001) made an attempt to classify the sources of USW. In this study, USW is conceptualized on the solid waste generated within the territorial limits of a municipality independently of its source of generation. Grounded on this assumption, and based on the economic activity that generates a solid waste with determinate physical and chemical characteristics, a hierarchical source classification of USW is suggested. Thus a connection between the source and type of waste is established. This classification enable the assessment of the volume of USW generated and provides 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). In selecting and designing the waste processing system and disposal facilities, the knowledge of the composition of USW is essential (CPHEEO, 2000).

2.1.3. Generation rate and future scenario

The quantum of solid waste generated in the country is increasing day by day on account of its increasing population and changing lifestyles. USW generated in the city increased from 3200 to 5355 tpd in this same period - registering a growth of around 67% (CPCB 2000). On the other hand, the daily per capita waste generated in India ranges from about 100 in small towns to 500g in large towns (NEERI, 2001) also results in the elevation of its quantity at the rate of 1.0-1.33% annually (TEDDY, 2002). A study conducted by the CPCB, (2000) in country estimates that waste generation from 48 Mt in 1997 is expected to increase to 300 M tpd by 2047 (490 - 945g per capita). This enormous increase in solid waste generation will have significant impacts in terms of the land required for disposing this waste as well as on methane emissions. The burden that the increase in waste generation would impose is evident from the fact that the cumulative requirement of land for disposal of USW in India would reach around 169.6 km^2 by 2047 as against 20.2 km^2 in 1997 (CPCB, 2000). Hence it is very clear that solid waste generation and population growth are highly competitive in the process.

2.1.4. Factors affecting composition

The composition of the waste depends on a wide range of factors such as food, food habits, cultural traditions, lifestyles, climate and income etc (Deepa *et al*, 2002, Somashekar *et al.*, 2002). Daskalopoulos *et al*., (1998) showed that the population and mean living standard of the country are the two main parameters affecting the annual quantity and composition of the USW generated. Because USW arises as a direct consequence of human activities, the population of a country has been chosen as the first major parameter determining the quantity of waste generated: more the people living in a country, the more waste produced was clearly seen in Table 2.1. The mean living standard (refers to the quality and quantity of goods available to the people) of the population of a country is the second major parameter that can be related to the rate of USW generation. It indicates the ability of the population to consume goods and products and therefore generate waste.

Table 2.1: Status of urban solid waste generation in metro cities:

City	**Bangalore**	**Kolkata**	**Chennai**	**Delhi**	**Mumbai**
Area (km^2)	226	187	174	1,484	437
Population (Million)	5.31	6.00	5.00	12.20	12.50
USW generation (Tons/day)	2200	3100	3050	6000	6000
USW/capita (kg/d)	0.41	0.52	0.61	0.49	0.48
Garbage pressure t/km^2	9.73	16.55	17.53	4.04	13.71

Source: TEDDY, 2002

2.1.5. Physical characteristics of USW composition

USW in India can be broadly categorized into organic matter (putrescibles), recyclables and ash materials. Of these three, the organic waste component has remained constant over the past decades at the level of 40% (according to EPTRI, 1995, In India 42.5% was the total compostable matter). The ratio between the other two components has changed in past decades and likely to show further change in the future (Shuchi *et al.*, 1998). This is mostly due to the occurrence of shift in the usage of recyclable materials namely plastic, paper etc (results of rag picking). Within India, there is a vast difference in physical characteristic of garbage generated by different cities is given in Table 2.2. Paper is the main source of variation and increases with increase in the population. In the Indian context, paper waste generally falls in the range of 3-7%, when the waste reaches the disposal site (Asnani, 1998). The plastic and metal contents are lower than the paper content and do not exceed 1% except in metropolises. This is mainly due to the fact that large-scale recycling of these constituents takes place in most medium and large cities (as a results of rag picking). The biodegradable fraction is quite high, arising from the practice of using fresh vegetables in India.

Table 2.2: Physical characteristics of solid waste from some cities in India *(in per cent)*

Cities	Paper	Plastic	Metal	Glass	Ash & Earth	Total Compostable
Calcutta	3.18	0.65	0.66	0.38	34.00	47.00
Delhi	6.29	0.85	1.21	0.57	36.00	35.00
Chennai*	5.90	-	.70	-	16.35	56.24
Nagpur	1.88	1.35	1.33	1.34	41.42	34.81
Bangalore	4.00	2.00	-	1.00	15.00	78.00
Bombay	10.00	2.00	3.6	0.2	45.60	40.00

*A.P. Jain, 1994;

Source; Background information for Conference of Mayors and Municipal Com-missioners, Urban and Industrial Energy Group, Ministry of Non- Conventional Energy Sources, New Delhi,

1. Cited from: http://www.cleantechindia.com/eicnew/techoption/energy.html, Source: India's Development Report, 1997
2. Cited from: http://mospi.nic.in/comenv2000tab7.4.3.htm
3. 20th WEDC Conference, A.P. Jain, 1994

2.1.6. Chemical Characteristic of waste

Knowledge in chemical composition is essential in selecting proper treatment options for the urban wastes. Chemical analysis of Indian wastes carried out by NEERI, India and others has shown that total nitrogen varies from 0.56% to 0.71%, phosphorous from 0.52% to 0.82%, potassium from 0.52% to 0.83% and C/N ratio is between 21- 31%. Hence the calorific value has been found to be ranging between 800 and 1010 Kcal/kg and density of waste between 330 and 560 kg/m^3 (Asnani, 1996).

2.1.7. Comparison of USW composition with other countries

Comparative physical characteristic of solid wastes produced by cities in developed countries versus that found in Indian cities are given in Table 2.3. This table clearly shows that the quantity of waste produced in developing countries is lesser than that in developed countries. Unlike in developed countries, the wastes of Indian cities have a high fraction of degradable organic matter, from 35 to 75%. This fraction of garbage has a high energy potential (Sharma, 2001), compared to only 12% to 15% of U.S.A and U.K (Table 2.3).

Table 2.3: Comparative study of waste production (as percentages of total weight) in India and Developed Countries

Particulars/component	India	UK	USA	Switzerland	Japan
USW generated (kg/day)	0.3-0.6	0.82	2.5	0.6	1.47*
Putrescible waste (%)	31-67	13.00	15.0	14.5	36.9
Paper (%)	0.25-8.75	50.00	54.5	33.5	24.8
Glass (%)	0.07-1.0	6.00	9.1	8.5	3.3
Rags (%)	0.3-7.3	3.00	2.6	3.0	3.6
Plastics (%)	0.15-0.7	1.00	1.7	2.0	2.2
Carbon/nitrogen ratio (C:N)	25-40	44.00	50.0	40.9	NA
Density (kg/m^3)	250-500	128.0	NA	NA	NA

NA-not applicable; * Source: CPHEEO, 2000

2.1.8. **Power production potential from USW in India**

The urban areas of India produce about 30 million t/yr of solid waste (Table 2.4) from household and commercial activities every year. It is estimated that there is a potential of generating about 1000 MW of power (Table 2.5), from MSW in India. Table 2.4 clearly depicts the estimated quantities of different wastes from urban and industrial sectors in the country produced every year (its potential is shown in Table 2.5). Its Energy Recovery Potential (MW_e) is shown in Fig 2.1. If this potential sector be effectively used, it will not only contribute substantially to the overall power generation capacity but will also give a good return on investment, apart from improving the environment. In addition to this, pollution load on environment is reduced.

Table 2.4: Different categories of urban, municipal and industrial wastes and their quantities

Wastes	**Estimated quantity**
Municipal solid waste	30 Mt/y
Municipal liquid waste	12000Mt/y
Food and fruit processing wastes	4.5 Mt/y
Paper and pulp industry wastes	1.6 X 10^3 m^3/d
Press-mud	9Mt/y

Source: TEDDY, 2002

Table 2.5: Power generation potential of urban and industrial wastes (MW_e)

Sources/technology	**Urban and industrial waste**
Units	MW
Potential	1700
Achieved Dec. 2000	15.20
Mar.2003	25.8

Source: TEDDY, 2002-2003

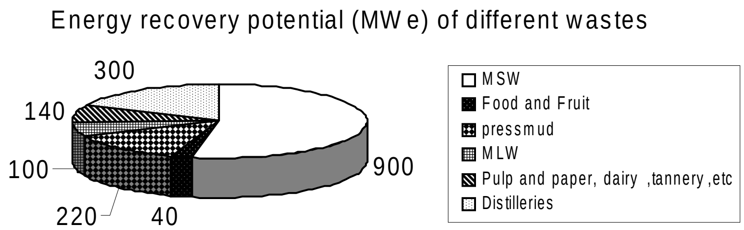


Fig 2.1. Energy recovery potential ($MW_{electrical}$) of different wastes from urban and industrial sectors shown in Table 2.4 Source: http://www.undp.org.in/programme/GEF/march00/page12-14.html

2.1.9. World scenario

Table 2.6 shows data on solid waste of three different countries. This table shows the quantity of the solid waste available and its potential for generating electricity, in turn is useful for finding out the country's wealth on renewable source usage.

Table 2.6: Solid waste potential of world countries

Country	Quantity Available (Mt)	Electricity capacity (kW)	Electricity Generation (TJ)	Direct Combustion (TJ)	Total energy production (TJ)
Germany	7.3	555000	9526	19787	29 313
U.K	2.6	158600	4892	1340	6232
U.S.A	167	2862000	71405	217722	289127

Source: WEC, 2001

2.1.10. Role of technology

The solid wastes contain valuable resource and potential power is not tapped when utilizing various improper technologies. This problem can be mitigated through adoption of environment friendly technologies for treatment and processing of waste before it is disposed off. These technologies not only lead to generation of substantial quantities of decentralized energy but also reduce the quantity of waste besides improving the quality of waste to meet the pollution control standards (MNES, 2003). Proper treatment option is chosen to utilize these wastes as a raw material to produce some useful material (compost) or energy. The main objective of the treatment option is to utilize the recycling potential and utilization of energy of solid waste, etc. At the same time, the load on waste management system especially, on the disposal is also reduced. Possible conversion routes for these wastes to recover useful (organic fraction) resource are illustrated below (Fig 2.2).

- Composting
- Energy recovery and
- Landfill

Most of the countries in the world utilized the option of landfill for the disposal of wastes for a long time. The degradable component of the wastes in the landfill gives rise to the liquid and gaseous end products such as leachate and biogas (Jaffrin *et al.*, 2003). The gaseous products of waste decomposition pollute the air and contribute to global warming. Similarly the liquid end product, called leachate, also contributes air pollution (by means of noxious odors) and ground water pollution (by percolation). These problems are clearly outlined elsewhere (IEA bioenergy update, 2004) converting organic wastes into a useful form of energy or compost reduces various environmental impacts. The composting route results in uncontrolled release of CO_2 into the atmosphere without capturing energy of the waste (Yu *et al.*, 2002). Of the above three treatment methods, energy recovery seems to be effective by offering the following advantages:

- The total quantity of waste is reduced by nearly 60-90% depending upon the waste composition and the adopted technology (anaerobic digestion).
- Demand for the land, which is already scarce in cities for the land filling, is reduced.
- The cost of transportation of waste to far away landfill sites is also reduced.

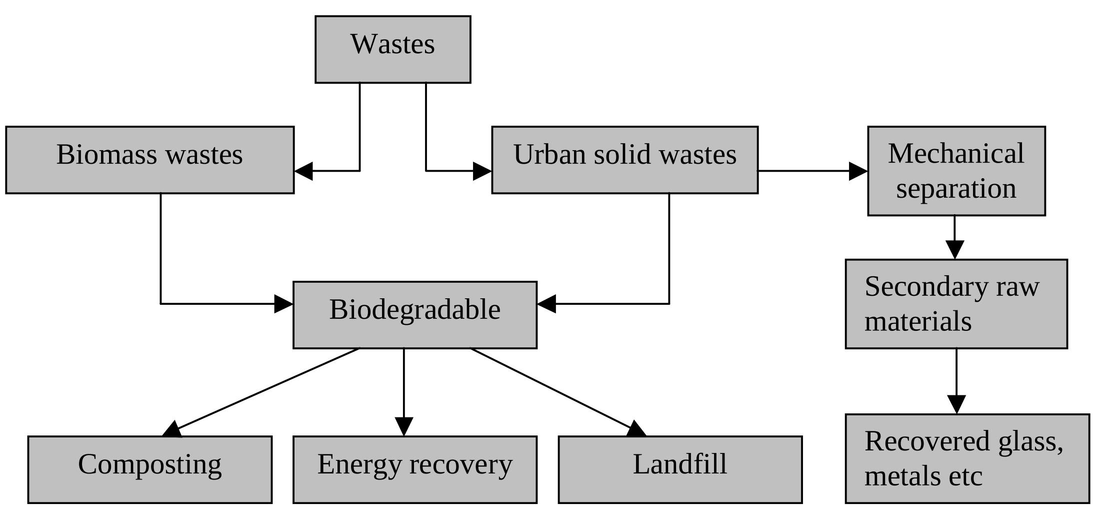


Fig 2.2. Pathways for solid waste treatment for recovery and recycling process.

Inspite of above said methods, the final destination of USW in India is disposal. Most are land filled or dumped (Gerlagh *et al.*, 1999). These wastes followed a different trend of destination in Bangalore city is given in Annexure 1.

2.1.10.1.Types of energy recovery process

Energy can be recovered from the solid wastes either by adopting thermo-chemical technology or by bio-methanation.

2.1.10.1.1. Thermo – chemical conversion

This process involves thermal decomposition of organic matter to produce either heat energy or fuel oil or gas. It is useful for the wastes containing high percentage of organic non-biodegradable organic matter and low moisture content. The main technological options under this category are given in Fig 2.3

- Incineration
- Pyrolysis
- Gasification

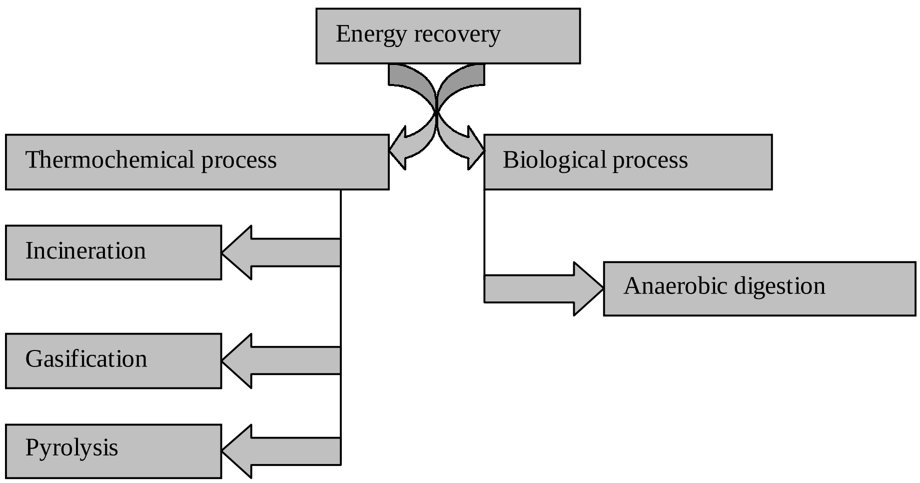


Fig 2.3. Pathways available for organic wastes to recover energy.

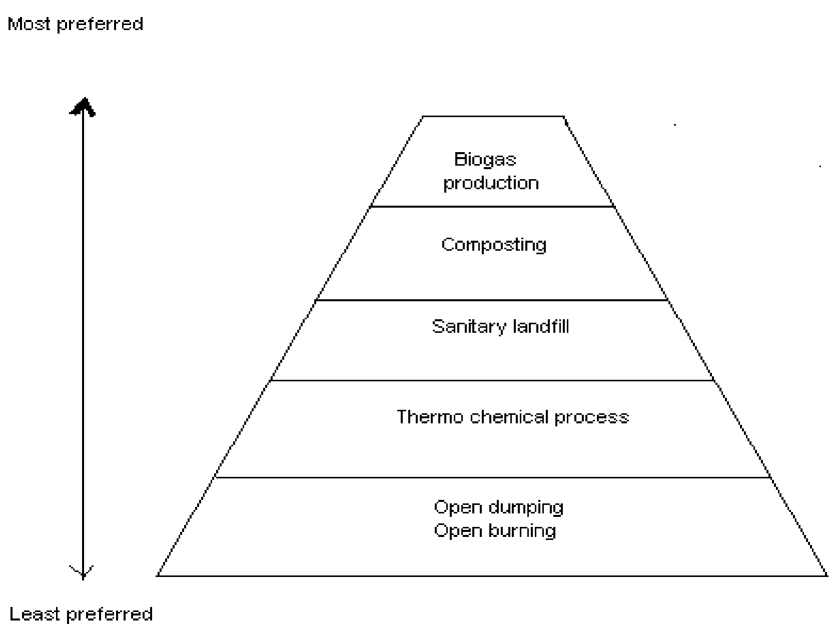
2.1.10.1.2. Bio chemical conversion

It is based on the decomposition of organic matter by microbiological action to produce methane gas. This option is mostly preferred for the waste having a high percentage of biodegradable organic matter along with high moisture content that aids in microbial fermentation. The main technological option under this category is bio-methanation or anaerobic digestion.

2.1.11. The biomethanation option

Thermo-chemical processes are cost efficient (Murphy, 2004) but not applicable to the developing countries like India on account of the low calorific value and high organic content of waste (Asnani, 1998; Gerlagh *et al.*, 1999). It is not useful in recovering valuable resources that is possible by anaerobic fermentation (Braber, 1995). This leads to the utilization of anaerobic digestion process for energy recovery. This has the potential to make a significant contribution to sustainable development (environmentally benign and economically secure) (IEA, 2004). One of the principal objectives of anaerobic treatment of solid waste is to reduce the bulk and mass (Lopes *et al.*, 2004). This will not only generate significant quantity of biogas i.e. about 250-350m^3/ton of waste (NEERI report, 1996) but also generate the digested material, used as a high-grade soil conditioner (CPHEEO, 2000). It also leads to preventing environment degradation. Thus from Fig 2.4 it may be seen that biogas technology is accorded the highest place in the hierarchy of choices. It is effective in terms of treating solid waste along with energy recovery and cost effectiveness. A part of the cost is recovered by substituting fossil fuels and or electrical energy in the treatment process One of the main advantages includes resource recovery without pollution. Residual or digested waste is further composted to yield a good compost. Gas can be used for in-plant as well as for valorization. Thus the recovery of energy in the form of biogas from USW is chosen for this study. Typical biogas composition of organic solid waste is given in Annexure 1.

Fig 2.4: Hierarchy of technological options for OFUSW



2.1.12. Overview of biogas programme in India

Experience with biomethanation systems already exists in India. However, a large part of this is related to farm scale biogas plants and industrial effluents. There is a little experience in the treatment of solid organic waste (CPHEEO, 2000). The National Biogas Management Programme (NBMP) is a modified version of the National Project on Biogas Development (NPBD), which was implemented during 1981-82 to 2001-02. Its main objectives are (i) to provide clean and cheap source of biogas energy; (ii) to produce and use enriched organic manure; (iii) to develop management systems for production of value added products.

Against an estimated potential of setting up of 12 million biogas plants, a cumulative of 3.8 million biogas plants have been set up so far in the country. These include community, institutional, night soil, and family type biogas plants (Table 2.7).

Table 2.7: Biogas potential in India

Sources/technology	Biogas plants
Units	Million
Potential	12
As on March 2003	3.8
India's Position in the world	II

Source: TEDDY, 2002

2.1.13. Status of biogas production in the world

The yearly production of biogas in the European community was estimated at $430X10^6m^3$ (1990) containing 65% methane or 240,000 tons of oil equivalents (toe; Pauss, 1992). The production from 474 agricultural biogas plants was 60 X 10^6m^3 of biogas per year. The production from 195 industrial biogas plants was 370 X 10^6m^3 of biogas per year (Pauss, 1992). Thus agricultural biogas plants in the European community outnumber industrial biogas plants by the ratio of 3 to 1. Type of technologies predominantly adopted for agricultural biogas plants include CSTR (app.250), plug flow reactor (app. 70), batch reactor (50) etc. Whereas for the industrial biogas plants technologies such as UASB (app.55), CSTR (app. 33), up-flow fixed bed (app. 20), down flow bed (app.18) reactors etc. Thus usage of the different technologies employed in the process depends on the type of waste treated.

2.2. Principle of biogas production

Anaerobic biodegradation of organic material proceeds in the absence of oxygen and in the presence of anaerobic microorganisms. It results in two products: biogas (CH_4 - 60% + CO_2 - 40%) and a digested organic matter.

2.2.1 Microbiology and biochemistry of biomethanation

The metabolic reactions that occur during the anaerobic digestion of substrates consists of a complex set of reactions, which are catalyzed by consortia of microbes. These reactions are termed hydrolysis, acidogenesis, acetogenesis and methanogenesis as in the Fig 2.4 (Cho *et al*., 1995). Mostly bacteria are involved in such a transformation .

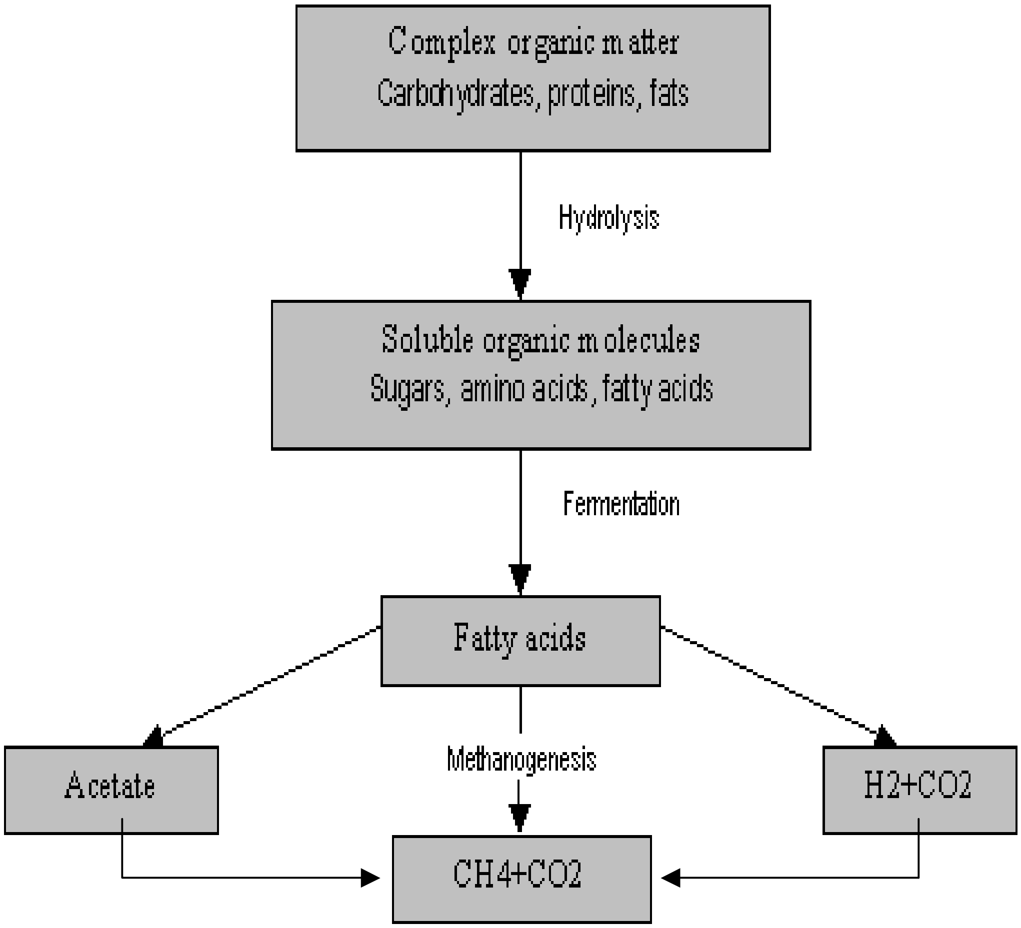
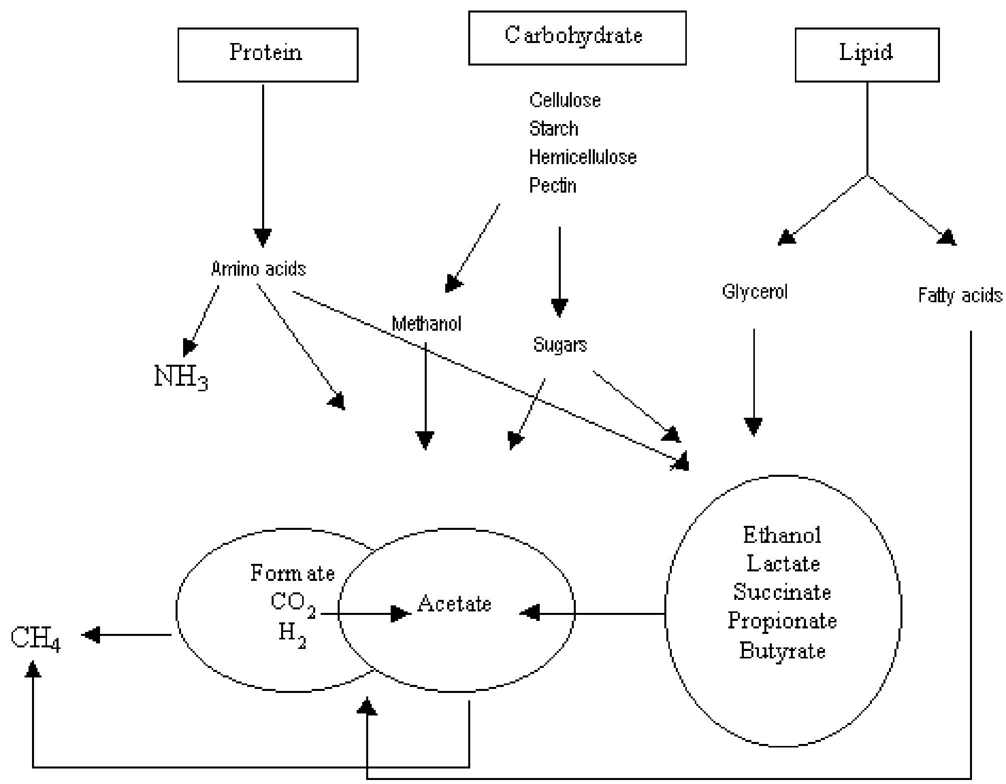


Fig 2.4. Overall scheme of anaerobic digestion process.

2.2.1.1. Hydrolysis

In the first stage of hydrolysis, or liquefaction, hydrolytic bacteria convert the complex polymers to their respective monomers. For example, celluloses are converted to sugars or alcohols, proteins to peptides or amino acids, and lipids to fatty acids. This is carried out by several hydrolytic enzymes (cellulases, amylases, lipases, proteases etc) secreted by microbes and is presented in Fig 2.5.

Fig 2.5. Anaerobic breakdown of complex organic matter.



2.2.1.2. Acidogenesis

Simpler substances thus formed are converted to long chain fatty acids by acid formers by means of the fermentative reaction. The hydrolytic and fermentative activity is of significant importance in high rate organic waste treatment and sometimes may become rate limiting (Verma, 2002). The acidogenic bacteria has a higher growth rate than methanogens and acetogens (Liu *et al.*, 1997; Bhattacharya *et al*., 1996). Thus most often the conversion efficiency of a feedstock is determined by hydrolytic and fermentative action.

2.2.1.3. Acetogenesis

Once many complex intermediates and long chain fatty acids are produced as intermediates, acetogenic bacteria convert long chain fatty acids to simple organic acids (formic, acetic and propionic), carbon dioxide and hydrogen. The principal acids produced are acetic acid, propionic acid, and butyric acid. Acetic acid can even be produced from the CO_2 and H_2. Since about two thirds of the methane formed in a biogas reactor is derived from acetate (Gujer, 1983), a decrease in the activity of the acetate utilising methanogens severely affects the anaerobic digestion process. Sometimes conversion of acetate to hydrogen and carbon-di-oxide can also takes place, only at low partial pressures of hydrogen, i.e. in the presence of hydrogen consuming organisms (Schnurer, 1999). The products formed in this phase are due to a number of different microbial species, e.g., *Syntrophobacter wolinii*, a propionate decomposer and *Syntrophomonas wolfei*, a butyrate decomposer. Complete conversion of one mole of acetic acid yields 0.78 SCF SI units of methane (Schwartz, 1973).

2.2.1.4.Methanogenesis

Finally in the fourth stage, methane is produced by a group of bacteria called methane formers (also known as methanogens) in two different pathways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digester results in that the acetate reaction is the primary path for methane (Omstead *et al*., 1980). Addition of hydrogen in to the digester alone does not result in methane production thus confirming utilisation of the acetic acid is also possible step in anaerobic reactors (Kumar, 1993). All these products are substrates for methanogens. This phase of anaerobic digestion comprises the activities of two groups of bacteria: hydrogenotrophic and acetotrophic methanogens. The methanogenic bacterial consortium includes *Methanobacterium, Methanobacillus, Methanococcus, and Methanosarcina spp*., and *Methanothrix spp.* These bacteria are highly sensitive to oxygen concentration in the system. Their inactivity depends on an increasing fatty and acetic acids concentration within the environment, consequently lowering the pH (pH needs to be in the range of 6.5 - 7.5). The methanogenic treatment process relies on a balanced symbiotic relationship between metabolically distinct microbial populations such as acidogenic and methanogenic bacteria (Hessami, 1996; Plaza *et al*., 1996; Lastella *et al*., 2002). The methanogens depend on obligate proton reducing acetogens for the supply of methanogenic substrates (acetate, H_2 and formate). The acetogens in turn depend on the methanogens for the removal of those chemicals. This removal is necessary, because the acetogenic reactions are -= only when those chemicals are at low concentrations. This relationship has been termed as syntrophic, which means, "feeding together", because they depend on each other for their food. These two groups have an intimate ecological link. However, at short retention times or when inhibitory substances are present in the feedstock, methanogenesis may be incomplete and the acids may accumulate. Accumulation of these acids can lead to digester failure, so methanogenic reactions are crucial for the stable operation of digesters. Stoichiometry of anaerobic reactions likely to takes place inside the digesters is as follows:

1. Acidogenic fermentation of glucose:

$C_6H_{12}O_6 \longrightarrow CH_3\,(CH_2)_2\,COOH + 2CO_2 + 2H_2$

$C_6H_{12}O_6 + 2H_2 \longrightarrow 2CH_3COOH + 2\,H_2O$

$C_6H_{12}O_6 + 2H_2O \longrightarrow 2CH_3COOH + 4H_2 + 2CO_2$

2. Acetogenic oxidation reaction:

$CH_3(CH_2)_2COOH + 2H_2O \longrightarrow CH_3COOH + CO_2 + 3H_2$

$CH_3CH_2COOH + 2H_2O \longrightarrow CH_3COOH + CO_2 + 3H_2$

3. Methanogenic reactions:

$CH_3COOH \longrightarrow CH_4 + CO_2$
$4H_2 + CO_2 \longrightarrow CH_4 + 2\ H_2O$
Source: Denac *et al*., 1988

Boone *et al*. (1993) described the investigation of the microbial ecology of the anaerobic degradation of the biomass feedstock showed the presence of *Methanosarcina mazei*, an acetoclastic methanogen abundant in many biomass digesters can use wide range of substrates such as acetate, hydrogen and carbon-di-oxide (Tabassum, 2000). This was supported by Mladenovska (2000) who reported the presence of *Methanosarcina* strains, isolated from full-scale reactors treating different kinds of organic wastes could be distinguished from each other by the ability to grow on and utilize acetate. A mixture of several organic wastes gives a more active and efficient population of acetate utilizing methanogens in the reactors. However, some authors had presented entirely different results. Alagappan (1994) studied the kinetics of methanogenic reactions using solid phase biomass fermenters. Results showed that the CO_2 reducing methanogens are more and are rapid growers than the aceticlastic methanogens. Aldrich (1993) studied the morphology of *Methanobacterium mazei* and *Methanobacterium thermoautotrophicum* abundant in many biomass digesters. In the same year, Hedrick and White studied the application of analytical microbial ecology to the anaerobic conversion of biomass to methane. The results of this application have been used to monitor the operation of a unique design of high solid high productivity methanogenic reactor. McHugh *et al.* (2003) examined the methanogenic community structures of six anaerobic sludges revealed the presence of *Methanosaeta* sp.
The role and importance of anaerobic microbes in the biogas production has been presented above. The utilisation of complex substrates by methanogens is also presented. Results discussed above indicate the need for a careful start up of anaerobic digesters.

2.3. Factors affecting anaerobic digestion

Biogas conversion process is microbiological in nature and is affected by the following factors as discussed below.

2.3.1. **Temperature**

Anaerobic digestion can occur under two main temperature regimes namely, mesophilic (between 20-45°C usually 35°C) and thermophilic (between 50-75°C usually 55°C). Temperature is one of the most common factor affecting methanogenesis processes in a biogas digester (Castillo *et al*., 1995; Chynoweth and Pullamanapallil). Enzyme kinetics, dissociation constants and death rates are greatly affected by small changes in temperature. Bacteria present within digesters are influenced by such changes in enzyme kinetics. As temperature rises, enzyme activation increases while at the same time enzyme denaturation also increases. In addition, higher temperature also increases the irreversible destruction of many of these vital proteins. Such mechanisms will cause a typical bacterium to have a range of temperature viability as well as an optimum temperature for growth and functioning (Harmon *et al*., 1993). Griffin *et al*. (1997) found that the mesophilic digester did not respond favorably to an aggressive start-up method. A more gradual start-up improved the digestion process at mesophilic conditions. Yu *et al*., (2002) showed that the retention time in a two-phase system could be reduced by heating or preventing heat loss (insulating). Castillo (1995) showed, that the temperature at 25°C was economical, since the biogas production was more homogenous and constant. This influences the gasholder capacity whereas at the increased temperature (35°C) the energy consumption by the process was greater than energy from the additional biogas produced. Thus the low temperature operation was economic and sustainable (Castillo *et al.*, 1995). The optimum temperatures for anaerobic digestion are either 35°C or 55°C, mostly depending on the application and its operating conditions (Hessami *et al*., 1996).

2.3.2. pH

The pH is known to affect enzymatic activity owing to the fact that only a specific and a narrow pH range are often suitable for the maximum activity. A pH range between 6.7-7.4 is reported suitable for most methanogenic bacteria to function (Verma, 2002). The rate of methanogenesis may decrease if the pH is lower than 6.3 or higher than 7.8. The main reason for the absence of biodegradation was the rapid acidification of the waste (Verma, 2002). This is generally due to the over production of VFA by the activity of hydrolytic acidogenic bacteria capable of degrading the waste in the first few days of incubation (Gomec, 2003). The biological evolution of methane is inhibited at acid production phase. Saturating the waste with water could reverse this inhibition (Martinez, 1999). Gomec, (2003) studied the effect of pH on hydrolysis/acidogenesis in terms of soluble chemical oxygen demand (SCOD) and VFA production as well as TSS and VSS destruction both in the anaerobic solubilization of domestic primary sludge and activated sludge at mesophilic temperature. Results indicate that the pH control enhanced the biogas production. This was due to an increase in SCOD, resulting from a quicker hydrolysis and fermentation during the first 5 days. Besides, total COD removals were calculated at higher quantities in the pH controlled reactors indicating that pH control increased the performance of the anaerobic digestion.

2.3.3. Volatile Fatty Acids

The long chain fatty acids were found to be inhibitory to the several kinds of essential reactions in the anaerobic digestion because of their toxicity to the bacteria (Hanaki *et al.*, 1980). The rate of methane production from hydrogen was lowered by long chain fatty acids. The methane production from acetate was inhibited so strongly that a long lag period appeared. Wang *et al*., (1999) investigated the efficiency of anaerobic digestion to evaluate the effect of C2-C6 VFAs on the methane fermentation and to examine the behavior of VFAs in anaerobic digestion. The VFA concentrations and methane production in anaerobic digestion were increased by pretreatment methods such as ultrasonic disintegration, thermal and freezing treatments. This experiment clearly shows that decomposition rates of the VFAs with a straight chain were greater than those of their respective isomers with a branched chain. Inhibition of degradation of the VFAs by acetate in a digester was also examined. It is known that VFAs are important intermediary compounds in the metabolic pathway of methane fermentation and cause microbial stress, if present in high concentrations resulting in a decrease of pH and ultimately leading to a failure of the digester. Hence it is necessary to investigate the optimum conditions and efficiencies of digesters by examining VFAs. Pind *et al*., (2002) focused on the effects of VFA on the anaerobic process, showed that the high concentrations of propionate affected the degradation of all VFAs. At shorter retention times, VFA production could exceed the utilization rates, leading to the digester failure (Ghosh, 1991).

2.3.4. Inoculum-substrate ratio

Fernandez, (2001) reported that the ISR variation has less impact on anaerobic degradability than on specific methane productivity (SMP). While maximum anaerobic degradability was reached in those tests with high ISR, the greatest values of SMP were with the lowest values of ISR ratio. A low ISR caused a slow hydrolysis, although the methane production was fast. Lopes *et al.,(* 2004) affirmed that the inoculum used in the process, substantially improved the performance of the process. For this study, Lopes used bovine rumen fluid as an inoculum for the organic fraction of solid waste. Results clearly indicated that the better performance of the inoculated reactors might be related to the potential increase in number of indigenous anaerobic microorganisms of rumen that contributed substantially to degradation of the organic material in the reactor. The data obtained shows a strong influence of the bovine rumen fluid inoculum on anaerobic bio-stabilization of fermentable organic fraction of USW. Martin, (2001) showed, variability and slowness in the rate of solid-state anaerobic digestion may be largely due to inadequate seeding.

2.3.5. Leachate circulation

Distribution of recirculation leachate on to the solid fraction has been shown as an important factor affecting the degree of substrate degradation. It acts directly on the microorganisms-substrate contact and can favour the substrate rate biodegradation (Castillo *et al*., 1995). Martin, (2001) proposed that the leachate recycle might confer no benefit on a well-seeded digester. Its only role may be to compensate for erratic seeding by transporting substrate into clusters of seed particles. Nopharatana *et al*., (1997) proposed the directing of leachate to the bed of waste inturn provides moisture, buffering capacity and sources of microorganisms.

2.3.6. Effect of microbial population

Sundh *et al*., (2003) reported the microbial communities of biogas processes could respond quickly to changes in the feeding rate. The growth rate of acidogens is typically much higher than that of methane formers. Thus the potential advantage of stage separation will depend on whether the turnover rate is limited by the degradation of the readily degradable compounds or by polymer hydrolysis. Hydrolysis, being the first step in overall process, is normally the rate-limiting step of the overall anaerobic digestion process, if the substrate is in solid form. Griffin *et al*., (1997) showed that the levels of *Methanosaeta* sp., decreased rapidly as acetate level build up. Noike *et al.,* (1985) found that the anaerobic degradation of cellulose needs a longer retention time than that needed for methanogenesis. The dominant type of methanogenic bacteria changes as the SRT of the methanogenic reactor changes. *Methanosarcina* is dominant at short SRTs, while *Methanothrix* is dominant at long SRTs. M*ethanosarcina s*hows higher substrate utilization than *Methanothrix*. Thus the hydrolysis of cellulose limits the rate of anaerobic acidogeneis in an anaerobic digester. Microbial ecosystem needs time to adapt itself to the new substrate (Raynal *et al.*, 1998) inside the digester for degradation.

2.3.7. Ammonia

Ammonia produced in the protein degradation may cause problems in anaerobic digestion as unionized ammonia inhibits anaerobic microorganisms, particularly methanogens. Sterling *et al*., (2001) determined the feasibility of monitoring hydrogen gas as an indicator of digester

upset resulting from ammonia overloading. This experiment clearly revealed the amount of ammonia nitrogen in the digester feed impacted digester hydrogen production, methane production and VS removal. Small increases in ammonia nitrogen resulted in increased hydrogen and methane production. Large increases caused the inhibition of hydrogen and methane production. Total biogas production reduced to 50% of the original rate with increases in ammonia nitrogen. This is mainly due to the methanogen inhibition metabolism by ammonia, resulting in lower pH. With an insufficient alkalinity, the digester undergoes acidosis, resulting in the cessation of methane production. It has been reported by Van Velsen (1979) that methanogenesis is severely inhibited above 2000mg/L ammoniacal nitrogen (Callaghan, 1999). The problems associated with ammonia inhibition in a high solids anaerobic digestion process can be corrected by one or more of the following methods:
(1). Diluting the contents of the digester to reduce the ammonia concentration in the liquid phase.
(2). Adjusting the C/N ratio of the feedstock and
(3). External ammonia absorption (Kayhanian, 1994).

2.3.8. Pretreatment methods

Three types of pretreatment are reported in literature, viz., enzymatic hydrolysis, acid hydrolysis, and alkali pretreatment, for improved digestibility of lignin- rich biomass waste. These methods could be used either as a full treatment step for complete hydrolysis to sugars or as an alkali pretreatment step for breaking certain links in the hemicellulose-lignin polymeric system so as to provide increased diffusivity to hydrolytic enzyme. Alkali pretreatment methods have accordingly been adopted by several researchers for achieving increased volatile acid and gas production in anaerobic digesters. Gunaseelan, (1994) reported that the high lignin content of *Parthenium* was one of the factors accounting for the low methane yield. Alkali pretreatment of *Parthenium* with NaOH significantly enhanced the methane production and cellulose reduction. Hamzawi *et al*., (1998) found that alkaline pretreatment significantly increases the biodegradability of the waste mixture in the co-digestion of sewage sludge and OFUSW.

2.3.9. Influence of bed materials

To maintain a high bacterial concentration in the reactor, immobilization methods of microbial cells onto various supports have been studied (Andersson and Bjornsson, 2002). Chanakya *et al*., (1998) envisaged that anaerobically digested herbaceous biomass could be deployed as methanogen support in the anaerobic digestion of several liquid wastes for biogas production. Methanogenic activities measured on such biomass support material exhibited a potential to achieve much higher biogas production. Results clearly indicated that the fermentor functioned well even at 21 ±1ºC with gas production rates up to 3L/L/d and thus appeared to have potential for small-scale high rate biogas production from various combinations of liquid and solid biomass wastes. Yang (2004) reported the effects of bed materials on the performance of methanogenic fluidized bed reactors with acetic acid as a sole organic substrate. Four bed materials such as carbon filter, rock wool, sponge (*loofah*-commercial name) and polyurethane foam were evaluated and compared for their methanogenic characteristics and immobilized microbes. Among these, *loofah* sponge and polyurethane foam were suggested to be suitable for the bed material in anaerobic digestion, since these materials showed good methane yield. This was mainly due to the better performance of porous structure of polyurethane foam and *loofah* than the fibriform structure of the carbon felt and rock wool. Thus, this result clearly revealed that the material characteristics have some influence on the methane fermentation. Microscopic observations of the immobilized microbes revealed that different bed materials could provide specific conditions for the adherence of distinct microorganisms types. The phylogenetic analysis of 16s rRNA indicated that the major methanogens immobilized on the bed materials were M.*formicicum,* M.*barkeri* and M.*mazei*. In a same way, Baumann, (1997) investigated the anaerobic biodegradability of substances, products and wastewaters using continuous anaerobic fixed bed reactor. Dupla *et al*., (1995) investigated the dynamic evaluation of a fixed bed anaerobic digestion process in response to organic overloads and toxicant shock loads using online instrumentation. In case of organic overloads, the fixed bed reactor can be considered as very robust despite very high VFA concentrations. Indeed in both cases (with and without pH regulation in the feeding line), recovery of the process was possible. In addition pH regulation in the feeding wastewater minimized the inhibition of the methanogenic biomass and it helped the overall process to recover faster. When ammonia shock loads were applied, a complete inhibition of the process was expected, but the biofilm protected the microorganisms and no effect could be noticed. Yang *et al*., (2004) studied the performance of the fixed bed reactor packed with carbon felt during anaerobic digestion of cellulose. Results showed that biomass distribution in the felt and on the felt surface was high, when compared to the liquid phase, clearly indicated that most of the microbes were immobilized on the carbon felt fixed bed in the reactor. Thus the reactor with the carbon felt bed would be suitable for the efficient anaerobic digestion of cellulose.

2.4. Biological Methane Potential assay (BMP)

BMP assay was developed to determine the ultimate CH_4 yield (B_0) of organic substrates and for monitoring anaerobic toxicity. B_0 of a variety of biomass were determined using a modified method of Owen *et al*., The BMP is a valuable, quick and inexpensive method for determination of the potential extent and rate of conversion of biomass and wastes to methane. A similar assay has otherwise been named as (ABP) anaerobic biogasification potential (Gunaseelan, 1997). Gunaseelan (2004) evaluated the extents and rates of fruit and vegetable solid waste (FVSW) conversion to methane by means of BMP. The ultimate methane yields of fruits and vegetable feedstock ranged from 0.18 to 0.73 L/gVS and 0.19 to 0.4 L/gVS addition. According to Gunaseelan, (2004) different parts within the same variety showed different yields in orange, pomegranate, grapevine and sapota. Among the FVSW tested in this study, the varieties of mango peels, citrus wastes, pomegranate rotten seeds and pressings exhibited methane yields significantly higher than the cellulose. Most of the FVSW showed methane yields greater than 0.3L/gVS added and thus represent an excellent choice for commercial methane production. In a same way, Chynoweth *et al*., (1993) reported the BMP of biomass and waste feedstock. This was evaluated in terms of inoculum, inoculum to feed ratio and particle size for analysis of extent and rate of conversion of biomass and waste feedstock to methane. Results showed that the rumen and sludge inocula exhibited similar solubilization of organic matter, 2:1 inoculum to feed ratio was shown to give maximum conversion rates. Particle size did not influence rate in the range of 1-8 mm. Thus the results of this assay can be used to compare differences in extent and rate of BMP as a function of inoculum, inoculum to feed ratio and particle size.

2.5. Techniques employed for anaerobic digestion:

The anaerobic biological treatment of the organic fraction of USW has received attention during the last few years. A conversion of these wastes to methane provides some energy and has a beneficial effect on the environment. The production of methane during the anaerobic digestion of biologically degradable organic matter depends on the amount and kind of material added to the system. So, waste biomass subjected to anaerobic digestion for the above said potential energy value could be performed in various ways. The leading concepts of now -a- days are:

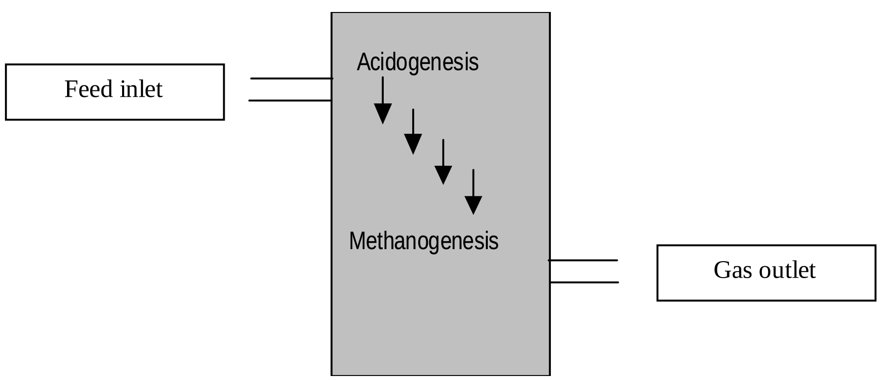
- Single-phase digestion.
- Two phase digestion.
- Co-digestion.
- Dry fermentation.

These four options were effectively utilised for USW treatment. Several studies have been made on the bioconversion of USW by different researchers. For example Mata Alvarez *et al.*, (1992) carried out experiments on Barcelona's central food market organic wastes, Lane, (1984) on fruit and vegetable wastes, Nand *et al.*, (1990) on canteen wastes, Cho *et al.*, (1995) on Korean food wastes and Sharma, (1999) on water hyacinth.

2.5.1. Single Phase Digestion

In the single-phase digestion, the acid forming bacteria and methane forming bacteria exist in the same biological environment (Fig 2.6). That is, complex organics in the wastes first acted upon by the hydrolytic, fermentative, and acidogenic bacteria results in the production of

Fig 2.6. One-step digestion



VFA's, inturn acted upon by the methanogens, results in the production of biogas. Acidogens present at the top portion of biomass bed, rapidly hydrolysing the polymeric substances results in the production of VFA, this inturn get in to contact with those methanogens at the bottom, is possible through leachate recycling process.

2.5.2. Two-phase digestion

In the conventional digesters, the acid forming and methane forming bacteria exists in the same biological environment. In such an environment, the VFA production exceeds than the conversion rates of VFA's to methane. This may results in acids accumulation, leads to pH drop and a consequent inhibition of methanogenesis. To overcome these problems, two-phase anaerobic digestion was suggested (Fig 2.7). This is possible by isolating the two major microbial phases in the two separate reactors (acidogenesis and methanogenesis). This concept was widely used by various scientists to recover the methane from valuable waste resources.

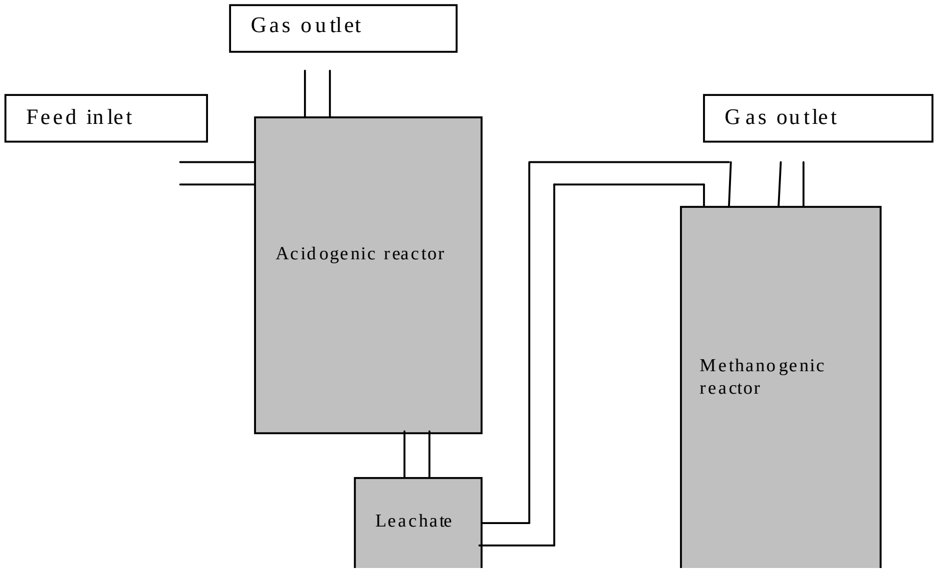


Fig 2.7.Two-step digestion

2.5.3. Dry fermentation:

Dry fermentation or high solid digestion came in to light, to overcome the problems created by the slurry phase fermentation. It describes the systems in which the total solids concentration in the digester is about 20-25%. They can show a very high rate of gas production per unit reactor volume. The main advantages of dry fermentation is as follows:

- The addition of water is very limited, decreasing post treatment costs and reactor volume.
- Heating requirements during the process are minimised due to exothermic energy released during anaerobic microbial decomposition.

It would appear that continuous dry fermentation offers the greatest potential for digestion of the organic fraction of solid waste, either on its own or co digestion with other high solids organic wastes.

2.5.4. Co-digestion

An interesting option for improving yields of anaerobic digestion of solid wastes is co-digestion. In this the use of a co-substrate is employed, which in most cases improves the biogas, yields due to positive synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates. More works have been done on biogas by utilising this property (Mata-Alvarez *et al*., 2000). For this property, it is important to choose the appropriate criterion for assessing the “optimum mix” of the different mixtures of wastes. It must also be recognized that, with a practical co digestion facility, it might not be possible always to operate with the optimum blend of wastes as long term storage would not really be a sensible consideration, particularly in countries with high ambient temperature (Misi *et al*., 2001). For instance in North America, this option has been examined in a study evaluating the technical feasibility of the anaerobic co-digestion process for typical solid wastes

(Hamzawi *et al.*, 1998). Using biological activity tests, an optimal mixture, for biogas production was identified as 25% OFUSW and 75% sewage sludge (65% raw primary sludge, 35% thickened activated sludge (TWAS)). Also based on the rate of biogas production, the most anaerobically biodegradable components of OFUSW were paper and grass. TWAS and newspaper were found to be the least biodegradable components. The authors also developed empirical models based on alkaline dose, total solids concentration in feed and particle size, biogas production and removal of TS and VS. All five experimental factors were found to be significant with respect to the response variables studied. Callaghan *et al*., (1999) tested the several mixtures of cattle slurries with a range of different wastes, allowing them to digest in 1L-batch digesters. The criteria for judging the success of a co-digestion were VS reduction, total methane production and methane yield. In terms of the VS reductions (%), there was little difference between the various digestions. In terms of the cumulative methane production, the co-digestions with fruit a vegetable wastes, fish offal and dissolved air floatation sludge were more effective than the digestion with cattle slurry alone. Compared with their control (cattle slurry alone), both co-digestions with poultry manure (7.5 and 15%TS) gave higher cumulative productions of methane, and the system with the lower concentration of poultry manure gave a higher specific methane yield.

2.5.5. Sources of methane chosen for the study

From the above-mentioned solid wastes a wide range of biomass wastes have been considered as potential sources for methane production (Fig 2.8).

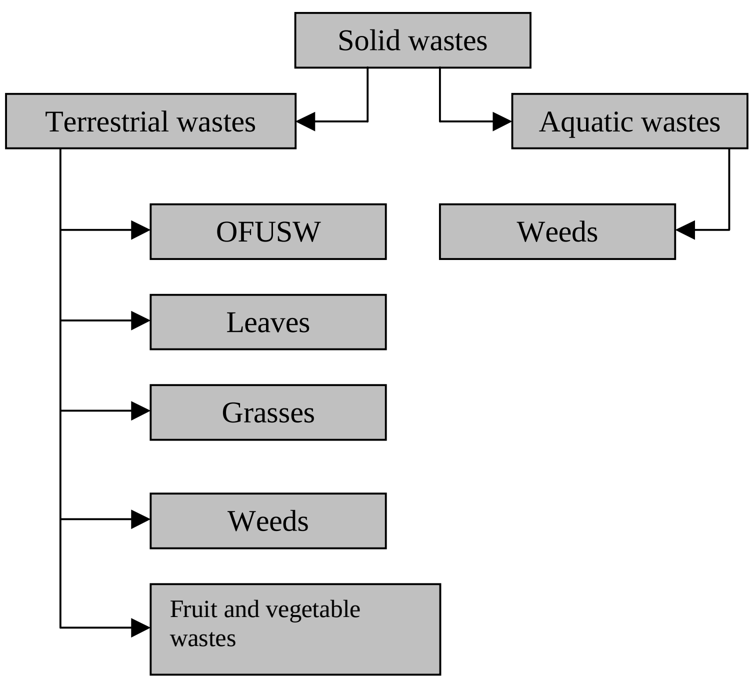


Fig 2.8. Selected types of methane yielding wastes

2.5.5.1. Organic fraction of USW

The composition of USW varies from place to place, due to its heterogeneous (different) nature. The composition of USW is affected by various factors, including regional differences, climate, and extent of recycling, collection frequency, season, cultural practices, as well as changes in technology. Reserved form of chemical energy in these wastes can be renewed by means of biogas production. Rodriguez *et al*., (2000) carried out the pilot plant studies to observe the mechanism of anaerobic digestion of USW and also to study the behavior of a sanitary landfill under controlled conditions leads to the optimization of the operating mode of a sanitary landfill deposit by reducing the pollution load of the leachate formed and by increasing the production of biogas. Chanakya *et al*., (1992) utilized major part of SW for biogas production. The digester employed in this study constitutes solid phase acidogenic digester and up flow bed methanogenic digester packed with acid washed granite chips, with the capacity of 2L and 0.5L respectively. Feed rates adopted for this study was 1g TS, increased up to 2g TS /week for 63 days and 102 days respectively. The total 19g TS of urban garbage samples gave rose to 6.37gVFA and 1.73L gas production, showing the utilization efficiency of 33.5%. Thus the major part of OFUSW gave good yield of methane, if it is properly and biologically converted to methane. Vieitez, (1999), subjected finely chopped pieces of MSW to the digestion. The digester employed in this study constitutes cylindrical, jacketed, cone bottomed solid bed reactor with the volume of 14L capacity gave the bed volume of 12L and methane phase reactor filled with plastic rings gave the void volume of 90% and culture volume of 8L. 1.227 kg of dry chopped MSW compacted to a density of 160 kgm^{-3} was adopted as a loading rate. 7.4L of inoculum was used to initiate the digestion, includes 3L of digested sludge with 4.4L of tap water, results in the production of 900ml leachate in turn contains 13g/L of VFA, contributes the specific methane yield of 0.12 SCM/kg of VS showing conversion efficiency of 40%. Hamzawi (1998) evaluated the technical feasibility of the anaerobic co-digestion of sewage sludge with the organic fraction municipal solid waste. Using biological activity tests, an optimal mixture was identified with 25% organic fraction of municipal solid waste and 75% sewage sludge based on biogas production. It was found that the alkaline pre-treatment increased the biodegradability of the sewage sludge/OFUSW mixture over that of the untreated control. Thermo chemically pre-treated feedstocks inhibited anaerobic biodegradability as compared to the control, whereas the anaerobic biodegradability of thermally pre-treated feed was not found to be significantly different from that of the control. The empirical models were developed based on alkaline dose, total solids concentration in feed and particle size, biogas production and removal of TS and VS. All five experimental factors were found to be significant with respect to the response variables studied (Hamzawi *et al.,* 1998). Rao *et al.*, (2000) concluded that the municipal garbage is a high potential bioenergy source and it can be effectively utilized for biomethanation process. Results showed that biogas yield of $0.661 m^3/kg$ VS, indicating the high biodegradability of the feed. This yield was found to be 2.5 times the yield obtained from the cattle dung, indicating that anaerobic conversion of municipal garbage to biogas is a suitable option for commercial energy production.

2.5.5.2. Fruit and vegetable solid wastes

These wastes are characterized by high percentages of moisture (> 80 %) and VS (> 95 %) and have a very high biodegradability. The methane yield of FVSW is very high. Lane, (1984) carried out some trials to determine the long-term stability of digestions fed with fruit and vegetable wastes. It was found that recovery of settled solids from the discharged digester effluents and their return to the digester enables 88-96% VS removal, provided adequate alkalinity levels are maintained. For balanced digestion, alkalinity (mg/L) of 0.7 X volatile fatty acids (VFA, mg/L) is required and it should not be less than 1500. The performance of digestion of asparagus waste was stable at OLR of 4.2 kg VS m^{-3} d^{-1} with 90% removal of VS. Bouallagui *et al*., (2003) evaluated the performance of tubular digesters at higher loading rates, in order to establish conditions for optimal conversion of FVW into biogas. The work was carried out in semi-continuously mixed mesophilic tubular digesters. The overall performance of the reactor was depressed by changing the feed concentration from 8%-10%TS. The most significant factor of the tubular reactor is its ability to separate acidogenesis and methanogenesis longitudinally down the reactor, allowing the reactor to behave as a two-phase system. In this digester FVW could be treated anaerobically with a high stability, high depurination rate and energy recovery with a good process economy. Viturtia *et al.*, (1995) evaluated the two-phase continuous anaerobic digestion of these feedstocks in the mesophilic range using a hybrid up flow anaerobic sludge bed anaerobic filter reactor. In this study phase separation has been achieved without difficulty. This was very clear from the values of pH and VFA concentration in both hydrolyser and methanizer. When the systems were operated at hydrolyser and methanizer HRT of 2.6 and 1 day respectively, methane yield as high as $0.51m^3\ kg^{-1}VS$ was achieved (Viturtia, 1995). Hence two-phase digestion was also possible for the conversion of these wastes in to biogas was clearly depicted from the results. High biogas yields are obtained from digesting a mixture of fruit and vegetable wastes in a batch two-phase system with digested pig manure as inoculum, results in maximum gas production. Also evaluated, that the one phase system seems to be more appropriate for this type of waste (Mata-Alvarez *et al.*, 1993). Thus it is very clear from the above study, that the hydrolytic step was affected by OLR, since at high organic loads hydrolysis does not seem to be very effective. Furthermore, at higher loads, more methanization takes place in the hydrolyser than in methanizer, because VFA are in a lower concentration and, thus phase separation is not so effective. At low organic loads, VFA concentrations are poor, because they are immediately optimised and the yields per kg VS are high. Thus to upgrade yields in a two-phase system, more investigations would be needed concerning the system set-up, the control of pH in both reactor, etc., in order to optimise conditions in both the hydrolyser and methanizer. Thus the one phase system would be the best choice. Since it is simpler, can be applied successfully to the treatment of this type of waste without any type of control action. As a solution to the problem of ammonia inhibition during the anaerobic digestion of chicken manure, it has been proposed that co-digestion with cattle slurry could be a possible disposal route (Callaghan *et al*., 2002). In fact in his previous study, co-digestions were used, as a screening trial to determine which wastes could be best with cattle slurry. This showed that chicken manure, fish offal and FVW were the most promising combinations. Also, tested several mixtures of cattle slurries with a range of different wastes, allowing them to digest in 1-L digesters. The criteria for judging the success of a co-digestion were VS reduction, total methane production and methane yield. When fruit and vegetable solid waste was co-digested with cattle slurry with the feed containing 30% or more FVW, high concentrations of VFA's were produced. Despite this, mixtures of CS and FVW, gave a good co-digestion in terms of methane yield, but the VS reduction decreased slightly. Chicken manure was not as successful as a co-digestate. As the amount of CM in the feed and the organic loading was increased, the VS reduction deteriorated and the methane yield decreased. This appeared to be due to the concentrations of free ammonia present in the liquors. Lomas *et al*., (1999) also observed the same kind of process inhibition by ammonia.

2.5.5.3. Leaves

Chanakya *et al.*, (1993) evaluated the solid phase fermentation process to overcome problems in conventional slurry based reactors. Their experiment demonstrated the feasibility of solid waste conversion of biomass to biogas. In digesters that were fed with intact, untreated leafy or USW biomass feedstock in a weekly fed batch mode without spent feed removal, acidogenesis and methanogenesis were shown to occur in different layers of the decomposing biomass bed.

2.5.5.4.Grasses

Zhang, (1999) studied the anaerobic phased solids digester system for the conversion of rice straw to biogas. Ligno-cellulosic rice straw digestion is difficult to degrade biologically. Hence different pre-treatment methods such as physical, thermal and chemical treatment on the digestion of rice straw were investigated. Results clearly depict that the combination of grinding, heating and ammonia treatment resulted in the higher biogas yield. Thus, it was very clear that the pre-treatment has some significant role on the digestibility of the straw. Lawn grass-major fraction of USW was chosen and subjected to this digestion (Yu *et al.*, 2002). The digester employed in this study was 8m^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. This package gives the total porosity of 190 L/Column, operated like up flow anaerobic filter. Maximum loading rate in this digester was determined to be 2.7 kg of COD/m^3 of UAF per day. Yu *et al.*, (2002) also studied the effects of temperature on the gasification efficiency by using heated UAF in one of the reactor. Higher gas production was reported in the heated UAF was due to the higher COD conversion (35.6 kg of COD compared to the 26.4 kg of COD conversion in ambient UAF column). This COD conversion contributes 0.344 m^3 and 0.339 m^3 of CH_4 /kg of COD removed. Hence it is very clear that one kg of grass showed the yield of 0.15 m^3 of methane (Yu *et al.*, 2002).

2.5.5.5.Terrestrial and aquatic weeds

The use of weed plants, as a potential source of biomass is a rather recent concept. Aquatic macrophytes have been the subject of great interest for the past few years, because of their potential uses in wastewater treatment. The concept of using aquatic plants for water treatment and the harvested biomass as an energy source is gaining attention throughout the world. *Eichornia crassipes*, Water hyacinth, until 1940's and 50's was considered an obnoxious weed clogging up agricultural canal systems, dammed streams and encouraging mosquito breeding (Gopalakrishna, 1989). The prolific growth of water hyacinth and the ease of harvest techniques make it a suitable feedstock for biological conversion to methane. It can be utilised in both the fresh and dried forms serves as an alternative feedstock for the biogas production and can also be employed for phytoremediation purpose (Singhal *et al.*, 2003).

These non-conventional crops on wastelands and aquatic lands can be considered as potential biomass and used efficiently to recover the reserved form of energy, because:

- Weeds have ability to trap a significant amount of solar energy.
- Weeds are capable of growing on soils generally unsuitable for conventional crop production.
- The genetic base of weeds is such that many can grow under a wide range of cultural and climatic conditions.
- Weeds grow in natural stands without inputs and irrigation.

Hence the large-scale utilisation is one of the best strategies for weed management.

a. Terrestrial weeds

Parthenium hysterophorus, paper mulberry are some of the weeds used and studied as sources for methane production. Gunaseelan (1994) reported that anaerobic digestion of mixtures of chicken manure and *Parthenium* (flowering stage) enhanced methane production in batch digesters. Anaerobic digestion of *Parthenium* in CSTR at 30°C, 10 day HRT and 4.13 kg VS m^3 d^{-1} produced methane yield of 0.11 m^3 kg^{-1} VS added and volumetric methane productivity of 0.46m3 gas m^{-3} d^{-1}. Results on pre-treatment showed greater than 95% increase in methane production from NaOH treated *Parthenium* than untreated *Parthenium.*

b. Aquatic weeds

Chanakya *et al.*, (1992) utilised water hyacinth for biogas production. The total 19g TS of fresh and dry water hyacinth gave rose to 3.15g VFA, 4.02g, inturn corresponds to 1.64L, 1.63L gas production, showing the utilisation efficiency of 16.6%, 21% respectively. The ultimate methane yields from water hyacinth, based on BMP assay, showed that CH_4 yields were higher in shoots than roots (Shiralipour *et al*., 1984). The ultimate methane yield from water hyacinth, based on ABP assay was 0.34m^3 kg-1 VS added. Alkaline treatment with 50% NaOH increased the ultimate biodegradability by approximately 15%, and neither particle size reduction nor steam treatment exhibited any effects (Gunaseelan, 1997).

2.6. Bio-digesters

The bio-digester is a physical structure, commonly known as the biogas plant. Since various chemical and microbiological reactions take place in the bio-digester, it is also known as bioreactor or anaerobic reactor. The main function of this structure is to provide anaerobic condition within it. As a chamber, it should be air and watertight. It can be made of various construction materials and in different shape and size. Construction of this structure forms a major part of the investment cost. Some of the commonly used designs are discussed below.

2.6.1. **Floating drum digester**

Experiment on biogas technology in India began in 1937. In 1956, Jashubhai J Patel developed a design of floating drum biogas plant popularly known as Gobar Gas plant. In 1962, Patel's design was approved by the Khadi and Village Industries Commission (KVIC) of India and this design soon became popular in India and the world. In this design, the digester chamber is made of brick masonry in cement mortar. A mild steel drum is placed on top of the digester to collect the biogas produced from the digester. Thus, there are two separate structures for gas production and collection. With the introduction of fixed dome Chinese model plant, the floating drum plants became obsolete because of comparatively high investment and maintenance cost along with other design weaknesses.

2.6.2. **Fixed dome digester**

Fixed dome Chinese model biogas plant (also called drum less digester) was built in China as early as 1936. It consists of an underground brick masonry compartment (fermentation chamber) with a dome on the top for gas storage. In this design, the fermentation chamber and gasholder are combined as one unit. This design eliminates the use of costlier mild steel gasholder, which is susceptible to corrosion. The life of fixed dome type plant is longer (from 20 to 50 years) compared to KVIC plant. Based on the principles of fixed dome model from China, Gobar Gas and Agricultural Equipment Development Company (GGC) of Nepal has developed a design and has been popularizing it since the last 17 years. The concrete dome is the main characteristic of GGC design.

2.6.3. Deenbandhu model

In an effort to further bring down the investment cost, Deenbandhu model was put forth in 1984 by the Action for Food Production (AFPRO), New Delhi. In India, this model proved 30% cheaper than Janata Model (also developed in India) that is the first fixed dome plant based on Chinese technology. It also proved to be about 45% cheaper than a KVIC plant of comparable size. Deenbandhu plants are made entirely of brick masonry work with a spherical shaped gasholder at the top and a concave bottom. Preliminary studies carried out by BSP did not find any significant difference in the investment costs of GGC and the Deenbandhu design plants. Recently, Environmental Protection and Social Development Association (EPA), a NGO, has constructed modified Deenbandhu design plants in Bardiya district, which is also approved by Biogas Support Programme (BSP). In addition to above designs developed particularly for household use in developing countries, there are other designs suitable for adoption in other specific conditions.

2.6.4. **Bag digester**

This design was developed in 1960s in Taiwan. It consists of a long cylinder made of PVC or red mud plastic. The bag digester was developed to solve the problems experienced with brick and metal digesters. A PVC bag digester was tested in Nepal by GGC at Butwal from April to June 1986. The study concluded that the plastic bag bio-digester could be successful only if PVC bag is easily available, pressure inside the digester is increased and welding facilities are easily available (Biogas Newsletter, No. 23, 1986). Such conditions are difficult to meet in most of the rural areas in developing countries.

2.6.5. **Anaerobic filter**

This type of digester was developed in the 1950's to use relatively dilute and soluble waste water with low level of suspended solids. It is one of the earliest and simplest types of design developed to reduce the reactor volume. It consists of a column filled with a packing medium. A great variety of non-biodegradable materials have been used as packing media for anaerobic filter reactors such as stones, plastic, coral, mussel shells, reeds, and bamboo rings. The methane forming bacteria form a film on the large surface of the packing medium and are not carried out of the digester with the effluent. For this reason, these reactors are also known as "fixed film" or "retained film" digesters (Bioenergy Systems Report, 1984).

2.6.6. **Up-flow anaerobic sludge blanket**

This UASB design was developed in 1980 in the Netherlands. It is similar to the anaerobic filter in that it involves a high concentration of immobilized bacteria in the reactor. However, the UASB reactors contain no packing medium, instead, the methane forming bacteria are concentrated in the dense granules of sludge blanket which covers the lower part of the reactor. The feed liquid enters from the bottom of the reactor and biogas is produced while liquid flows up through the sludge blanket. Many full-scale UASB plants are in operation in Europe using waste water from sugar beet processing and other dilute wastes that contain mainly soluble carbohydrates (Bioenergy Systems Report, 1984). There are also other designs of anaerobic reactors, which are of less interest due to their limited utility. Reduction in investment cost using alternative construction materials has been one of the main driving forces in the development of new designs. In an effort to achieve this objective, use of bamboo, plastics and other such cheap construction materials have also been tried with varying degree of success (Cortsen, Lassen and Neilsen, 1995; Beteta, 1995). However, all such reported success stories are yet to take the form of implementation programmes in a mass scale.

2.7. Current status: Need for new biogas producing technologies

Variations in reactor design, operating conditions and feed composition will result in changes within the microbial populations present in the system. Further insight into these changes is not only beneficial from a microbiological point of view but also in the development of novel reactor designs and modes of operation. In addition, Wase (1984) reported that the choice of the digester is therefore considered in relation to the waste itself, results in the possibilities of increased use of anaerobic digestion as a treatment process arise from the introduction of improved reactor designs. The digester performance is highly sensitive to the quality of the feed of wastes, then yield and kinetics of the biological reaction involved in anaerobic digestion being strongly dependent upon waste composition (Archana *et al*., 1999). There are no simple biogas producing technologies capable of continuous operation using solid wastes without investing substantial capital and energy in to slurrification. Such slurrification does not suit for the Indian context. The CST (IISc campus) has addressed this problem and developed the plug flow and solid state stratified bed fermenters for the effective anaerobic treatment:

2.7.1. Solid state stratified bed reactor (SSB)

SSB reactor came in to existence to overcome the problems related to floating, pre-treatment and feedstock addition. By virtue of its ability to accept fresh or dried feedstock without serious operation problems makes it an attractive process option. The SSB digesters permitted the use of untreated, large sized biomass feedstock and avoided particle size reduction. Simple reactor design constitutes the digester, which inturn is connected to the gasholder. A two-reactor configuration may be simplified into a single reactor configuration when methanogen rich biomass bed is placed in the lower part of the reactor and operated in the following manner. When a small quantity of recycled digester liquid was sprinkled over the decomposing biomass bed in solid-state stratified bed digesters, VFA rich pockets were dissipated. When these VFAs reach the lower part of the biomass bed intensely colonised by methanogens, they are quickly converted to biogas (Chanakya *et al.*, 1995). Therefore it is possible to design and operate a two-phase system within a single vessel functioning as a stratified bed reactor. This greatly simplifies design and operation for small-scale rural use. In such a process, fresh feedstock needs to be introduced on top of the bed and spent biomass needs to be taken out from below in order to permit continuous operation. Such a fermentation process also overcomes another problem, namely, the need to add biomass feedstock without concomitant introduction of air. Untreated and intact biomass feedstock can thus be introduced through a hatch at the top of the biomass bed being predominantly acidogenic; the overall process is not affected (Chanakya *et al*., 1995). This is because the methanogens are colonised far below in the decomposed bed and oxygen (in air) introduced at the top does not reach these lower layers. This therefore greatly simplifies the feedstock addition and fermenter design. It is also not necessary to maintain a large liquid phase in the reactor because only an equivalent of 5-10% of the fermenter volume needs to be used as a liquid phase, which is continuously recycled.

The solids retention time in such fermenters are thus governed by:

- The duration for which there is a VFA flux (rapid acidogenic stage).
- The rate of compaction of biomass feedstock.
- The rate and extent to which methanogens colonize on decomposed biomass.
- The quantity of methanogen colonised decomposed biomass to be retained for converting the VFA fluxes to biogas.

2.7.2. Plug flow bioreactor

The plug flow digester is similar to the bag digester. It consists of a trench (trench length has to be considerably greater than the width and depth) lined with concrete or an impermeable membrane. The reactor is covered with either a flexible cover gasholder anchored to the ground, concrete or galvanized iron (GI) top.

In the plug flow digester, a volume of the medium with a suitable inoculum enters at one end of the tube and, if the rate of passage of the medium is correct, by the time the medium reaches the other end, denotes that the digestion is completed. For continuous operation, some of the digested effluent flowing from the end of the tube is separated and returned to the influent substrate. Rapid initial decomposition of the feed to volatile fatty acids takes place within 3-5 days of feeding. This takes place when the biomass is still forcibly submerged in water. As a result proper diffusion of VFA's is obtained which prevents their accumulation. When the biomass is still under water and the rapid VFA producing constituents are removed from them, methanogenic bacteria colonize on it and gas is produced from itself. The gas bubbles adhere to the biomass because of which its buoyancy increases and it soon begins to float. At this stage even though biomass remains a float there is adequate methanogenic activity and VFA produced is converted to biogas without facing VFA over-production and subsequent souring. Towards the end of 30-40 days SRT, much of the VS are decomposed but the feedstock is usually still float, albeit to a lesser degree and is manually removed to enable continuous operation.

2.7.3. Valorga process

The Valorga technology was developed initially in France and later by Steinmuller Valorga Sarl, a subsidiary of the German company Steinmuller Rompf Wassertechnik GmbH. The process was initially designed to treat organic MSW and was later adapted to the treatment of mixed MSW, biowaste (source separated household waste), and grey waste (organic residual fraction after biowaste collection). The Valorga process plant consists of essentially six units: waste reception and preparation unit, AD, compost curing, biogas utilization, air treatment, and an optional water treatment unit (when effluent is not treated in municipal wastewater treatment plant). The reception unit has a scale for weighing the trucks bringing in the organic materials. The waste is unloaded in a closed pit equipped with a foul air collection system. The feed material passes through an electromechanical system, designed according to the waste to be treated, that includes plastic bag opening and size reduction equipment. The waste is then conveyed and fed continuously to the AD unit. In the AD unit, the waste is mixed with re-circulated leachate into a thick sludge of about 20-35% solids content, depending on the type of waste. Therefore, the water requirement is minimal. The digester operates either in the mesophilic range or the thermophilic range. The Valorga digesters are concrete vertical cylinders of about 20 meters height and 10 meters internal diameter. They are designed so as to maintain plug flow through the reactor. They are equipped with a vertical partition in the center that extends over 2/3 of the diameter and over the full height of the reactor. This inner partition minimizes shortcircuiting of the sludge and ensures plug flow through the entire volume of the reactor. The orifices for introducing feed and removing digestate are located on either side of the inner wall. Mixing of the fermenting material is provided by a pneumatic system i.e. biogas at high pressure is injected through orifices at the bottom of the reactor and the energy of the rising bubbles serves to mix the sludge. There are no mechanical parts and maintenance consists of periodic cleaning of the nozzles at the bottom of the digester. The digested material exiting the reactor goes through a filter press that separates the compost material from the leachate solution. The leachate is reused for diluting incoming waste and any excess is transferred to the water treatment unit or the municipal sewage network. The filter cake is transferred to composting piles where it is subjected to curing in a closed building for about two weeks. Stones and other inert materials are removed. The compost product is considered to be of high quality and is sold as soil conditioner. The biogas produced is used to generate electricity and steam or is fed to the city gas network. The biofilters and the water treatment facilities ensure that the Valorga plants control all air and water emissions and meet local regulations (Source: Verma, 2002). Laclos *et al*., (1997) showed that the valorga plant in Tilburg (methane yield-210 to 290 m^3 STP/ Mg of VS) clearly demonstrate that anaerobic digestion can be considered as a reliable industrial process for the treatment of organic solid waste.

Boullagui *et al*., (2003) focussed on the performance of tubular digesters treating FVW. The results clearly revealed that the FVW could be treated anaerobically with a high stability, a high depurination rate and energy recovery with a good process economy. Also showed that the most significant factor of the tubular reactor is its ability to separate acidogeneis and methanogenesis. Lomas *et al*., (1999) studied the operational performance of down flow stationary fixed film (DSFF) anaerobic reactor treating piggery slurry showed the gas yield of 4.5 m^3/m^3/d for the 3 days HRT, suggested the convenience of the DSFF system for the design of full scale plants for slurries from piggery farms.

2.8. Application of biogas technology

Biomethanation results in the generation of three useful products namely biogas, digester sludge and spent residuals.

2.8.1. Utilisation of sludge

Hons *et al*., (1993) utilized the sludge generated by the anaerobic fermentation of biomass to methane for land application. This study was done with regarding the effects of loading rate of methane generator sludge on nutrient mineralisation, plant growth and nutrients uptake and potential water pollution. Results imply that the sludge can serve as a source of nutrients, especially nitrogen and phosphorus and also may used to help in neutralizing soil acidity. However over application of sludge results in excess of available ‘N’ leading to ‘NO3’ leaching.

2.8.2. Utilization of digested biomass

Digested biomass results from biogas plants can be used in two ways. Either in acting as a support for growing edible mushrooms or by acting as a methanogenic bio-film in treating liquid waste water. It acts as an excellent support material by providing the adequate potential for the cultivation of edible mushrooms. Since it retains 40-60% of the cellulose and lignin (Chanakya *et al*., 1993). Chanakya and Ganguli, (1994) reported the feasibility of mushroom cultivation on spent biomass from biogas plants.

Conclusion

Thus the above chapter clearly picturised the components of USW, their technological options. It also dealt with the reactions that are taking place inside the digester. In spite of reactor cost, anaerobic digestion by means of useful energy recovery and value added compost (employed as a soil conditioner) or reuse as bacterial support in high rate digesters (resultant spent material) seems to be very effective than the composting and other thermo chemical technologies. Hence an attempt is made in this study, to treat the different components of USW namely, fruit wastes, paddy straw, sugarcane trash, bagasse, paper mulberry and water hyacinth in SSB digesters. In addition, reuse of these digested material as a methanogenic biofilm in treating liquid wastes under DFFB mode was studied. It has also been reported that the combination of aerobic composting and anaerobic digestion is the effective one in treating organic fraction of bulky wastes.

Chapter 3: Materials and Methods

This section describes the methodology and analytical procedures followed for the study. First part describes the method used for anaerobic digestion of solid waste using solid-state stratified bed reactor (SSB) process. The decomposition pattern of various feedstocks has been studied. This decomposition pattern of the feedstocks studied was finally correlated with daily gas production rates. This correlation provided the basis to estimate efficiencies of conversion to biogas. In the second part decomposition of a liquid waste in a down-flow fixed bed reactor (DFBR) was studied. The overall intention is that solid wastes digested in a SSB reactor provide necessary support material for immobilization of methanogenic bacteria. In this, digested waste acting as bed material (immobilized methanogenic biofilm) is studied for their efficiency to treat the liquid waste; finally, a potential for simultaneous conversion of solid and liquid wastes. In addition, BMP assay was performed to determine the ultimate methane yield of feedstock studied.

3.1. Solid waste treatment

3.1.1. Experimental Runs

Experiment was carried out in two runs. Preliminary run recorded the fermentation of 11 feedstock for 70days. Fermentation characteristics and anaerobic digestion properties of these feedstocks and extent of gas production were studied (Chanakya *et al.*, 1997) extensively in the past. Based on the first run experimental results, feedstocks were chosen for second run experiment. Wherever the samples have produced biogas with the volumetric efficiency close to 1L/L/d in the first run were chosen to determine the reproducibility of such high biogas yield. In a second run experiment, reactors were run in duplicates. In addition vegetable waste representing major part of USW was also included to determine biogas production of that feedstock.

3.1.1.1. SSB-reactor design

Fermentor used in this study was built using PVC irrigation quality pipes and comprised of the following features (Fig 3.1):

- A 4mm thick PVC pipe (152mm dia) was used as corrosion-free fermenter vessel. It was built to provide a total volume of 8L with a working volume of 6L.
- A metallic cover seated in water sealed annular space placed at the top ensured anaerobic conditions. This hatch was lifted whenever feedstock addition was needed.
- A water jacket was built on the top to facilitate water sealed feedstock inlet. It also provided an anaerobic path for recycling fermenter liquid as a sprinkle on the digesting biomass bed.
- A perforated bowl placed on the top of the reactor vessel and in the path of recycled digester liquid assisted uniform sprinkling of recycled fermenter liquid on the biomass bed below.
- A bottom trough containing about 6L of fermenter liquid formed the liquid reservoir.

- A 100mm inverted PVC pipe was used to determine daily gas production by downward displacement measurement of air. This had a transparent polythene tube (Fig 3.2) on the outside, and facilitated in recording water level measurements (gas production) on a daily basis. Everyday the water level was to be brought to zero by evaluating the headspace using rubber bellows or vacuum pump.

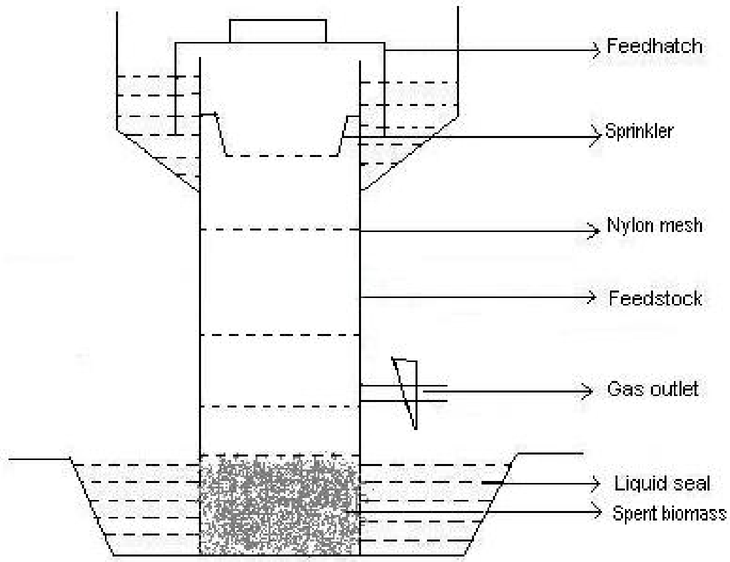


Fig 3.1. Sketch of SSB reactor.

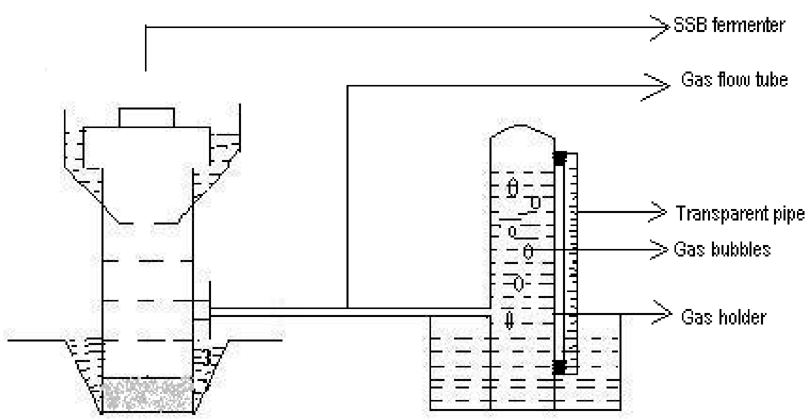


Fig 3.2. Sketch showing gas measurement by downward displacement of water.

3.1.1.2. Feedstock

Two types of feedstocks were used for the study, fresh feedstock and dry feedstocks, shown in the Table 3.1.

Table 3.1: Feedstock used for the study

S.NO.	Fresh feedstock	Dry feedstock
1.	Vegetable wastes Mixed fruit wastes Watermelon rind (25%) Orange peel (25%) Banana peel (25%) Sweet Lime (Mosambi) peel (25%)	Bagasse
2.	Water hyacinth leaves	Photocopying paper
3.	Water hyacinth roots	Sugarcane trash
4.	Water hyacinth whole plant	Paddy straw
5.	Paper mulberry	Dry water hyacinth

3.1.1.2. Collection

Feedstock used for the study purpose was collected from the various places and are listed in Table 3.2.

Table 3.2: Sources of feedstock chosen for study.

S.No.	Feedstock	Place of collection
1.	Water hyacinth	Hebbal lake.
2.	Paper mulberry	CST, IISc campus.
3.	Fruit waste, Bagasse	Fruit juice shop (IISc campus and in Yeshwantpur).
4.	Photocopying paper	IISc Xerox center and in CES library.
5.	Sugarcane trash and Paddy straw	From the small scale sugarcane juice expellers and shop.

3.1.1.3. Rationale for the choice of feedstocks

The above said feedstocks were chosen, based on the following properties, makes it an attractive feed for energy recovery through biogas. Mixed fruit wastes represent a significant component of USW found on the campus as well as about 20% in the city of Bangalore (Rajabapaiah, 1990, 1995). Paper mulberry is one among the major tree species that contributes to leaf litter in IISc campus (Kumar *et al.,* 2001). Paper mulberry has been chosen as a representative of rapidly decomposable species (Chanakya *et al*., 1999) for their leaf litter. Water hyacinth represents a plant often used in nutrient harvest from tertiary treatment of wastewater. These can be harvested to provide energy and tested under SSB conditions for energy recovery. Photocopying paper represents a large paper component of USW on the campus (Kumar *et al*., 2001). Paddy straw and bagasse represent natural material that can be used for packaging in urban areas as well as agro residues that have potential to survive long as biofilm support in DFFB reactors.

3.1.1.4. Feed rate

The feed rates adopted were 2 and 1gTS/L/d for fresh and dry feedstocks respectively. This feed rate was followed after the completion of the startup procedure. This feed rate has been arrived at from previous studies, which show that these are the maximum possible feed rates for these feedstocks for operating at 70d SRT.

3.1.1.5. Inoculum

Two kinds of inocula were used to ensure a rapid start-up of SSB digester a solid and a liquid inoculum. Digested biomass obtained from a $3m^3$ pilot scale SSB reactor was used as a starting bed (source of pre-colonized methanogens) and this was the 'solid' inoculum.
The digester liquid from the same pilot plant was used for initiating acidogenic digestion (liquid inoculum). This also served to hydrate dry feedstocks. The TS and VS of this inoculum are given in the Table 3.3.

Table 3.3: Characteristics of inocula used for study.

S.NO.	Inoculum	%TS	%VS	COD mg/L
1.	Solid inoculum-spent biomass	30	53	ND
2.	Liquid inoculum-digester liquid	0.1	ND	200

ND – not determined.

3.1.1.7. Start-up procedure

SSB Fermenters were placed in a plastic tub of 6L capacity as shown in Fig 3.1. To start the process, digested biomass from a pilot scale SSB fermentor was used as a starting bed, placed in the lower 5 cm of these lab scale fermentors. This bed contained digested biomass that had a large population of methanogenic bacteria. Such a bed is required to initiate the SSB process (Chanakya *et al.*, 1995). A perforated bowl (sprinkler) was placed at the top (Fig 3.1), and was followed by closing the feed hatch. The bottom trough in each of these fermenters was then filled with 5L of liquid inoculum. In order to ensure the right balance of methanogenic and acidogenic organisms, this inoculum was previously enriched with slow growing methanogens by adding 1mL/L acetic acid to the liquid inoculum for three consecutive days prior to startup. This ensured high activity of aceticlastic methanogens on the spent biomass bed also. Initially, 1L of the digester liquid was recycled everyday. This recycling through a sprinkler bowl facilitated the uniform distribution of digester liquid over the decomposing biomass bed. The daily recycling process resulted in the dissipation of VFA, generated in the acidogenic layer, which leached slowly to the lower parts of the biomass bed. This bed is intensely colonized by methanogens (Chanakya *et al.*, 1995) and leads to the rapid conversion of VFA leaching down to biogas. In addition to this, this liquid layer provided a liquid seal around the feed hatch. Consequently it maintained anaerobic conditions inside.

All the fermenters were initially operated for 15 days without the addition of biomass feedstock. This ensured that all the residual gas potential from the starting biomass bed fell to low levels. These fermenters were then fed with the respective feedstocks by removing the top cover, placing a nylon mesh containing pre weighed feedstock on the existing biomass bed and replacing the top cover immediately. Pre-compaction of the feed was not adopted during the study period.

These fermenters were fed at weekly intervals as mentioned under “feed rate”. A nylon mesh was placed between the layer of each week’s feed so as to facilitate the collection of week-wise samples of decomposed feedstocks for physico-chemical analyses to be carried out at the end of the study period. These fermenters were operated for 70 days in the above mode. Liquid recycling was carried out twice a day to provide a recycle rate of 0.5L/L/day. Recycle rate was increased up to 1L/L/day, when the pH levels fell or gas production levels decreased. This increased recycling rate ensured that the bed within did not have VFA rich pockets and caused inhibition to methanogenesis.

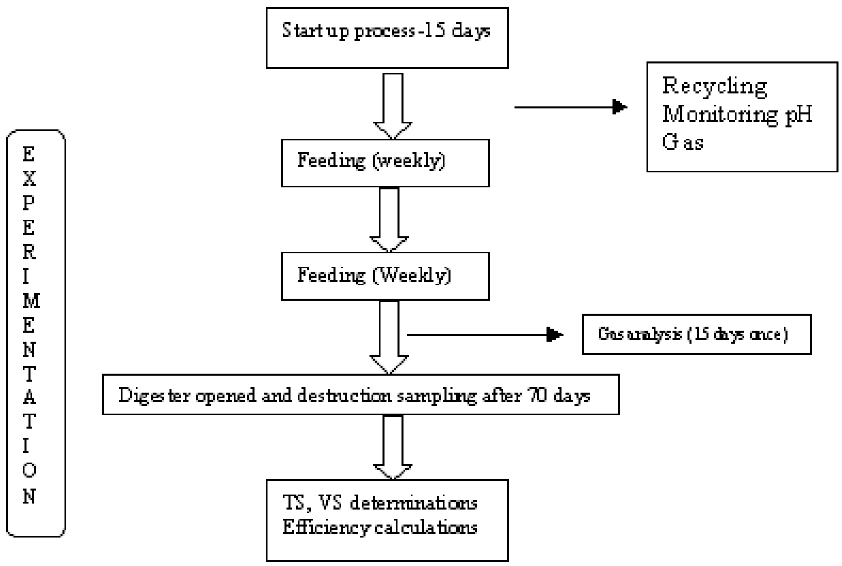


Fig 3.3. Overall experimental protocol

The sequence of operations and monitoring components are presented in Fig 3.3. The total run of the experiment lasted 70 days with a 15d-startup period, was followed by analysis of samples recovered from the destructive sampling of the fermentation feedstocks.

3.2. Biochemical methane potential assay (BMP)

This assay was carried out to determine the ultimate methane yield of the feedstock. To prepare 1% and 2% TS suspension, 0.5 or 1g dried and powdered biomass samples were weighed and added to 133mL serum vials (Fig 3.4) in triplicates. 50mL of methanogen-enriched inoculum was added when all the vials were fed with feed stock samples. Following inoculum addition, these serum vials were rapidly flushed with biogas first and second with high purity nitrogen to remove all traces of oxygen. Flushing twice ensured that good anaerobic conditions prevailed in the headspace and methane levels in headspace were greatly diminished. These vials were closed with rubber stoppers immediately after flushing with biogas. After flushing with nitrogen using hypodermic/spinal needles, they were sealed with aluminum crimps. Then these vials were incubated at 35°C (± 2°C) in an incubator for determining the BMP.

Inoculum used for the study purpose was prepared using the digester liquid effluent from the pilot scale biogas reactor, which was filtered, through a mesh (2mm-pore size) to remove digested particles of leaf etc. It was supplemented with 1ml of acetic acid as a stimulant for aceticlastic methanogens for three consecutive days. After the third day, it was observed that the aceticlastic methanogenic population was high, this inoculum was used for the BMP assay. Control bottles received only the inoculum and not the substrate.

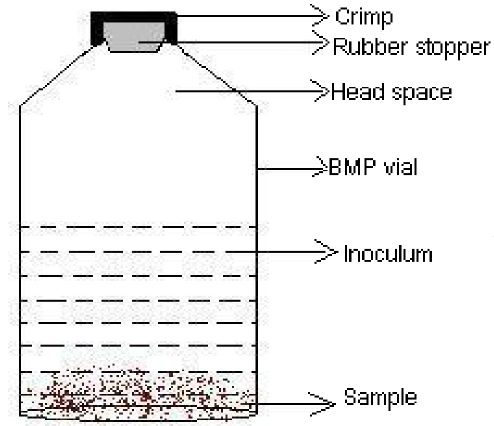


Fig 3.4. Sketch of BMP vial.

3.2.1. Measurement of produced gas in the BMP vials

The volume of gas produced in the BMP vials was measured by the downward displacement of water in an inverted burette (Fig 3.5). In the beginning gas volume was measured on alternate days. Then the sampling gap was increased to 7d, when the gas production rate decreased after 15 days. Subsequently between 35-90d the gas production was monitored at 15d intervals.

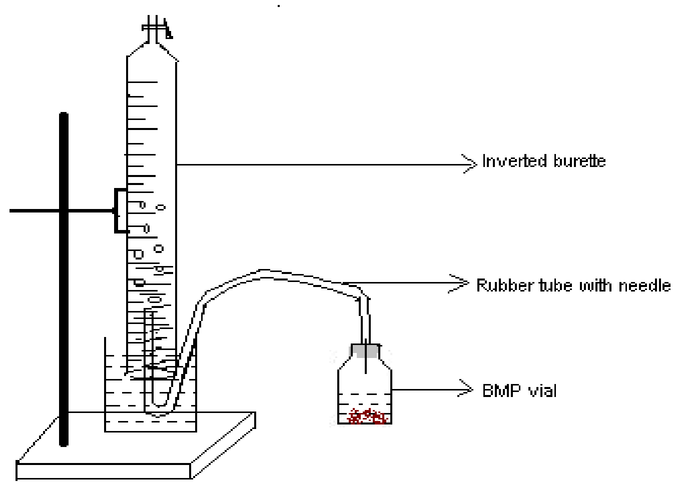


Fig 3.5. Sketch showing the set-up used for measurement of gas production from BMP vials

3.2.2. Composition of biogas

150 μL of headspace gas from the BMP vials were sampled using a microlitre syringe and its composition was determined using a gas chromatograph (Chemito 3800). The conditions of operation were as follows: - Detector- thermal conductivity detector (TCD), carrier gas – hydrogen, flow rate- 20mL/min, temperature at various points in the GC was injector - 45°C, oven - 48°C, block - 90°C ± 0.5°C, mean constant temperature setting - 200°C. The TCD block was set to 90°C ± 0.5°C with a current level set to achieve a 200°C mean constant temperature (MCT) of the coils. This generally gave a current level of 180 μA. The signal was attenuated 64 times to suit a 1mv full-scale deflection (FSD) on a strip chart recorder to obtain hard copies of the chromatogram.

3.2.3. Estimation and interpretation of BMP results

The biogas potential was determined by carrying out biological methane potential assay (BMP) of the individual feedstock under laboratory conditions in micro-digesters with three replicates for each of the two concentrations tried. BMP assay has been developed to determine the ultimate biodegradability and associated methane yield estimates of organic substrates (Chynoweth *et al.*, 1993; Gunaseelan, 2004). This basic procedure was modified to obtain, in addition to BMP, a greater extent of information on the fermentation properties and vulnerability to various forms of inhibition (Chanakya *et al*, 1997). This latter method is relatively simple and reliable method for comparison of extent and rate of conversion to methane. The results of modified BMP carried out under ideal conditions (temperature and known quantity of inoculum concentration) are presented in light of the following inferences that can be made:

1. Initial phase of the gas production (beginning of the fermentation period, 0-5d) is used as an index to predict the presence of a large VFA flux and resultant problems in methanogenesis (methanogenic inhibition, Cho *et al.*, 1995). A rapid initial gas production accompanied by high CO_2 concentration (product of acidogenesis- Denac et al., 1988) as well as very low CH_4 production is indicative of a rapid initial VFA flux and inadequate methanogenesis. Feedstocks that exhibit this pattern were considered to be liable for initial VFA flux and consequent VFA induced methanogenic inhibition.
2. The steady state gas production was examined to infer whether firstly such a steady state phase could occur under BMP conditions. Secondly, once such steady state biogas production occurred, the presence of a balanced methanogenesis and acidogenesis was looked for. The presence of balanced acidogenic and methanogenic activities was inferred from a proportion of methane concentration higher than 40% in the ensuing biogas. It is also seen that on occasions, the methane concentration gradually recovers to reach levels >40% which has been set as a bench mark for active methanogenesis (Chanakya *et al*., 1993).
3. Following the occurrence of a rapid or steady decomposition phase, the gas production levels off for various reasons – mainly from the lack of decomposable constituents in the feedstock sample. The time and duration for which such an event occurred was recorded. From this pattern it could be inferred that beyond a certain point (fermentation period) the gas production slows down and gas recovery beyond this is unlikely to be economic ($0.632_{max\ yield}$; Gunaseelan, 2004; Hashimoto, 1996). However, the value of 0.632 used in the above two studies refers only to straw and

this level needs to be identified separately for different feedstocks. The period or point beyond which the gas production levels off is considered as the beginning of the leveling off phase or the end of steady state and useful gas production. This point is considered specific to each of the feedstock (Chanakya *et al*, 1999).

4. A fourth inference of the modified BMP assay is the occurrence of a significant difference in the pattern of gas production between 1 and 2% concentrations of feedstock. The use of 1 and 2% concentrations in the modified BMP assay has been evolved from previous efforts in biomass fermentations where it was established that a >5-6g/L VFA was inhibitory to biogas production with leaf biomass feedstocks (Chanakya *et al*., 1992, 1993). The presence of a significantly inhibited gas production between 1 and 2% concentrations suggests that the VFA production rates are higher than that capable of being consumed by methanogens under existing fermentation conditions.
5. A fifth inference from the pattern of modified BMP is the occurrence of a late revival of gas production that occurs well after the leveling off takes place. From such an event it is deduced that there is a non-VFA induced inhibition of gas production for which there is insufficient data to explain the inhibition. Understanding this inhibition requires that further research be carried out.
6. The sixth and final inference is the ultimate biogas potential of a certain feedstock. The occurrence of an uninhibited gas production pattern well within reasonable range for solids to gas conversion is considered as the ultimate BMP under conditions of modified BMP assay as indicated before.

Another indirect inference is the maximum solids residence time (SRT) under batch conditions of modified BMP assay. The period after which the gas production levels off is considered the maximum SRT required for batch fermentation. It is then acknowledged that the SRT required under continuous fermentation will be only a fraction of this period. The results of these modified BMP assays are arranged in the order of the dried feedstock presented first and the fresh feedstocks presented later.

3.3. Liquid waste treatment

3.3.1. Fermenter design

Laboratory scale down-flow fixed bed reactor (DFFB), fabricated with transparent acrylic with a volume of 10L capacity was used for the study purpose (Fig 3.6). Digested biomass feedstocks was placed between two stainless steel meshes. In addition, it also contained two corrugated stainless steel meshes, one at the top and another one below, to prevent the biomass feedstock from floating as well as to assist easy release of gas. Between these meshes, the biomass feedstock to be studied for their efficiency as a microbial support for biomethanation process were packed to give a working wet density of 150-250 g/L depending upon the support. The sketch of DFFBR is shown in Fig 3.7. Each of these DFFBR was connected to 4L PVC gas storage vessel. Gas accumulation in these was measured by downward displacement of water shown in the Fig 15. After measuring the water level, it was restored to a liquid level of 0 by extracting/sucking out the gas within using suction pump on a daily/twice daily basis.

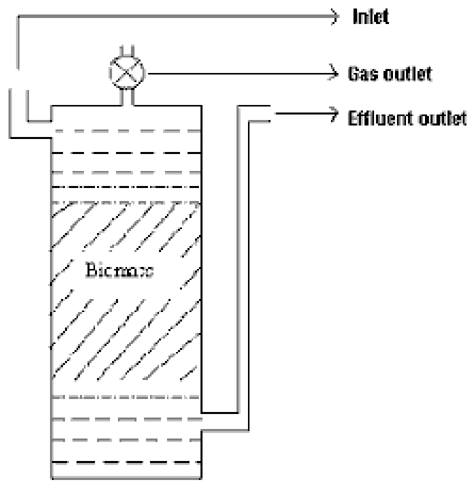


Fig 3.6. Sketch of laboratory scale DFFBR

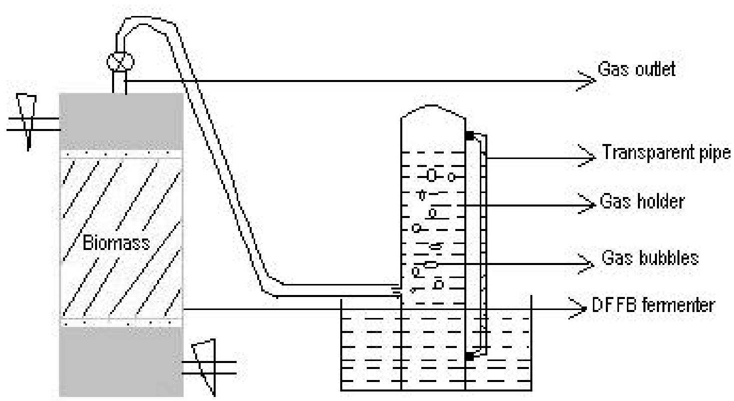


Fig 3.7. Sketch of DFFBR showing gas measured by downward displacement of water.

3.3.2. Materials used as biomass support

Two types of biomass and one synthetic support were studied for their ability in immobilizing the methanogens as biofilm on themselves namely, bagasse, bagasse + biomass (1:1) and reticulated PVC (Fujino spirals).

3.3.3. Collection

Support materials used for the study purpose were collected from the following locations, bagasse – sugarcane juice expellers, reticulated PVC – commercial brand Fujino spirals, and bagasse + biomass - sugarcane juice expellers + spent feedstock from the pilot scale PFBR.
In previous studies it was shown that green leaf biomass (Chanakya *et al.*, 1992,1998**)** and straw (Andersson and Bjornsson, 2002) provided good colonization of methanogens. However, these biomass supports had half-life of 120d. Bagasse and bagasse + biomass were used in this study with a view that these materials will have longer operational life compared to leafy biomass alone used as support.

3.3.4. Start-up

The reactors packed with the above mentioned materials were initially filled with digester liquid extracted from a SSB digester. This setup was allowed to stand for 15 days period to facilitate the growth of bacterial film on the packing materials. This also ensured that the residual gas from these bed materials fell to low levels before they were fed synthetic wastewater.

This typical liquid waste (synthetic wastewater) bearing known quantities of suspended and dissolved solids was prepared by boiling rice flour with 100-200ml of water. This was cooled and diluted further with digester liquid, and fed into the reactor. In order to study the efficiency of performance of the bed material, COD conversion rates of that typical were monitored. These reactors were operated at room temperature with a residence time (HRT) of 24 hours for the liquid waste. Feed rates in increasing steps were adopted to study the maximum conversion sustainable in this reactor. When reactors showed low pH or odour of VFA was detected, these reactors were then operated at 50% recycle to ensure the bacterial and nutrient sufficiency. The influent and effluent COD was determined daily to measure the COD degradation in the feed. A peristaltic pump was used for the feeding.

3.3. Physico-chemical analyses

The pH of digester liquid, influent and effluent, temperature and COD of the influent and effluent, gas production volume was monitored daily. Composition of gas collected was carried out to determine the methane content of biogas once in 15 days. In addition to this, TS and VS of synthetic liquid waste were determined. The TS/VS lost in each layer of the SSB fermenter and efficiencies of VS conversion to gas was also monitored at the end of study. These parameters were determined in accordance with APHA (1975).

a. Total solids (TS)

Total solids denote organic as well as inorganic matter in the feedstock. TS were measured according to APHA (1975). Between 15-20g of fresh feedstock was weighed (W2) in an empty crucible (W1) and dried in an oven maintained at 90°C for 24h (W3). Per cent TS was calculated as:

$$\% \text{ TS} = \frac{\text{W3-W1}}{\text{W2-W1}} \text{ X } 100$$

b. Volatile solids (VS)

Volatile solids represent organic matter of the feedstock (excluding the inorganic salts, ash). This was measured in accordance with APHA (1975). 2-3g of oven dried sample was weighed (B) in an empty crucible (A) and heated to 550°C for 1hour in the muffle furnace to constant weight (C). Per cent VS was calculated as:

$$\% \text{ VS} = \frac{\text{B-C}}{\text{B-A}} \text{ X } 100$$

c. Chemical oxygen demand (COD)

COD was estimated by standard method outlined in APHA (1975). A known quantity of sample was taken in the conical flask. 10ml of potassium dichromate (0.25N) was pipetted out into the conical flask. 20ml of sulphuric acid was measured and added to the conical flask rapidly. This mixture was kept undisturbed for half an hour for digestion. After half an hour, 4-5 drops of ferroin indicator were added and it was titrated against ferrous ammonium sulfate solution (0.25N). The change in the colour from blue green to wine red was the end point. COD of the sample was calculated as,

$$\text{COD (mg/L)} = \frac{\text{(B-A) X 1000 X 8}}{\text{C}}$$

Whereas, B = Volume of the titrant used against blank.
A = Volume of the titrant used against sample.
C = Volume of the sample taken.

3.4. Indicators of efficiency

The performance efficiency of the reactor and conversion efficiency of feedstock is estimated from the following indicators:

a. TS/VS lost

Initial TS/VS of the feedstock was determined before feeding in to the reactor. After destructive sampling, the final TS/VS was determined. The difference between the initial (mass of TS/VS fed) and final TS/VS (residual TS/VS in the digested feedstock) gave the quantity of TS/VS lost. i.e. degradation is calculated as,
TS/VS lost = Initial TS/VS-final TS/VS.

b. TS/VS to gas

The mass of TS/VS lost was determined after destructive sampling as mentioned above. It was presented as litres of biogas produced per gram TS/VS lost. This gave an index of process efficiency.

c. **Expected gas production level from TS and VS lost**

A mass balance approach was used to estimate the theoretical gas yield from the TS/VS lost. The mass of VS lost (cumulative) was assumed to be completely converted to biogas. The biogas equivalent of the VS lost was compensated to local conditions of temperature, pressure, and 4%water vapor to determine the theoretical gas production volume. The difference between the observed and the theoretical gave the TS/VS lost to microbial biomass, process inefficiency (such as, conversion proceed till the formation of VFA not further to gas) and physical leakage.

Chapter 4: Results and Discussion

The results obtained from the SSB fermentation of various feedstocks, the biogas potential (BMP assay) of the 11 feedstocks and the potential of two digested USW feedstocks for use as methanogen support are reported in this chapter. They are placed in three sections in the same order as above.

4.1. Fermentation pattern of feedstocks in SSB fermentors

Results in this section are grouped into dry and fresh feedstocks for convenience of comparison and discussion. The results and their interpretation for the 11 feedstocks are limited to a fed batch strategy of operation. These results of run 1 depict a pattern relevant to a start-up situation during the first 10 weeks of operation and digesters are at best expected to reach only a pseudo-steady state. The results of run 1 have two component operation parameters and conversion parameters. The results of run 2 however are expected to depict steady state operation with a chosen few feedstocks.

4.1.1. Feed rate

Feed rate for each feedstock was determined by considering the bulk density of the feedstock. Hence it differs for each feedstock. The ideal feed rates for dry and fresh feedstocks are between 1 and 2gTS/L/d. These feed rates were chosen based on past experience to give a daily biogas output between 0.25-0.55m^3/m^3/d (Chanakya *et al*., 1999). A gradual increase in the feed rate was adopted in the initial period to reach 1g (Fig 4.1) and 2g TS/L/d (Fig 4.2) for dry and fresh feedstocks respectively.

Under pseudo steady state operation with dry feedstocks a maximum of 0.5kg TS/m^3/d feed rate could only be possible. Higher feed rates, especially with feedstock like bagasse, did not result in adequate compaction. Feed rates in all the dry feedstocks could be maintained at 0.5kg TS/m^3/d. This appears to be a limiting factor under laboratory conditions.

The natural compaction rates during initial decomposition of fruit wastes and paper mulberry leaf litter permitted achieving a steady state feed rates of 2.0kg TS/m^3/d while fresh water hyacinth whole plant permitted only a 1kg TS/m^3/d feed rate. Fresh water hyacinth roots as well as shoots permitted a feed rate of 0.5kg TS/m^3/d under fermentation conditions adopted.

Photo copying paper among the dry feedstock and fruit wastes among the fresh feedstock showed adequate levels of compaction. The feed rate could be increased to 1.5gTS/L/d for photo copying paper. Chanakya *et al.*, (1998, 1999,1993) reported good gas yield by employing this kind of feed rate.

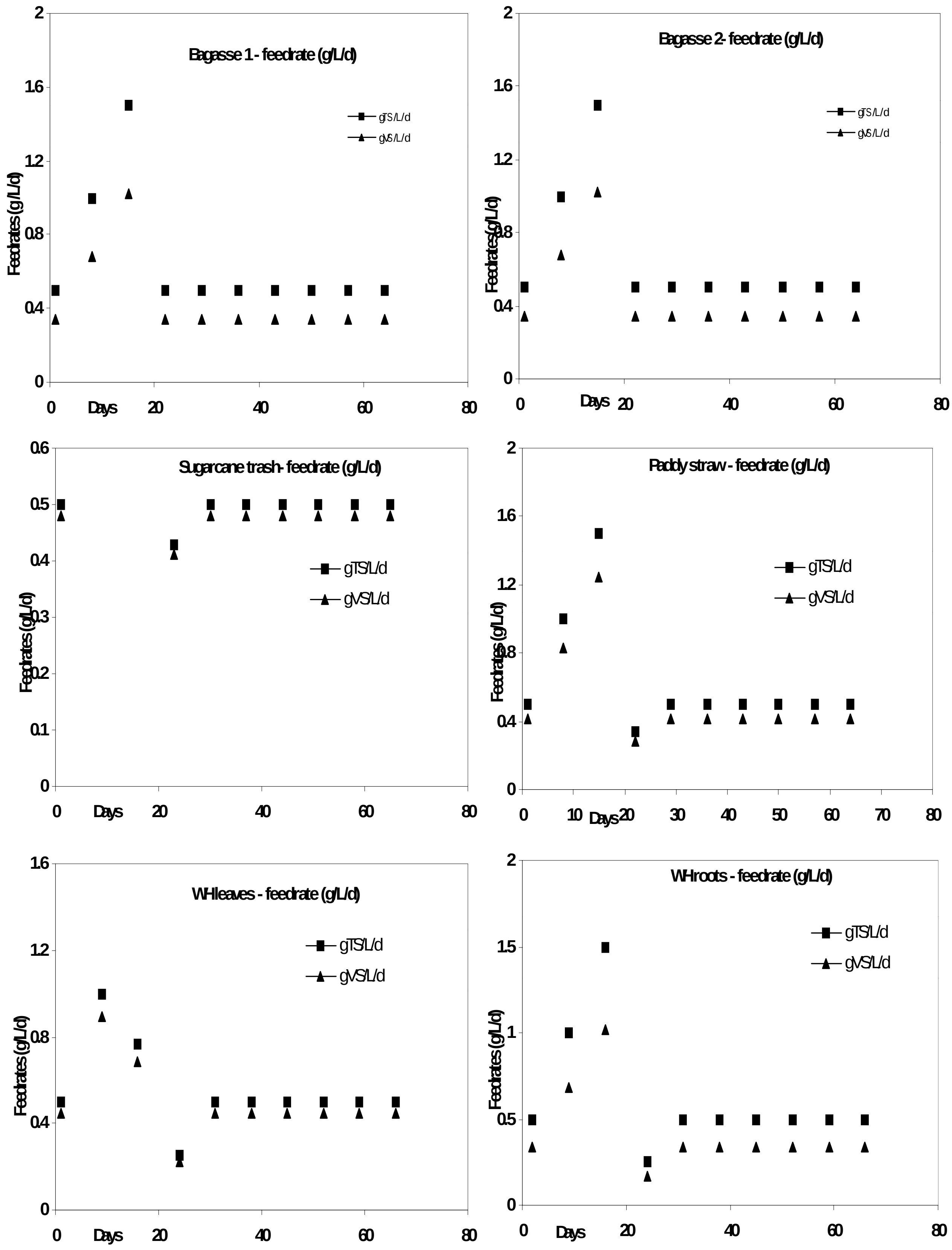


Fig 4.1. Feed rates achieved for dry feedstocks

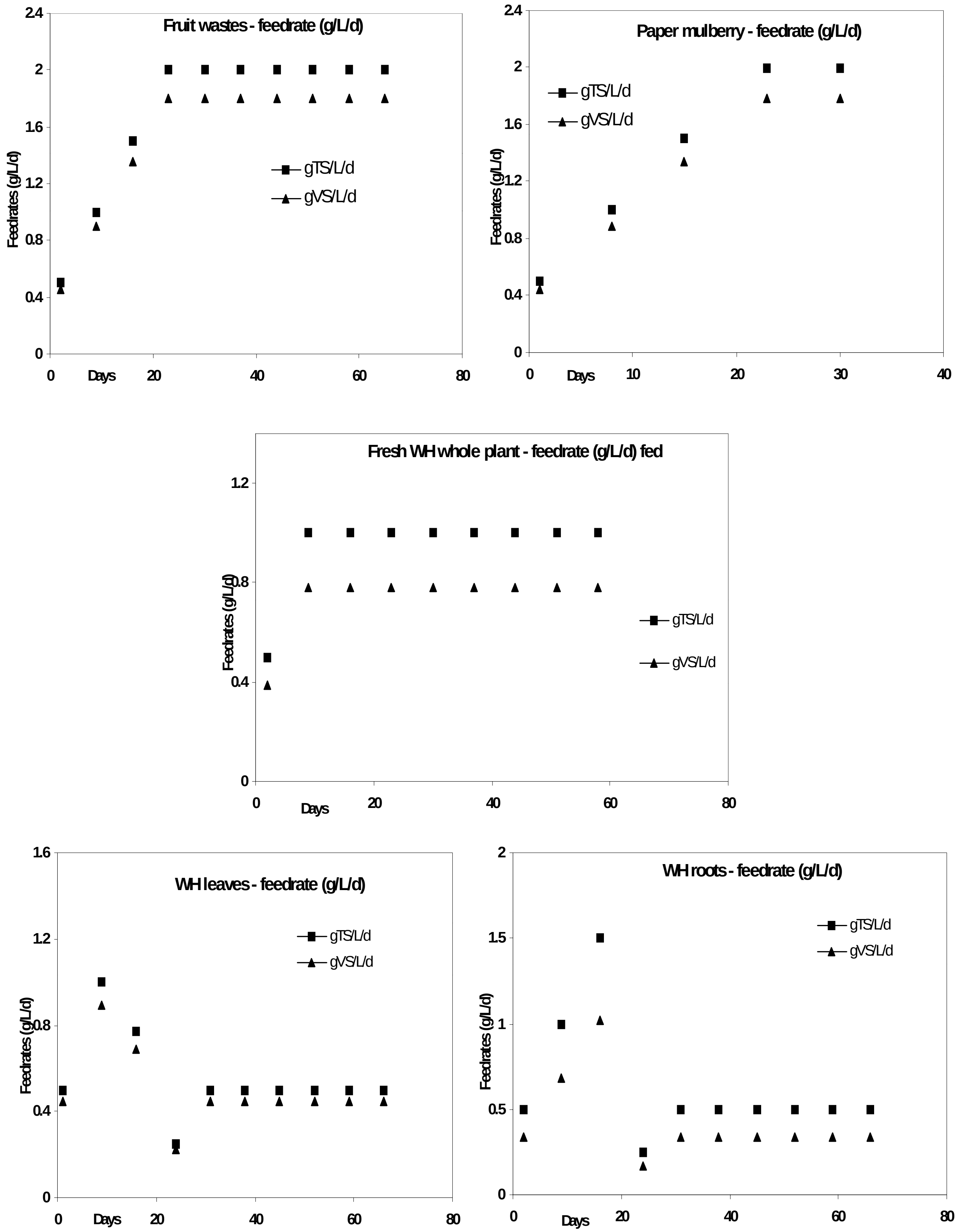


Fig 4.2. Feed rates achieved for fresh feedstocks in run 1.

4.1.2. Gas production

Among dry feedstocks, the daily biogas production ranged between 0.5 and 1.5L/d representing low conversion efficiencies. Table 4.3 shows conversion as a function of TS fed and corresponding gas production rates. Bagasse (2 replicates) and cane trash (1 replicate) showed moderate conversion at 0.31, 0.42 and 0.29 l/g TS fed respectively. Paddy straw, dry water hyacinth and photocopier paper showed very low gas production. Much higher gas production levels have been reported for these feedstocks under similar conditions (Chanakya *et al*, 1993,1992,1999; Zhang *et al*., 1999; Gunaseelan, 1997; Andersson and Bjornsson, 2002).

Bagasse feedstock took 40d to reach steady state of 1L. Similarly other dry feedstock took 20, 13 and 32d to reach steady state gas production for paddy straw, cane trash and copier paper respectively.

Fresh feedstocks such as paper mulberry and fruit wastes decomposed rapidly resulting in an average gas production of >3L biogas /d at pseudo-steady state. Yet the TS to gas conversion efficiency (Table 4.1) are low for these feedstocks. Viturtia, (1995) reported 0.5L methane yield by using the two-phase digestion of fruit wastes mixtures (0.42L methane yield for 16dHRT- Viswanath *et al*., (1992); 0.41L methane yield for 32d HRT with 75%VS lost-Lane, 1984). In relation to this, the gas yields achieved in this study is low. For other feedstocks reports in literature show 1L, 0.6L, 0.25L/d for fresh water hyacinth whole plant, water hyacinth leaves and water hyacinth roots respectively (Fig 4.4). Once again the TS to gas conversion efficiency was low.

Table 4.1: Observed Vs theoretical gas yield (based on ideal gas laws)

Feedstock	Total gas production (L)	Total VS fed (g)	Theoretical gas yield (L)	Observed gas yield L/gVS fed
Bagasse 1	59.5	186	163	0.31
Bagasse 2	79.9	186	163	0.42
Cane trash	64.8	259	227	0.25
Paddy straw	42.8	221	194	0.19
Dry water hyacinth	16.1	221	194	0.07
Copier paper	44.8	488	429	0.09
Fruit wastes	159	643	565	0.24
Paper mulberry	75.1	262	230	0.28
Fresh WH whole plant	66.67	278	244	0.23
Fresh WH leaves	45.1	234	205	0.19
Fresh WH roots	16.8	179	157	0.09

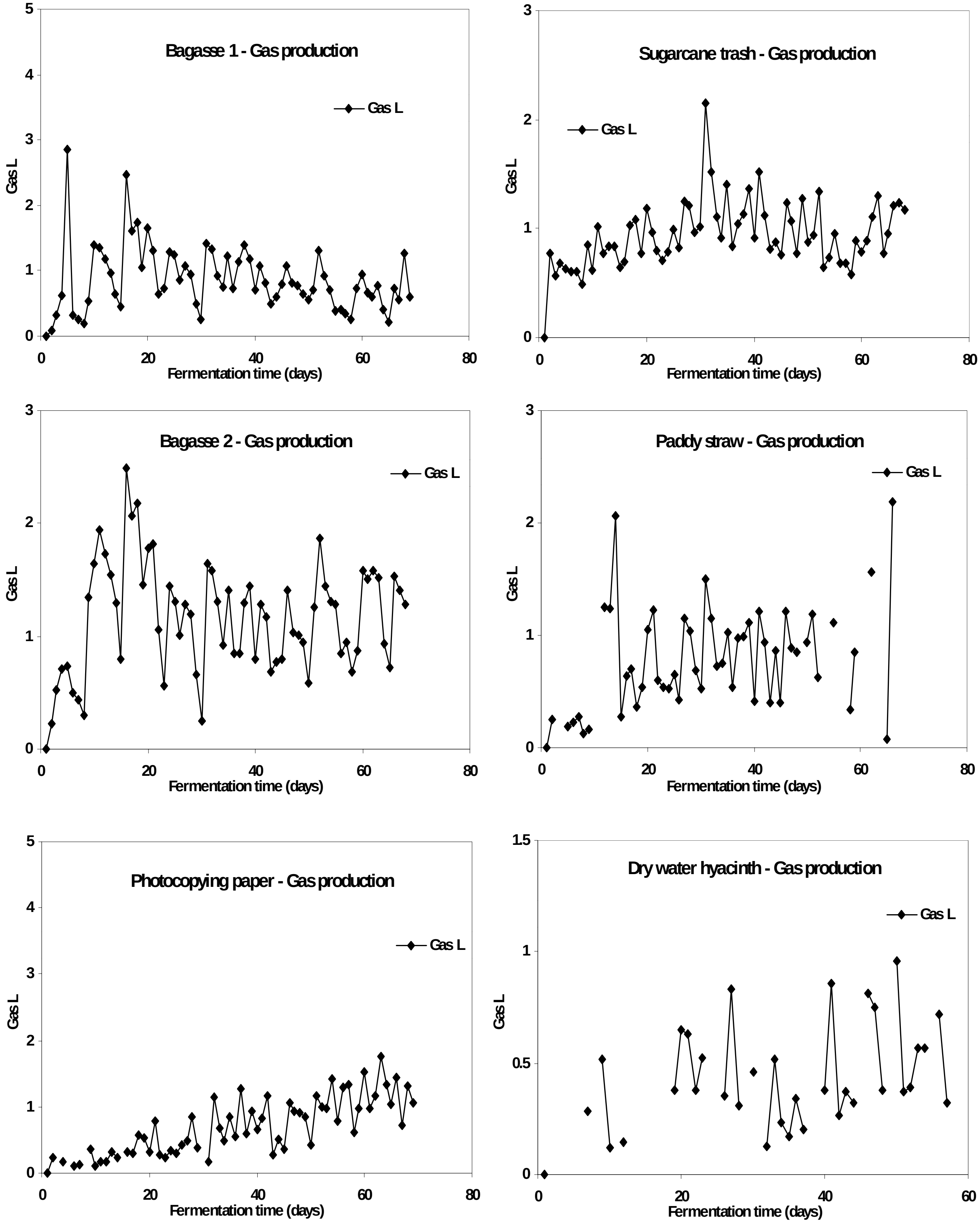


Fig 4.3. Daily biogas production rates from dry feedstocks.

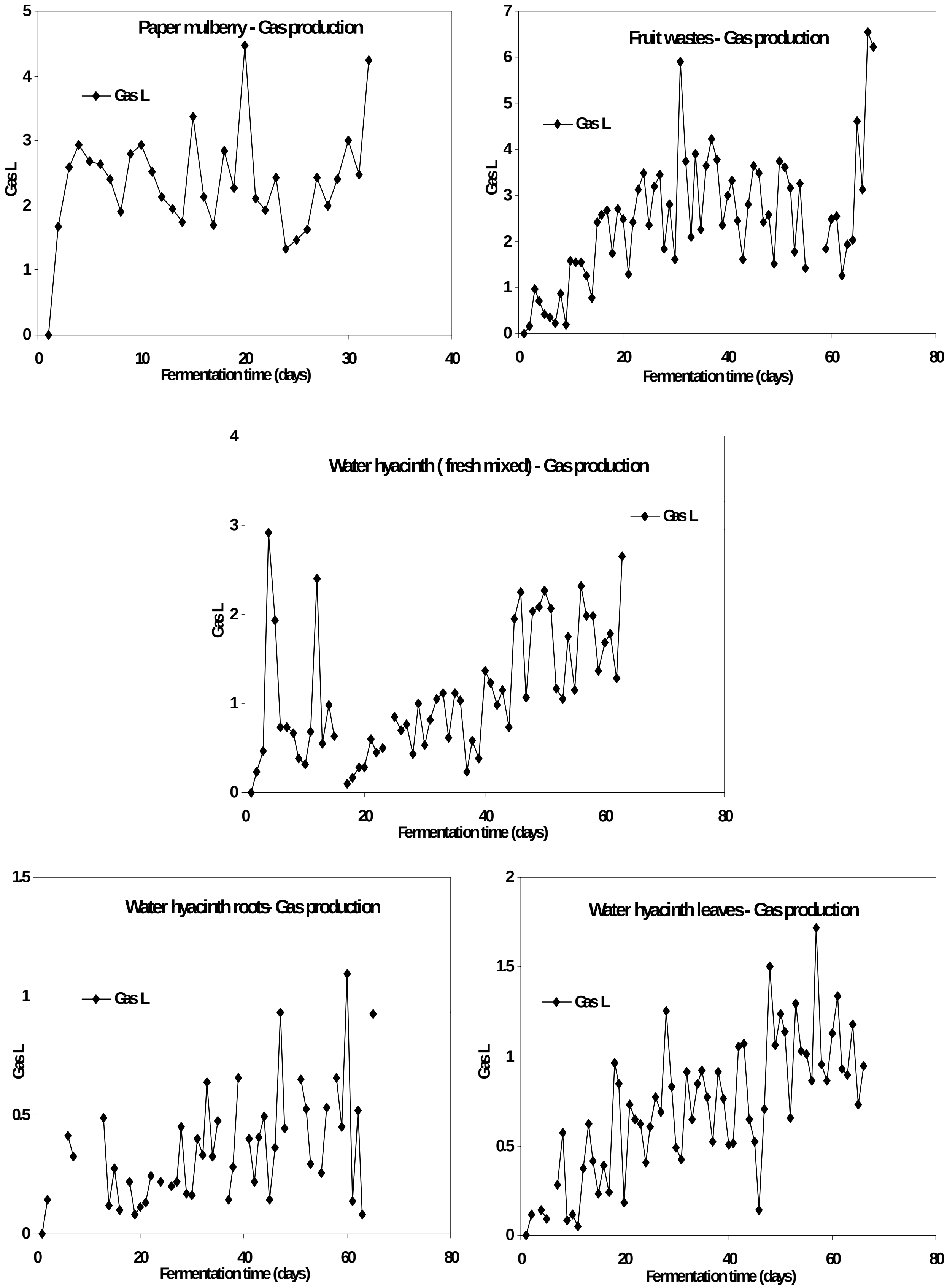


Fig 4.4. Daily biogas production rates from fresh feedstocks.

4.1.3. Feed rate versus volumetric efficiency

Among the dry substrates tried, bagasse, sugarcane trash and photocopier paper achieved volumetric efficiencies between 0.15 and 0.2 $m^3/m^3/d$ at feed rates of 0.5, 0.5 and 1.5kg TS/m^3/d (Fig 4.5). As stated earlier and shown in Table 4.1 bagasse and sugarcane trash have moderate TS to gas conversion values. Better performance with these two feedstocks, measured as higher volumetric gas production levels reaching 0.5 $m^3/m^3/d$ will be possible only when steps to increase current feed rates >0.5 kg/m^3/d can be achieved. Other dry feedstock showed an average volumetric efficiency of 0.1 and 0.05 $m^3/m^3/d$ for, paddy straw and dry water hyacinth respectively (Fig 4.5).

In the case of fresh feedstock, fruit wastes and paper mulberry showed a desirable level of performance in terms of volumetric efficiency (0.5 $m^3/m^3/d$). This result is comparable with previous reports done on this feedstock. Chanakya *et al.*, (1999) showed the volumetric efficiency of 0.5 $m^3/m^3/d$ at a much lower feed rate. In the case of fruit waste and paper mulberry from Fig 4.6 and Table 4.1 it may be deduced that the feed to gas conversion is low and there is potential to obtain higher gas production levels. Other substrates studied gave 0.15, 0.17 and 0.04 $m^3/m^3/d$ for water hyacinth whole plant, water hyacinth only leaves and water hyacinth only roots respectively (Fig 4.6).

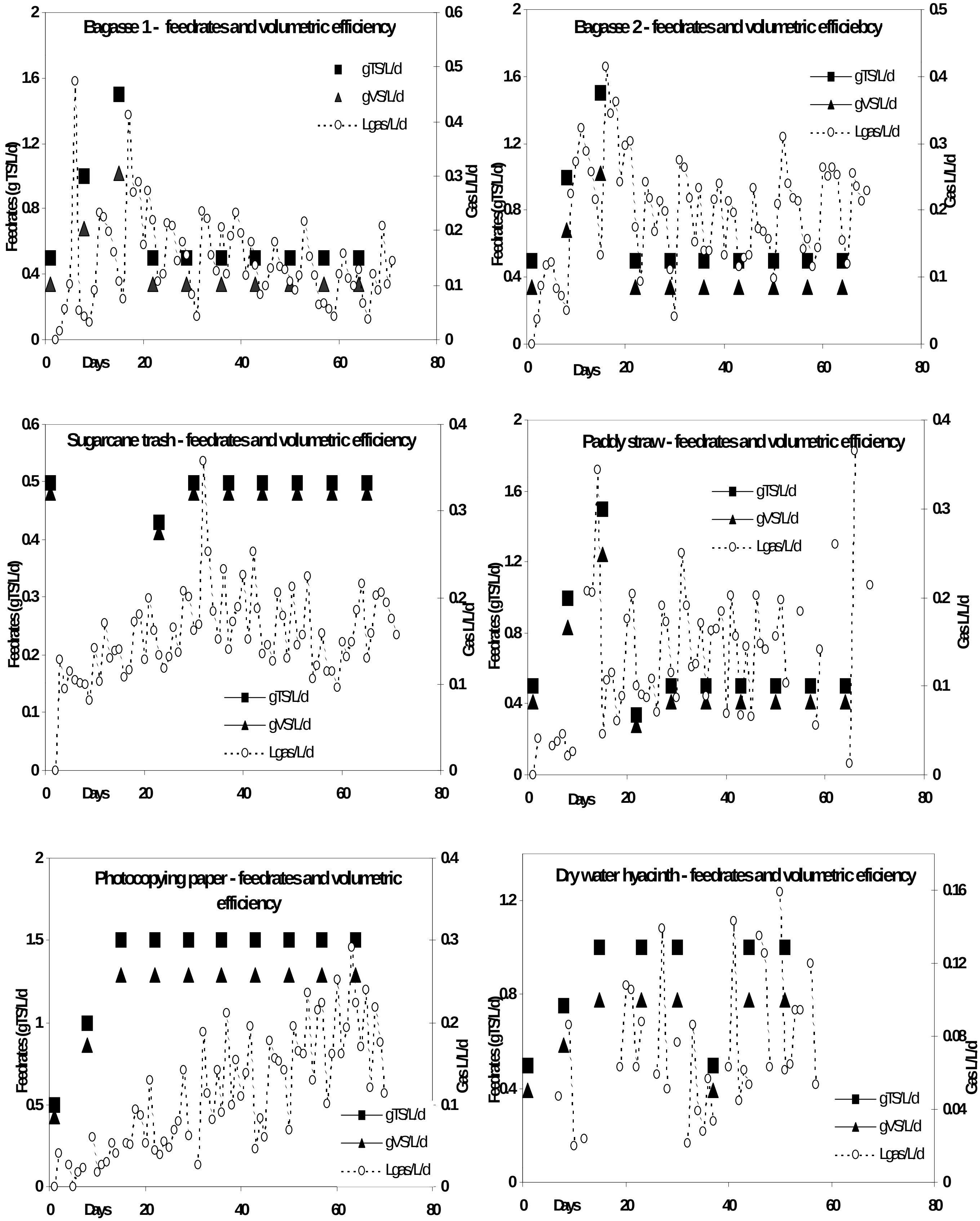


Fig 4.5. Feed rate Vs volumetric efficiency in dry feedstock

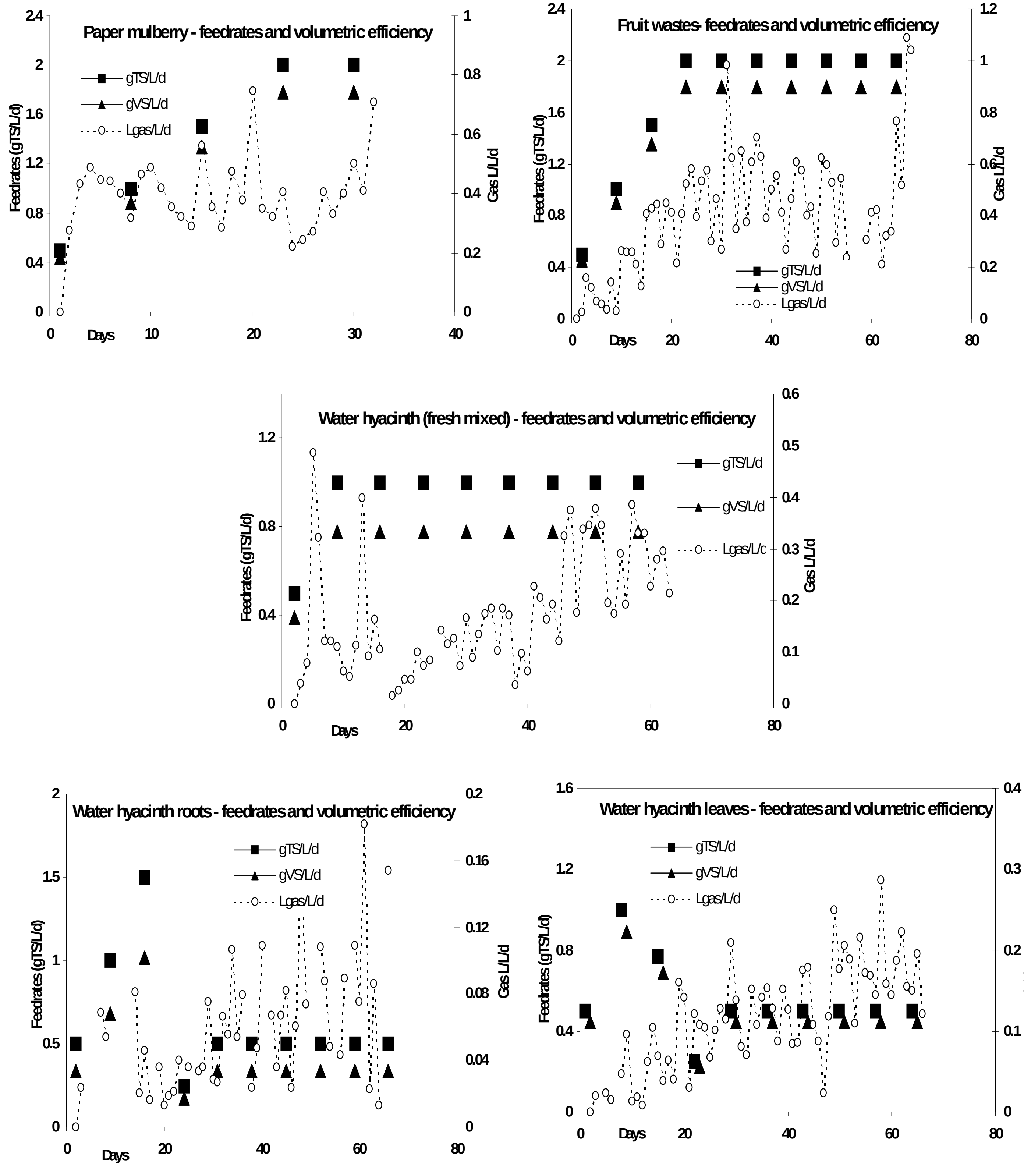


Fig 4.6. Feed rate Vs volumetric efficiency in fresh feedstock

4.1.4. Gas composition

Simple technique was adopted for feeding the fermentor i.e. by opening the feed hatch and replacing the pre-weighed feedstock in to it. This opening results in the concomitant introduction of air in to the fermentor thus diluting the biogas, without seriously affecting overall gas production rates (Chanakya *et al.*, 1993). The composition of gas measured from the start up to end period showed a methane content >50% in most of the cases (Fig 4.7 and 4.8). This indicates that the rate of acidogenesis and methanogenesis are well balanced (Chanakya *et al.*, 1998). Right from the beginning cane trash, paddy straw, water hyacinth showed good methane content of above 60%. This data suggests that firstly in all the reactors the methanogenesis remained healthy. Second, the modification in the gas outlet position, from the top of the reactor to the methanogenic zone, has functioned well even in a small laboratory scale reactor. The gas composition was however measured at wide intervals and thus cannot adequately diagnose day-to-day changes in digester health. This frequency needs to be increased in future studies.

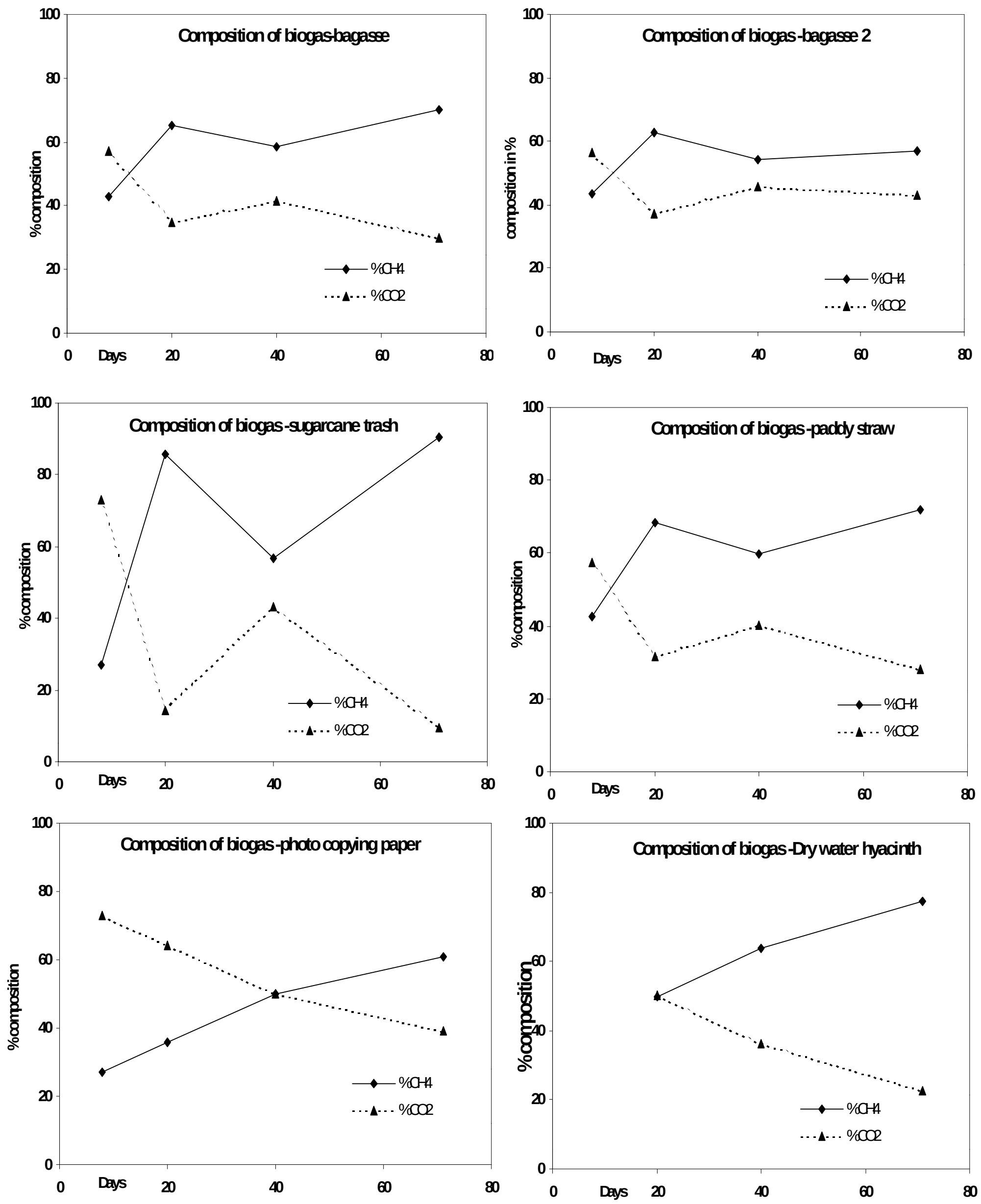


Fig 4.7. Composition of biogas in dry feedstock.

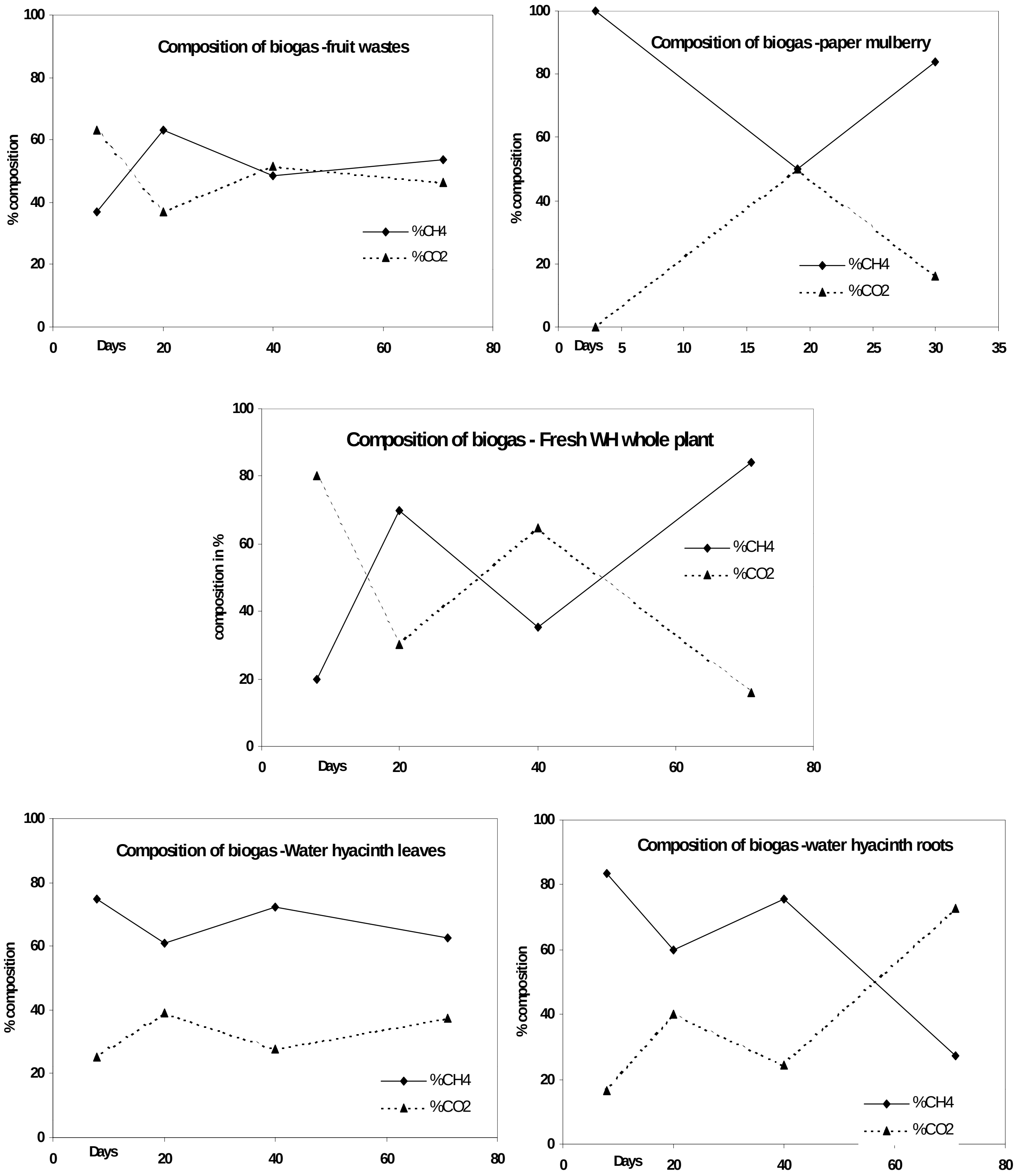


Fig 4.8. Composition of biogas in fresh feedstock.

4.1.5. Characteristics of the decomposing biomass bed in SSB reactors

4.1.5.1. Changes in total solids (TS) before and after fermentation

Difference in the initial TS fed and final TS (recovered) is presented in the Fig 4.9 and 4.10 for dry and fresh feedstock. Changes in the total solids fed were examined by comparing the TS of the feedstock before being fed in to the reactor and TS of residual mass removed after 70d fermentation. In all dry feedstocks it may be seen that there is some degree of an early loss in TS fed after which the rate of TS lost is slow. Only the older layers have exhibited large TS losses. This overall picture for dry feedstocks suggests that much of the gas recovered is from decomposition in (older and) lower layers that are expected to be in methanogenesis. The reasons for such a situation is not clear from available data and reasons for this need to be determined if the process has to be improved. Among the dry feedstock, bagasse, paddy straw, cane trash occupied first three places in reflecting the changes in terms of mass (TS) lost.

The case of fresh feedstock was entirely different, fruit waste, paper mulberry and water hyacinth whole showed large differences between mass fed and recovered – may considered to be converted (to gas). Water hyacinth roots and leaves showed lower TS losses. This suggests that the process of TS primary conversion has not been adequate in a few cases and needs to be improved in future experiments. Yet, under similar conditions some of the earlier studies exhibited reasonably large conversions. The above results suggest that change in the mass of TS fed occur to a larger extent in case of fresh feedstock rather than dry feedstock. It is suggestive of fresh feedstocks being more prone to the action of hydrolysis and resultant change.

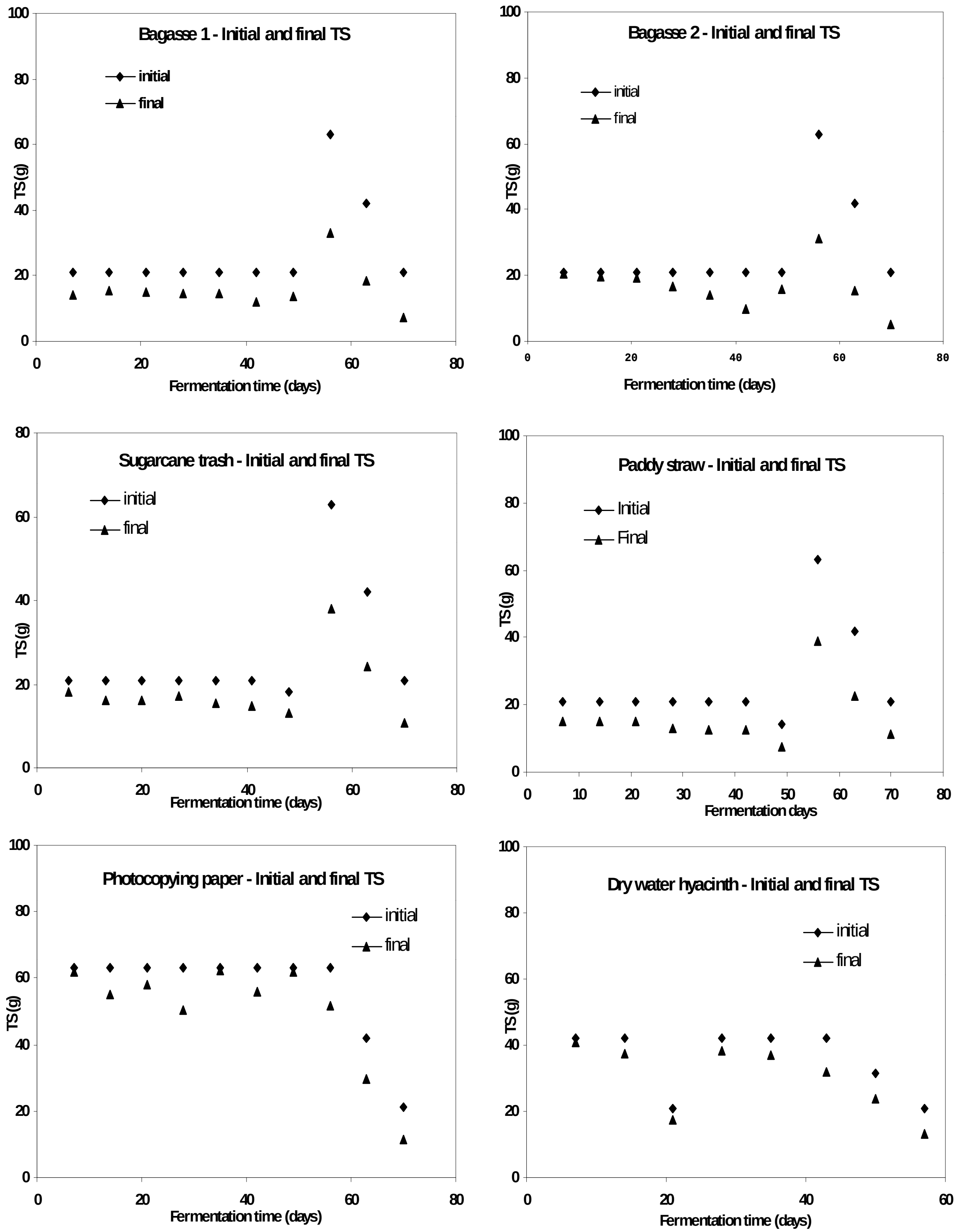


Fig 4.9. Changes in TS before and after fermentation in dry feedstocks.

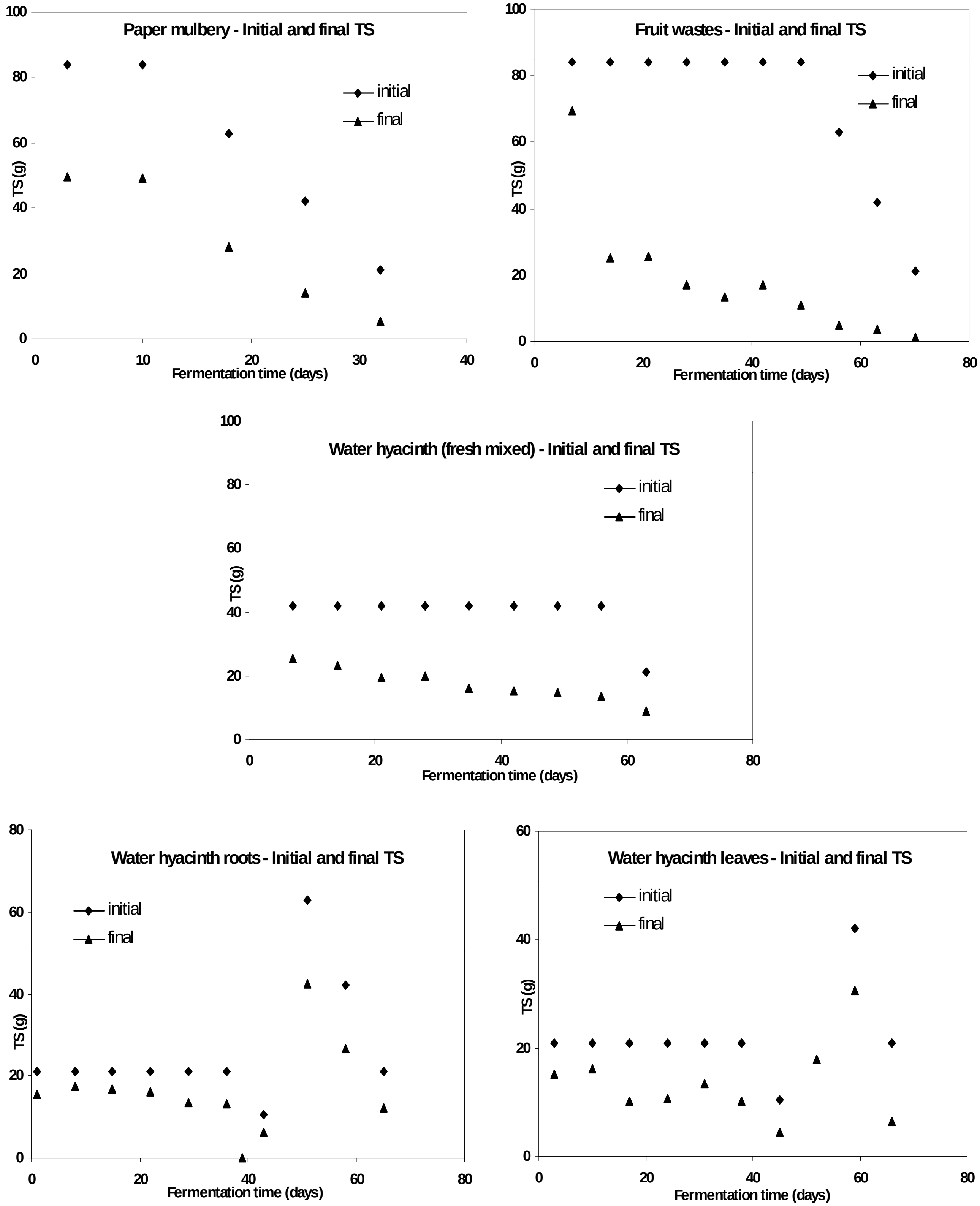


Fig 4.10. Changes in TS before and after fermentation in fresh feedstocks.

4.1.5.2. Efficiency of conversion

TS and VS destruction pattern of dry and fresh feedstock is presented in the Fig 4.11 and 4.12 respectively. It was seen that the dry feedstock decomposed slowly resulting in 25-40% destruction in VS in 40d, while fresh feedstock decomposed rapidly resulting in >50% destruction in most cases. Among the dry feedstock studied, bagasse and trash decomposed rapidly underwent a maximum VS destruction of 70% and 45% in 70d. On the other hand, fruit wastes among the fresh substrates tried, underwent an 80% VS loss. Others showed 60% (for water hyacinth whole plant and leaves) and 35% for roots alone in 60-70 days. Paper mulberry showed 50% loss in 32 days. Among the above changes in TS were supported by corresponding VS destruction for a period of 70d. From the data on the loss of mass from the biomass bed, it is clear that even though appreciable TS loss has been determined this has not been converted to gas production and related efficiencies. It is possible that the VFAs leaching down has occurred rapidly and failed to be converted to biogas in the methanogenic zone and has come to the reservoir under composed. Further investigation is needed to confirm this possibility.

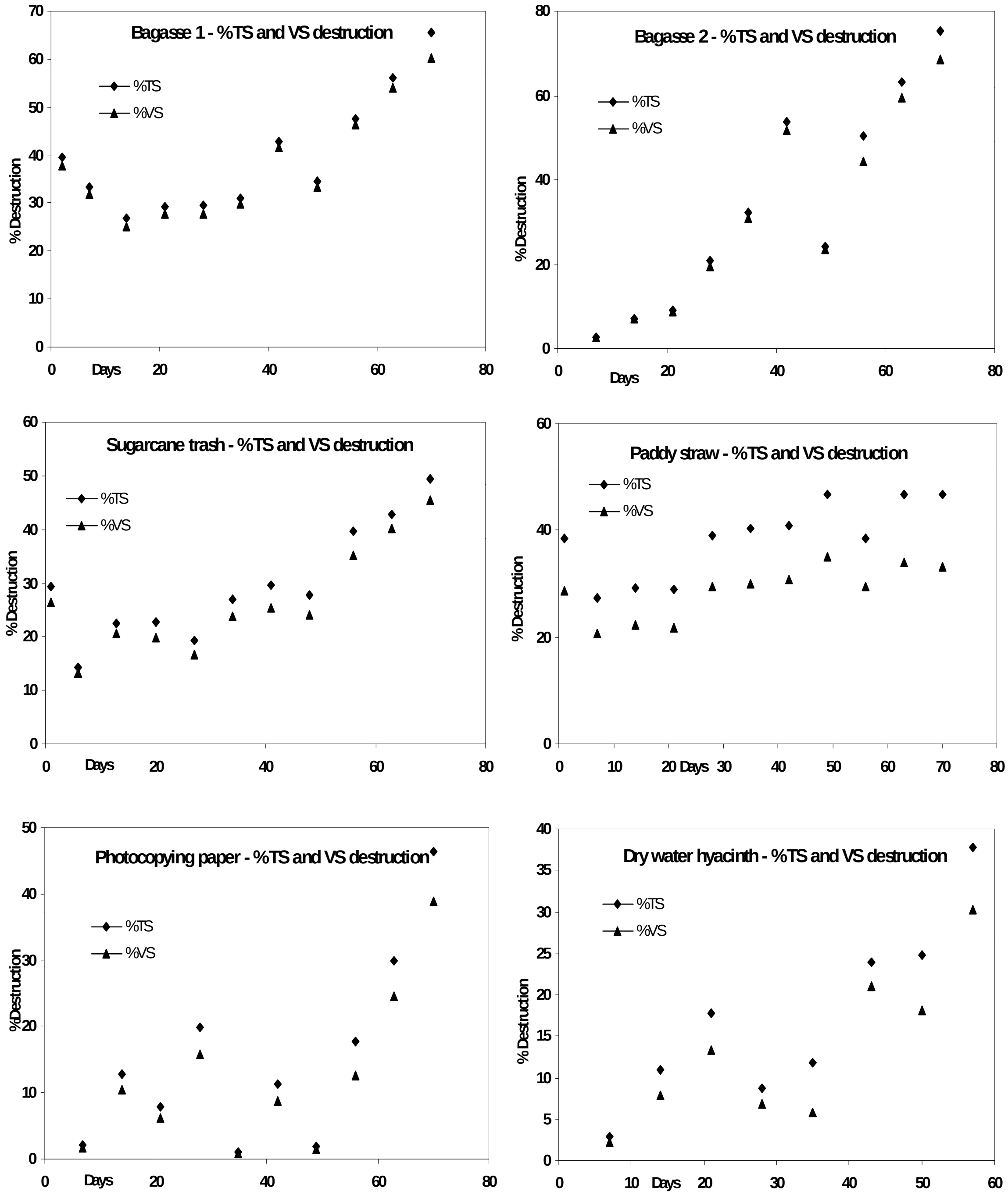


Fig 4.11. TS and VS destruction of dry feedstock.

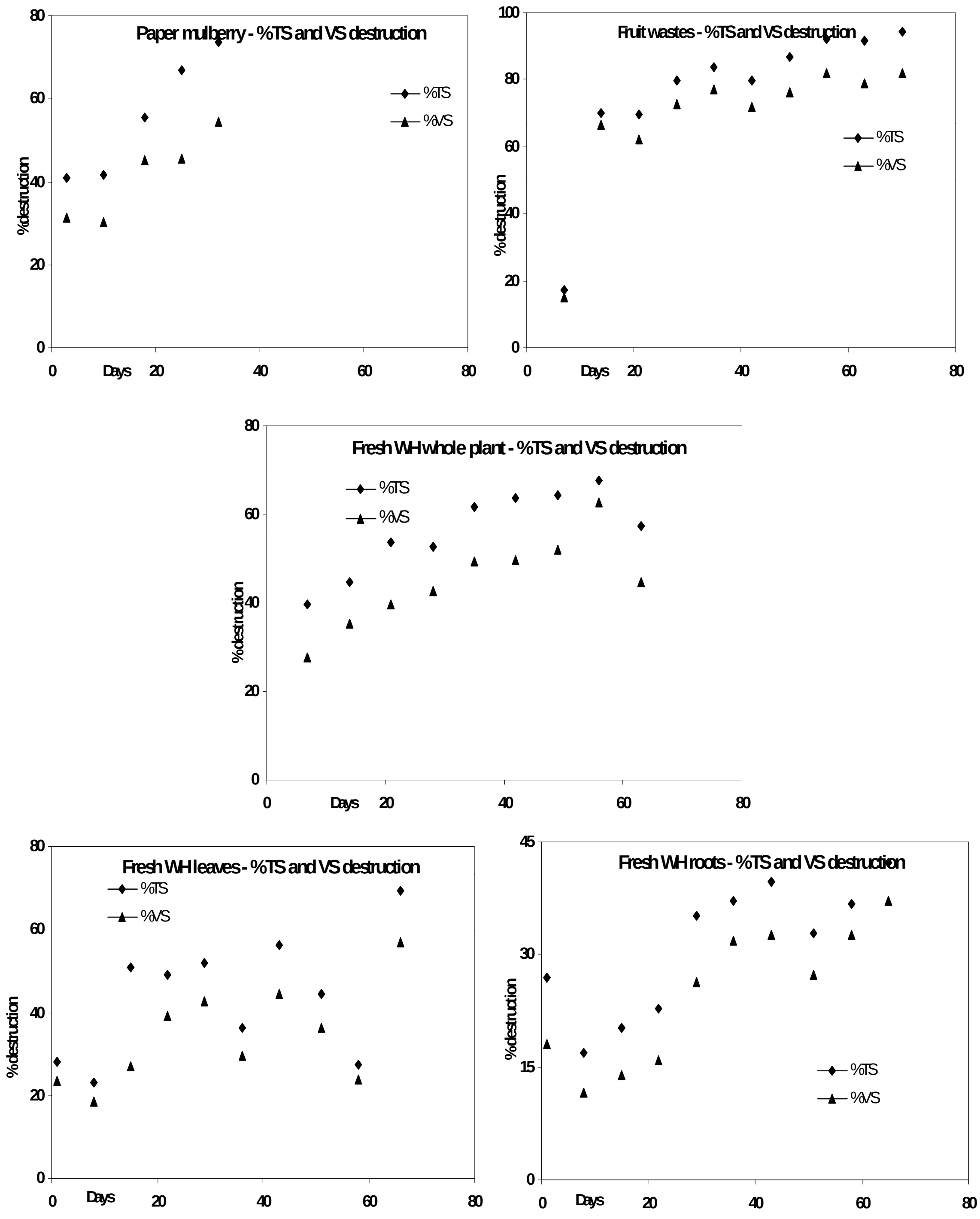


Fig 4.12. TS and VS destruction of fresh feedstock.

4.1.6. Fermentation of selected feedstocks (of USW) under SSB conditions

Feedstocks that gave the volumetric efficiency between 0.5 and 1.0L on an occasional basis during run 1 were studied once again in duplicates during run 2. This was meant to confirm an efficient gas potential found in run 1. Firstly the high feed rate of 2kg TS/m^3/d could not be sustained for paper mulberry and vegetable wastes. The compaction rates were inadequate to support such high feed rates. Only fruit wastes permitted such high feed rates (Fig 4.13). Volumetric efficiencies >0.5L was achieved for all feedstocks. It was observed that maximum of 4.8L/d for fruit wastes, 4.5L for paper mulberry and 3.6L/d for vegetable wastes were observed. A gradual steady state was observed in all the feedstock studied for 80d fermentation period. Composition of biogas checked once in 15 days also showed the methane content of above50% is the suggestive of healthy digestion process.

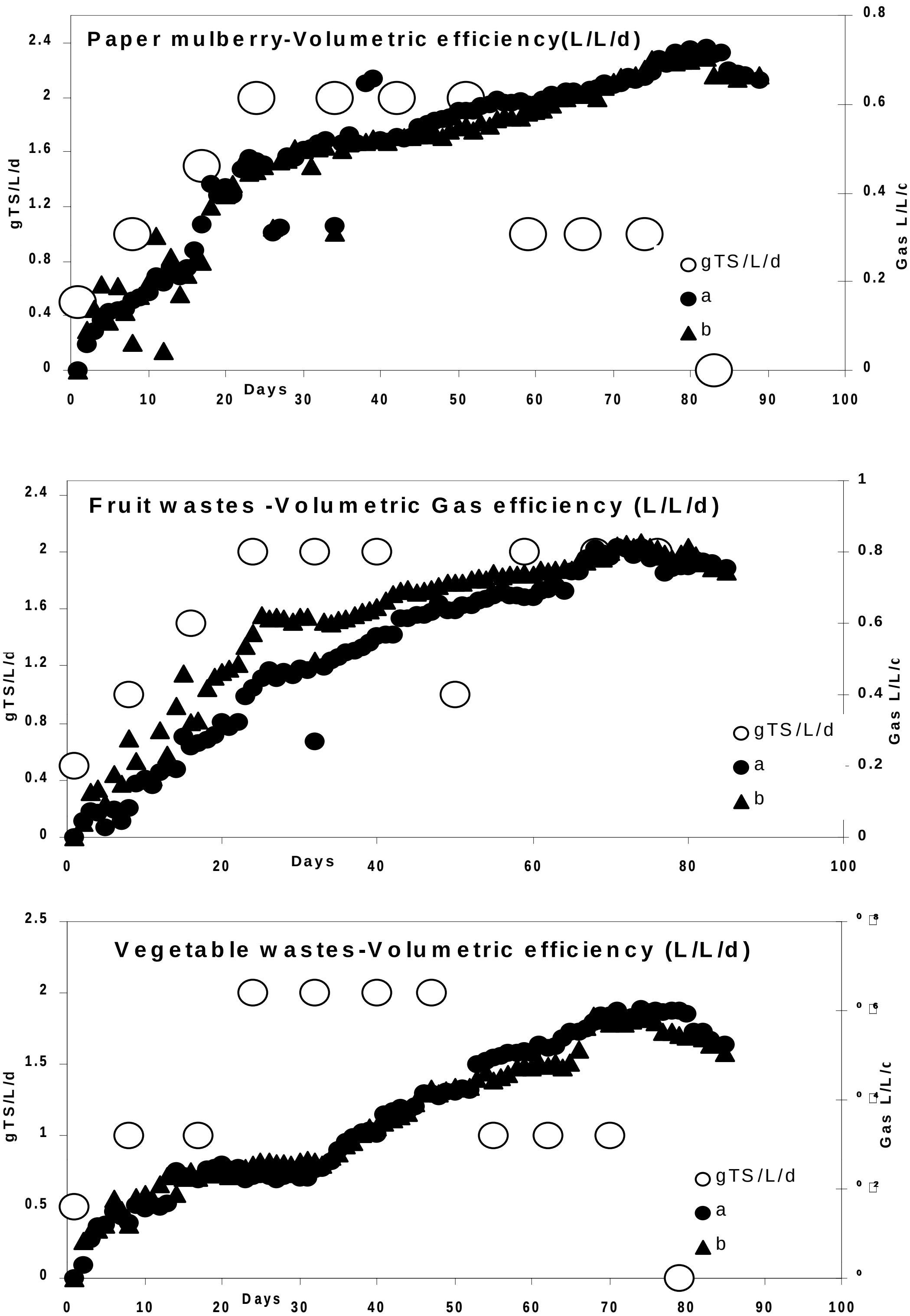


Fig 4.13.Volumetric efficiencies and gas production pattern of feedstocks in run 2 experiment

4.2. Biogas production potential

The sequence and method of inferences obtained from this modified BMP assay is outlined under methods. The same sequence of inferences is made on each of these BMP results.

4.2.1. Bagasse

Sugarcane bagasse is now often found in urban waste, arising largely from sugarcane juice expellers on roadside as well as dry bagasse being used as a filler and packaging material, domestic mushroom cultivation, seasonal domestic consumption, etc. Sugarcane bagasse has been found in a few bins near the institute. Usually it is dry, found in 1.8m long pieces and has a low bulk density. It has a fraction of un-expelled sugar. All these create technology challenges for biogas production from these feedstocks.
The BMP pattern of this feedstock has been presented in the Fig 4.14. In the 1% vials, there has been around 50mL of gas production most of which in the initial phase was CO_2. Although, it showed initial spurt of gas production suggesting a large buildup of VFA, methane production and methane composition in the gas did not seem to be inhibited from around 10th day of start. Whereas in 2% feedstock, significant inhibition of methane has been detected. The gas production appears to be in the steady state range from the very beginning of fermentation reaching up to a period of 80 days. Only after 80th day, some extent of leveling off seems to have occurred in 1or 2 replicates. Bagasse did not exhibit a clear cut-leveling phase even up to a study period of approximately 100 days. The difference in gas production levels between 1 and 2% is significant. While the 1% vials did not show a significant inhibition of methanogenesis, the 2% TS vials showed a very large inhibition of methane and methanogenesis. In this case methane content is generally been lower than 40%. Some degree of recovery was found towards the end of the BMP period. The ultimate BMP from this feedstock is quite high and reaching up to 571 m^3/kg TS or methane 300 m^3/kg TS fed. The extent of methane and biogas production found in the study closely resembles the levels reported in the literature (Chanakya *et al*., 1999).

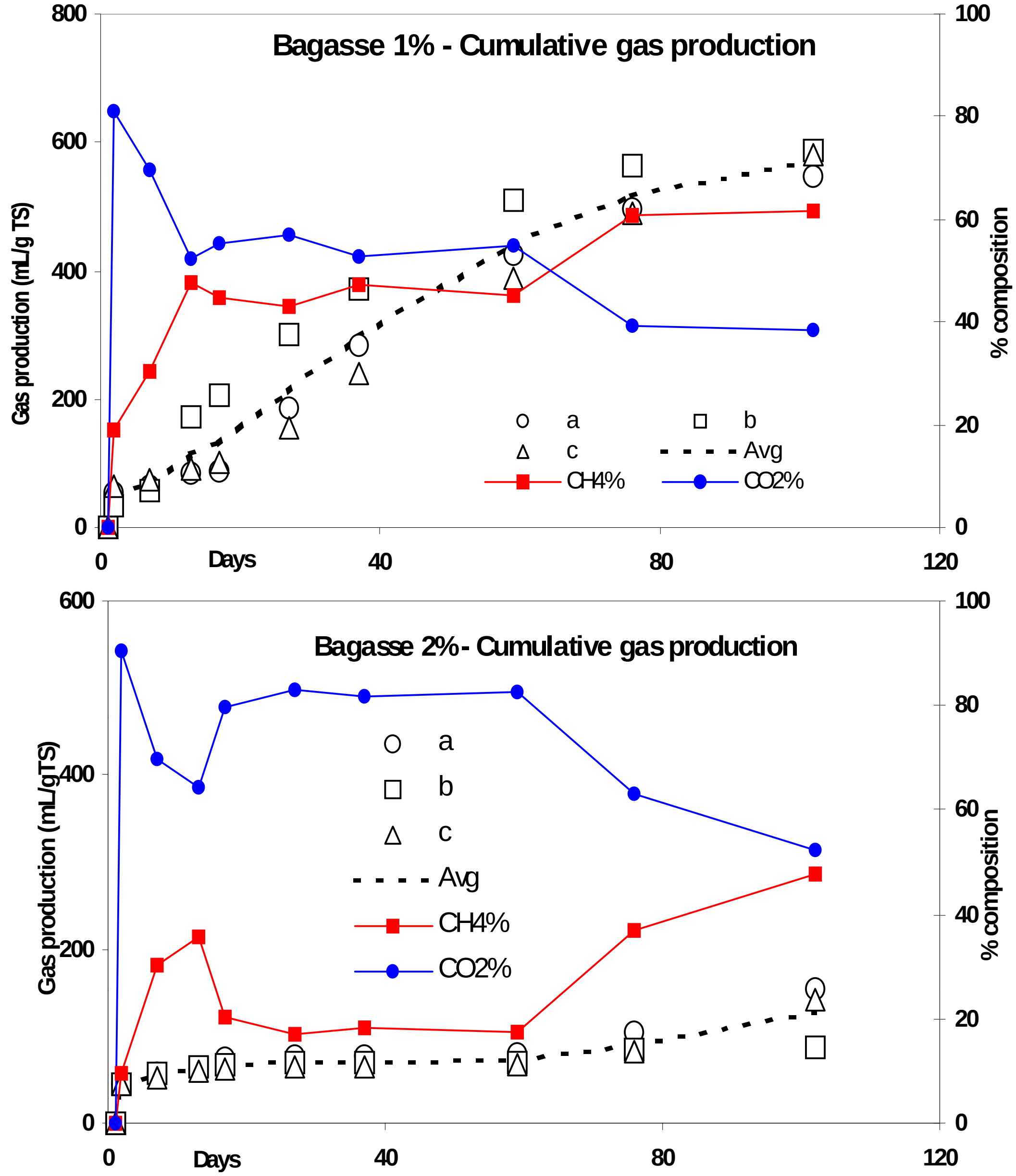


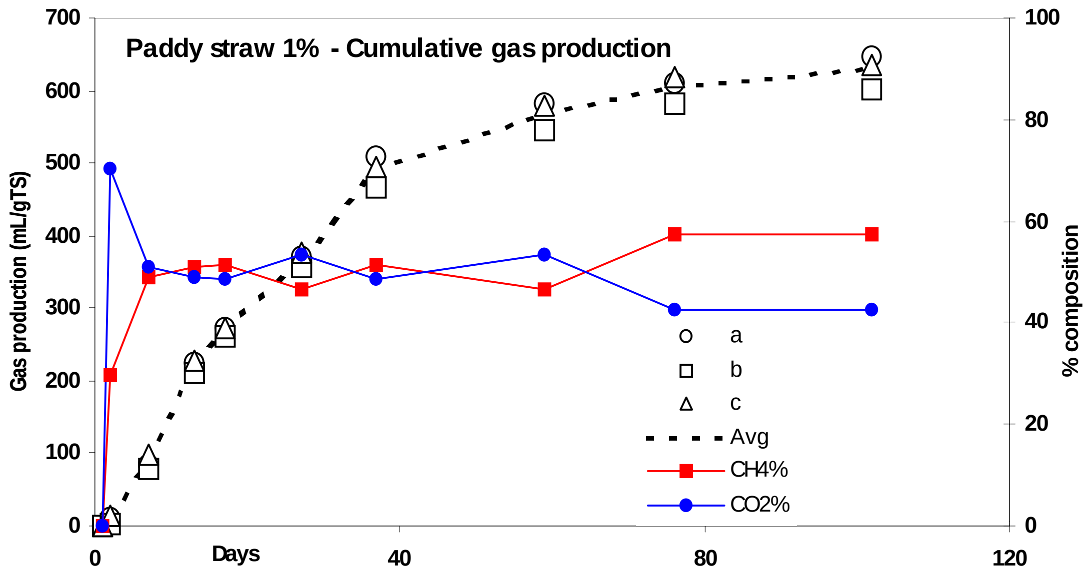
Fig 4.14. Cumulative gas production pattern of bagasse.

4.2. 2. Paddy straw

Paddy straw is used as a packaging material and it is also found to occur in significant proportion in some parts of USW – especially fruit packing. It has been increasingly found in and around fruit stalls. Paddy straw is a bulky material with a low packing density (Chanakya *et al.*, 1998) has large particle size and has a medium level of ligno-cellulosics (Zhang and Zhang, 1999). There is an initial rapid gas production of 100mL (1%). In spite of this high gas production, the methane concentration had remained high and always above 50%. This suggests that in spite of initial spurt in gas production and possibly a high VFA production, methane production is not inhibited. From a period of 5d, to fermentation period between 40 and 60d, the gas production is in steady state for 1% as well as for 2% TS. The methane content in the gas reflecting the health of methanogenesis has been high corresponding to balanced methanogenesis during steady state period of gas production. The gas production begins to level off after a 60d fermentation period in 1 and 2% ranges. There is very little difference in the pattern of 1 and 2% except in the magnitude of gas produced. No inhibition has detected even in 2%TS suggesting that this feedstock is unlikely to suffer from an initial VFA flux and resultant methanogenic inhibition under normal conditions. The ultimate BMP is 0.63m^3/kg TS of biogas corresponding to methane of 0.3 m^3/kg TS fed (Fig 4.15). High biogas production potential of paddy straw has been previously reported. Chanakya *et al*, 1999 have used paddy straw in solid-state fermentation and reported gas production levels of above 400mL/gTS fed. Similarly results from other efforts also shown gas production levels achieved above 400 mL gas (Zhang, 1999; Andersson and Bjornsson, 2002). In addition to this, paddy straw is known to contain silica up to 11% (13.1% Zhang and Zhang, 1999; Hills and Roberts, 1981) in its matrix, as a result of this, it poses a challenge to biogas production. While high biogas could be achieved under BMP conditions it could not be achieved under SSB conditions in this study.

4.2.3. Sugarcane trash

Sugarcane trash is almost always accompanied by the occurrence of bagasse. The leaves are long, fibrous and like bagasse has very low C/N ratio. The large size, low C/N ratio and dry state and accompanied with low bulk density pose a challenge to biogas production in conventional plants. At 1% TS cane trash showed a small spurt of gas production, indicative of rapid VFA flux (Fig 4.16). Yet the methane production and methane concentration seemed uninhibited both at 1% and 2% concentrations. Steady state gas production was noticed between 5d continuing up to 80d. During the period of steady state, methane concentration remained significantly high showing that no inhibition of methanogenesis occurred during this stage of decomposition. Leveling off may be seen after a period of 80 days. Thus under batch conditions, a retention time between 40 and 80d may be chosen depending on economics. There was no inhibition of methanogenesis found between 1 and 2% suggesting that with increased solids concentration in the reactor, methanogenesis is unlikely to be affected by VFA intermediates. The ultimate methane potential is high and reaching up to 0.59 m^3/kg TS and approximately 0.4 m^3/kg TS at 2% concentration.



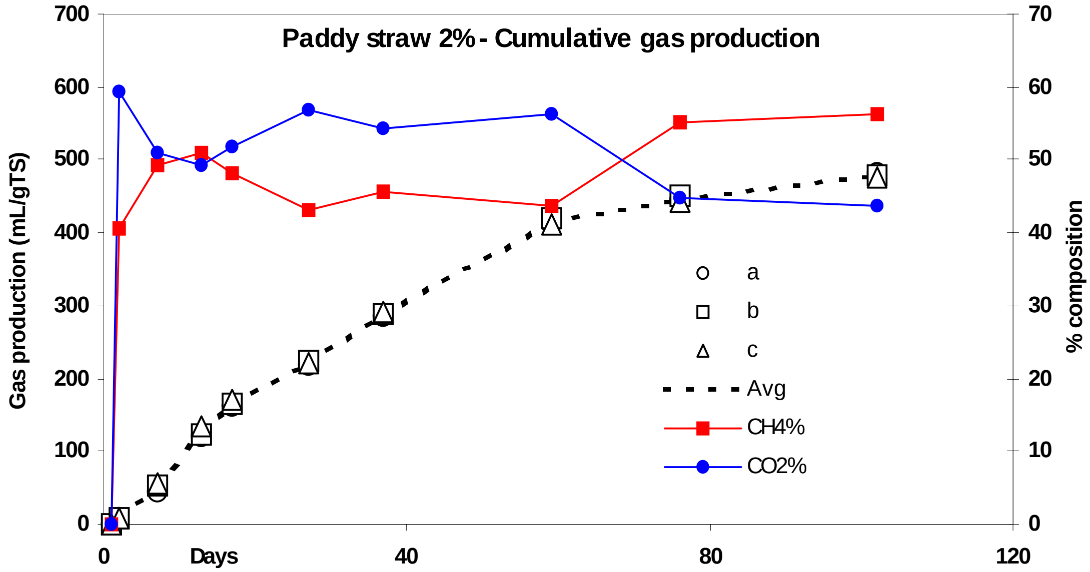


Fig 4.15. Cumulative gas production pattern of paddy straw.

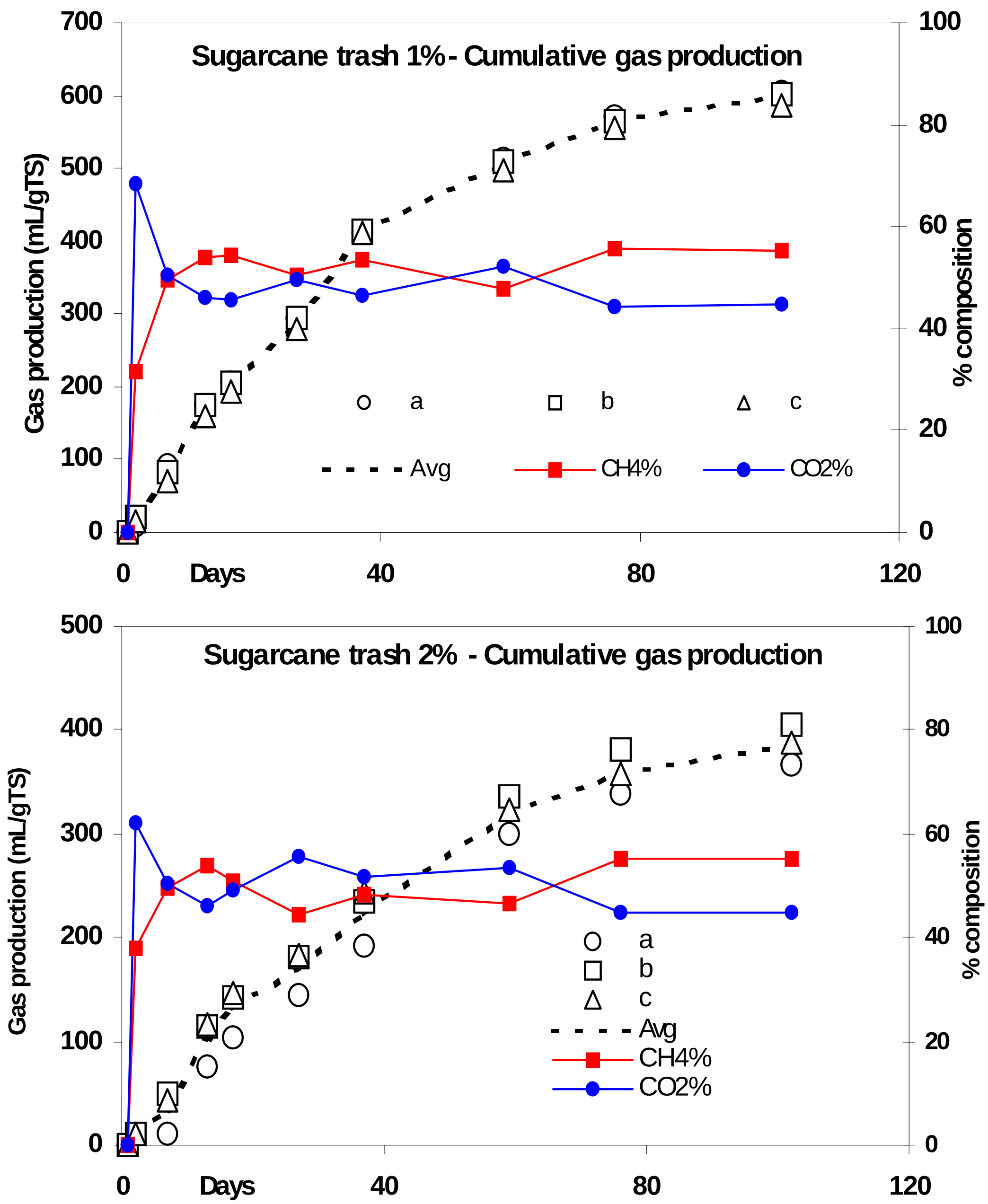


Fig 4.16. Cumulative gas production pattern of sugarcane trash.

4.2.4. Dry water hyacinth

Water hyacinth infests urban water bodies and is frequently harvested. Such harvested material end up in USW. Water hyacinth is also used as phyto-remediation (Singhal and Rai, 2003) and is therefore likely to find its way in to a USW from small-scale treatment plants. The BMP assay data for this feedstock was presented in the Fig 4.17. The 1% TS BMP vials showed the gas production levels up to 100mL in the first 5d suggesting the presence of a large component of easily decomposable material with potential for VFA induced methanogenic inhibition. Yet, as seen from Fig 4.17, methane content recorded was high reaching up to 60% from the early stages of decomposition. Steady state gas production phase extended up to a period of 40d in 1% and 2% TS. The leveling off phase was not very characteristic with this feedstock and gas production continued at lower rates up to the end of the study period. In the steady state period of gas production no methanogenic inhibition was noticed. Very little difference was found between 1 and 2% in terms of methane concentration and this suggests that the digesters operating at higher TS concentrations are unlikely to be inhibited by VFA induced inhibition. The ultimate BMP was found to be in the range of 0.49 m^3/kg TS / fed and around 0.3 m^3/kg TS CH_4. Previous studies reported that the ultimate methane yield from water hyacinth, based on ABP assay was $0.34 m^3 kg^{-1}$ VS added (Chynoweth *et al*., 1982; Viswanath *et al*., 1992; Gunaseelan., 1997; Gopalakrishna, 1989).

4.2.5. Water hyacinth leaves

Water hyacinth leaves and roots have separate applications and it is necessary to determine the BMP of leaves and roots separately. The BMP of water hyacinth leaves is presented in Fig 4.18. There is a rapid gas production initially totaling 15% of the overall gas production. Such a rapid gas production is the suggestive of VFA flux in the early stages of decomposition. From the high methane content of gas throughout the study period both in 1 and 2% TS, it suggests that VFA induced methanogenic inhibition has not occurred. A steady state gas production occurred between 5 and 59 days of fermentation during which there is no indication of VFA induced methanogenic inhibition. The gas production leveled off after 60d both in 1 and 2% TS. There is no secondary rise in gas production after leveling off. There is very little difference in gas composition between 1 and 2% TS although there is a significant reduction in gas yield. The BMP pattern does not exhibit any VFA induced methanogenic inhibition and suggests that the biogas plants can be operated at higher TS concentrations. The ultimate biogas yield is very high of about 0.632 m^3/kg TS and about 0.350 m^3 CH_4 /kg TS CH_4/gTS. Such high BMP has not been reported before. Although gas yields above 500mL/gTS has been reported by various studies previously (Chynoweth *et al*., 1982 - 0.34m^3methane/kg VS). It also has been reported that that methane yields were higher in shoots than roots (Shiralipour *et al*., 1984). In this study water hyacinth leaves failed to produce high biogas production in SSB reactors. It is believed that the recycle of digester liquid was not uniform and was the cause of low gas production in most water hyacinth based reactors.

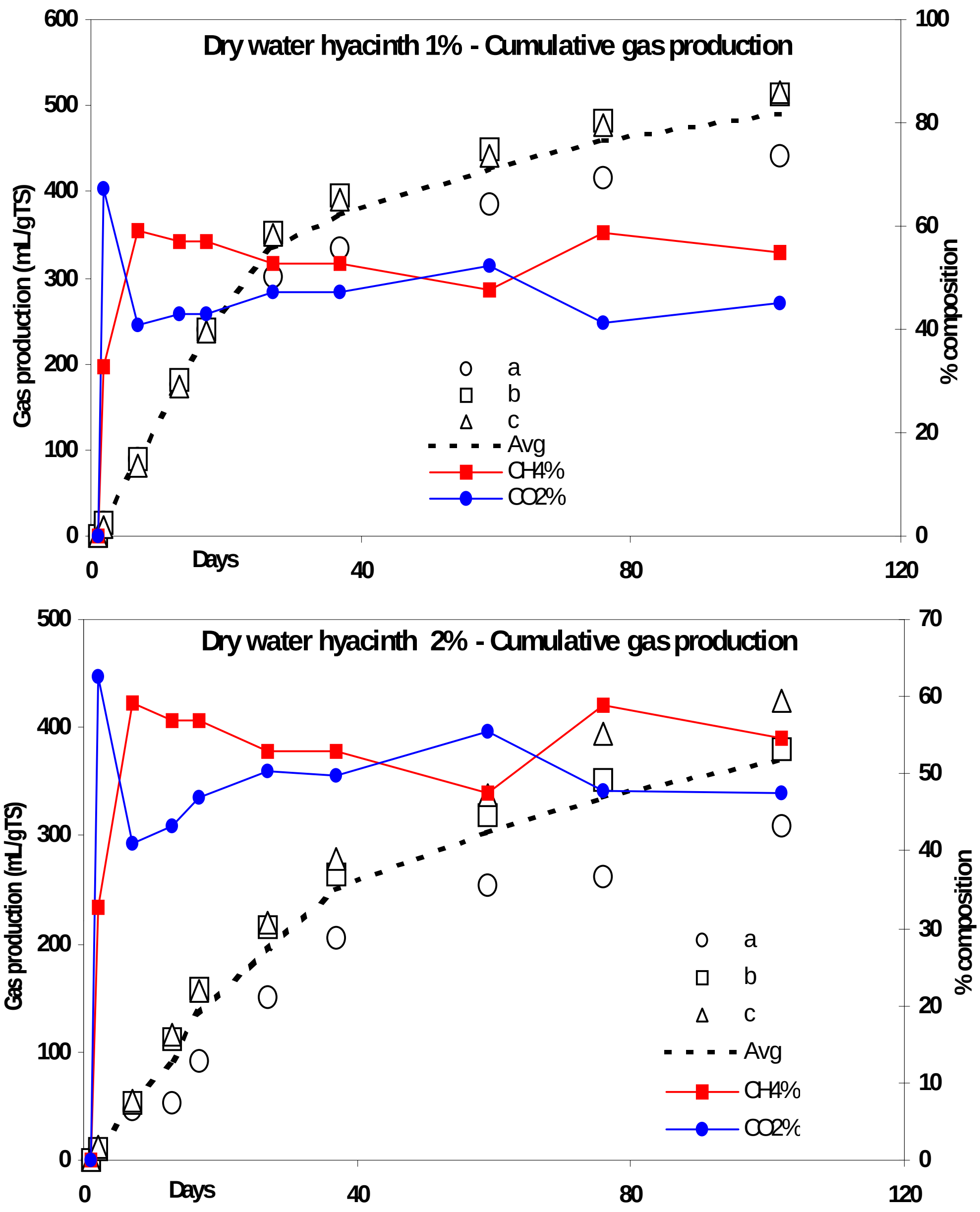


Fig 4.17. Cumulative gas production pattern of dry water hyacinth.

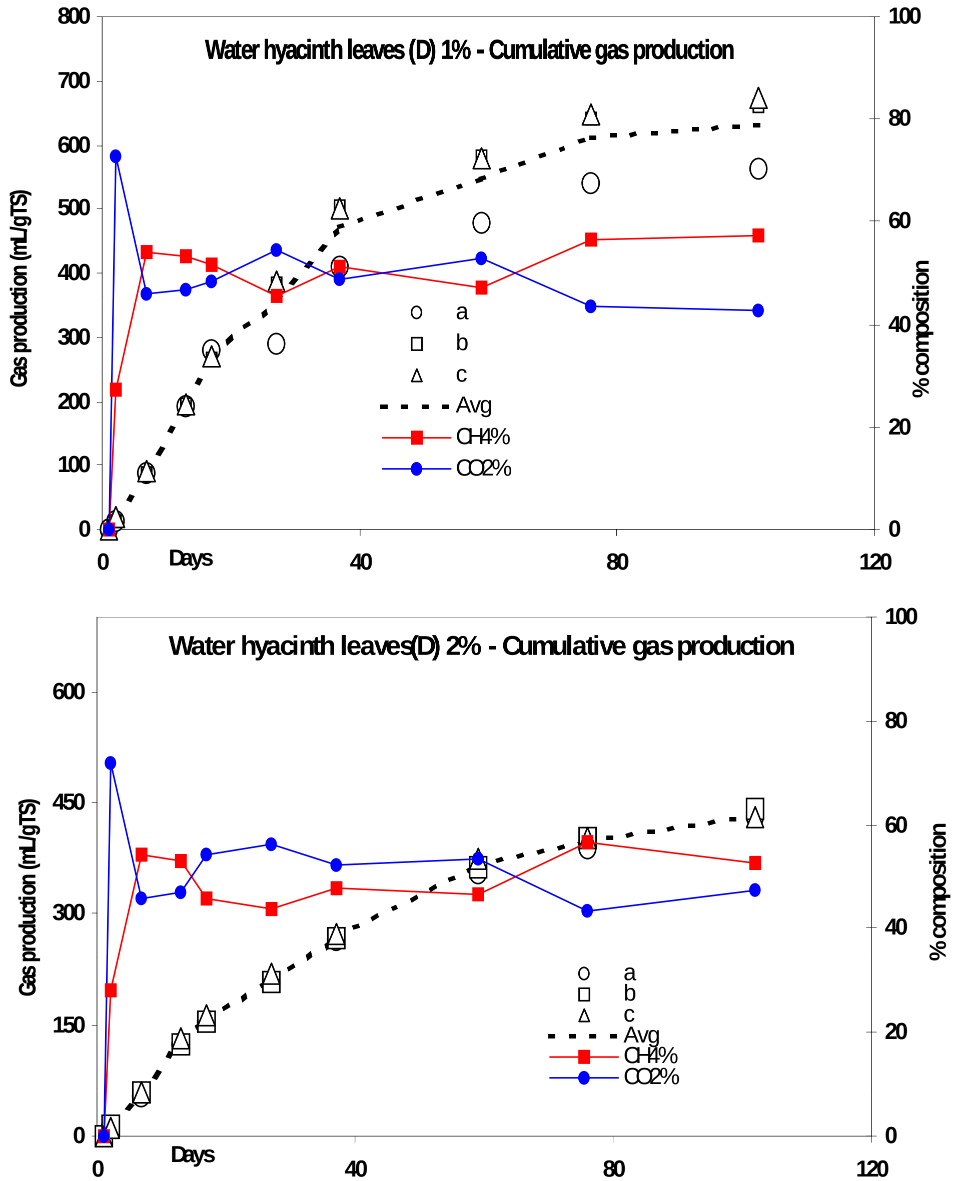


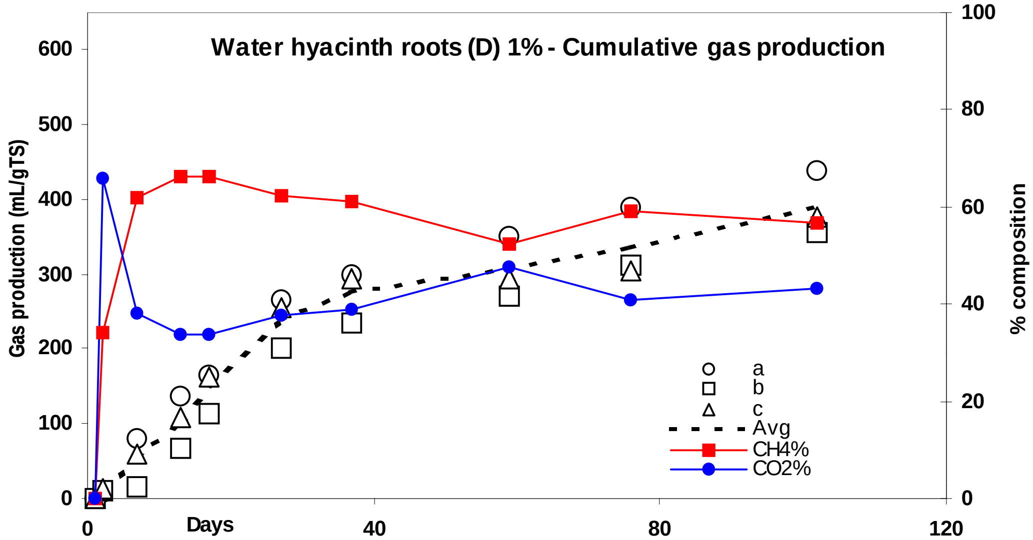
Fig 4.18. Cumulative gas production pattern of dry water hyacinth leaves

4.2. 6. Dry water hyacinth roots

There is an initial rapid gas production phase is the suggestive of VFA flux in the early stages of decomposition. From the high methane content of gas throughout the study period both in 1 and 2% concentration, it suggests that VFA induced methanogenic inhibition is unlikely at concentrations studied here (Fig 4.19). A steady state gas production occurs between 5 and 37th days of fermentation during which there is no indication of VFA induced methanogenic inhibition. The gas production began to level off after 40d both in 1 and 2% concentrations. There is no delayed rise in gas production after gas production levels have leveled off. There is very little difference in gas composition 1 and 2% concentration of water hyacinth leaves yet there is significant reduction in gas yield. The pattern does not exhibit any VFA induced methanogenic inhibition and suggests that the biogas plants can be operated at higher TS concentrations without the adverse consequences. The ultimate biogas yield is very high of about 0.39 m^3 /kg TS and about 0.25 m^3 CH_4 /kg TS. Such high yields could not be obtained under SSB conditions (Table 4.1). Previous studies had shown better gas yields than the present study (Cooley *et al.*, 1978).

4.2.7. Photocopying paper

Photocopying paper has been found to be a significant part of solid waste generated on the campus. In IISc, the component of paper can reach as high 15% by weight (Kumar *et al.*, 2001**).** Such paper is often soiled and not suitable for recycling. Photocopying paper poses an interesting challenge primarily because of its low bulk density (<30kg/m^3; Kumar *et al.*, 2001) as well as in the use of several agents for glazing and its impact on biogas production. The result of BMP assay of photocopying paper is presented in the Fig 4.20. A significant level of gas production is found to occur around by about 6 days of fermentation reaching levels of 75mL. However in spite of this large flux the methane concentration has generally be around 50% from the very beginning of BMP assay. Such a pattern suggests that biogas plants can be operated at higher solids content without fear of VFA accumulation or VFA fluxes. A steady state gas production is found to occur only for a short duration lasting approximately 25 days after which biogas production appears to level off. During this period, there has been no significant fall in methane content and suggests that VFA induced inhibition is not a cause for leveling off gas production early. Paper by virtue of its wide C/N ratio is starved of nutrients and it is possible as the early leveling off gas production is due to nutrient deficiency. However, further research is required to confirm this phenomenon. Among a few replicates, a pick up in gas production occurred after 70d reaching a final BMP of 0.6 m^3 /kg TS. An increase in gas production rates at a very late stage is suggestive of an inhibition of a nature not explained by available data. Further research is required. There is a very little difference in gas composition between 1 and 2% TS. The gas pattern is different between 1 and 2% solids. These suggest that the reactors operating on PCP can tolerate high solids concentration without fear of VFA fluxes. The ultimate BMP recorded was not clear and there was the wide variation between replicates reaching between 0.1-0.6 m^3/kg TS. BMP assay needs to be repeated with appropriate precautions.



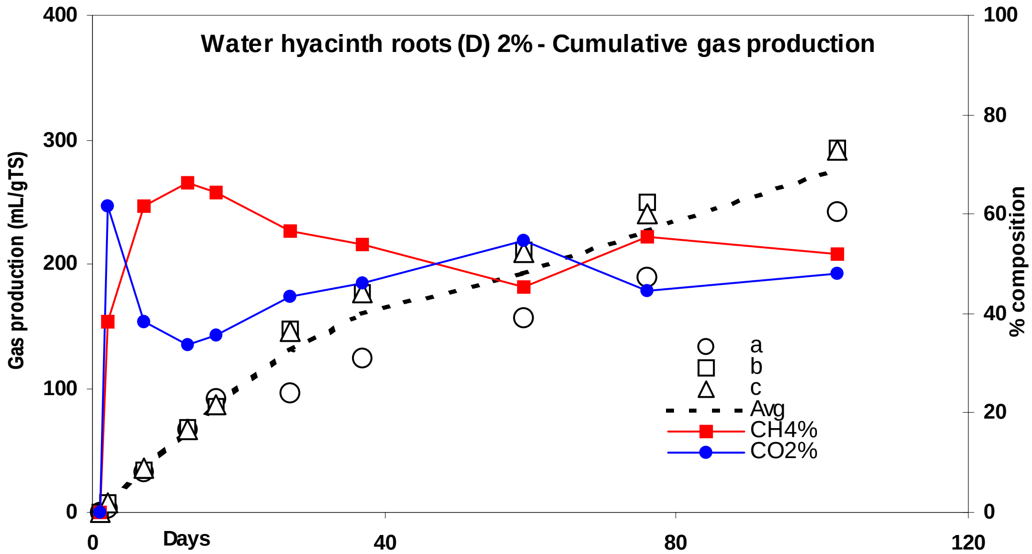


Fig 4.19. Cumulative gas production pattern of dry water hyacinth roots.

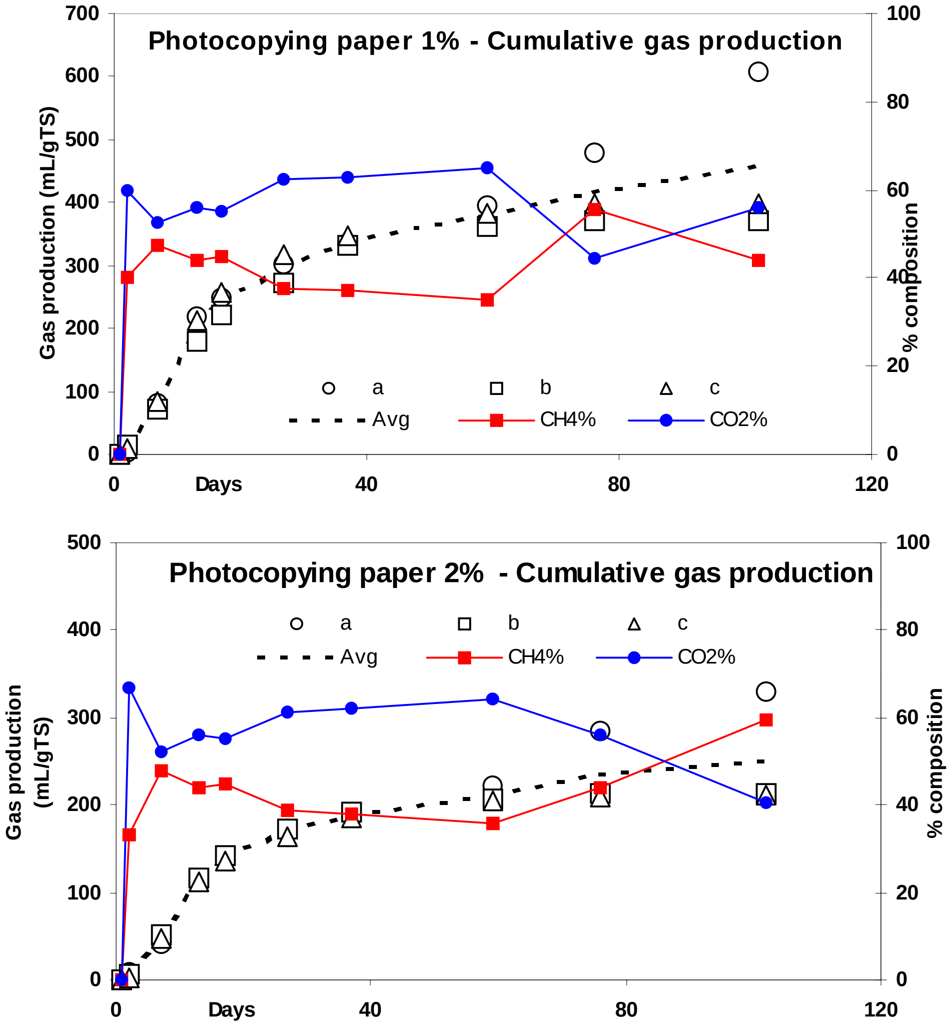


Fig 4.20. Cumulative gas production pattern of photo copying paper.

4.2. 8. Banana peel

Banana peel and banana stalks are known to be among the top few components of fruit waste found in USW collected in Bangalore. Banana peel is largely made up of pectic materials, is soft and is expected to be easy to decompose. Yet, because of the presence of simple decomposable material, fruit peels especially banana peel is likely to suffer rapid fluxes of VFA, VFA accumulation and the resultant methanogenic inhibition. The BMP assay is presented in the Fig 4.21. A very rapid rise in gas production and a low methane concentration in 1 and 2% vials are characteristic of VFA induced methanogenic inhibition and confirm above-mentioned expectations. The BMP pattern observed suggests the absence of steady state gas production phase with this feedstock. Low methane concentration is the suggestive of methanogenic inhibition up to a period lasting approximately 60 days. In the absence of the occurrence of gas production, leveling off has been observed between 15 and 60d of BMP assay. However after 60th day, once again gas production recovered along with rise in methane. A BMP of 0.36 m^3/kg TS has been recorded. However, as the gas composition is less than 50% methane, it is unlikely that the results of this BMP assay are useful. Further experiments are required to be done at lower TS to ensure that BMP levels are recorded without VFA induced methanogenic inhibition. The 1and 2% samples have shown low methane concentration suggesting that even in 1% TS methanogenic inhibition occurs. The ultimate methane potential cannot be obtained from the available data in the study. In previous work on banana peel (Gunaseelan, 2004; Nand *et al*., 1997) has produced very high levels of biogas, which suggests that this banana peel is good feedstock.

4.2. 9. Watermelon rinds

Watermelon is a seasonal fruit and is found in USW composition recorded earlier from near fruit shops. Watermelon rinds is a large sized object characterized by high moisture largely of primary cell wall of pectic origin. The large size and high moisture content pose a challenge to biogas production in conventional biogas plants. A large initial spurt in gas production is suggestive of gas production largely in the form of CO_2 both in 1 and 2% is the suggestive of large flux of VFA (Fig 4.22). In addition, a low concentration of methane is suggestive of VFA induced methanogenic inhibition. This is also seen in 2% where methane concentration rarely exceeds 10%. As a result of VFA induced inhibition or a pattern similar to that there is steady state gas production seen after 5 days of BMP. During this period, methane concentration is less than 20% in both the concentrations of TS and is the indicative of VFA induced suppression of methanogenesis. An early occurrence of leveling off gas production is found and permits till a 70d period in 1% and 80d period in 2%TS in micro digesters. After 40d period, as a gradual increase in methane concentration and also a recovery of gas production is seen 0.4 m^3 /kg TS. This late recovery of gas production is characteristic of an inhibited biogas production during the early stages. Both 1 and 2% TS BMP assay have very low methane concentrations where 2% concentration has rarely had methane concentration exceeding 5%. This pattern is the indicative of very large VFA flux and its methanogenic inhibition. From the current BMP assay ultimate biogas and methane potential cannot be determined. Further studies at lower concentration of TS have to be carried out to determine the BMP.

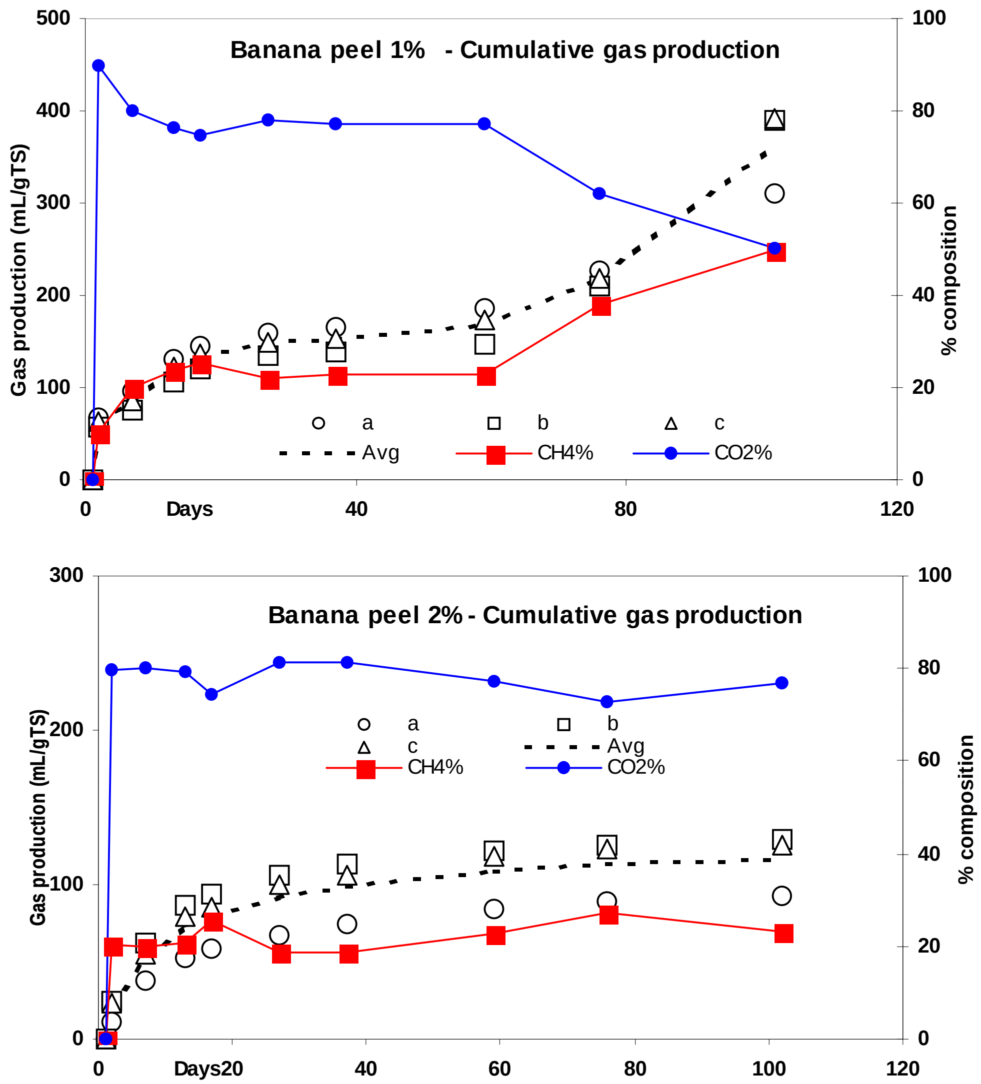
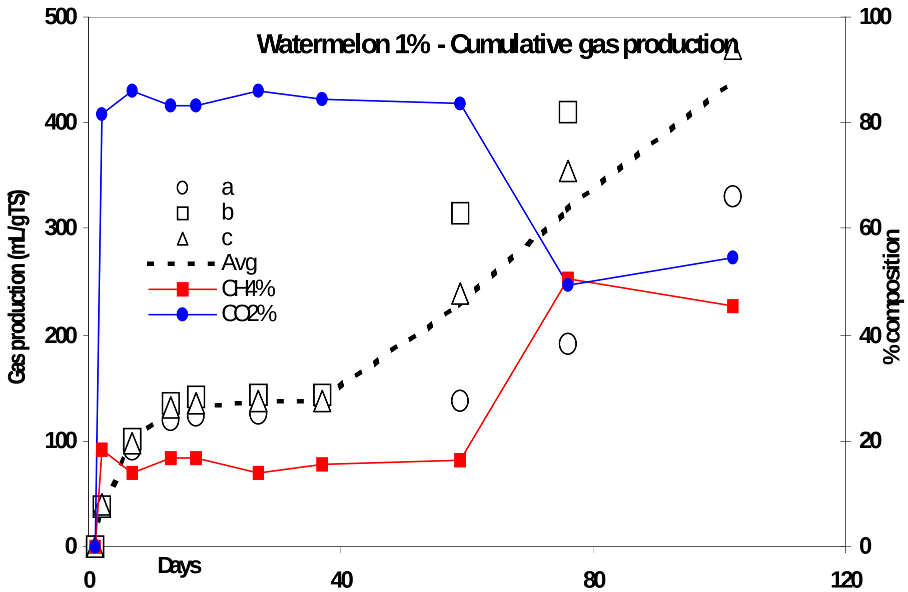


Fig 4.21. Cumulative gas production pattern of banana peel.



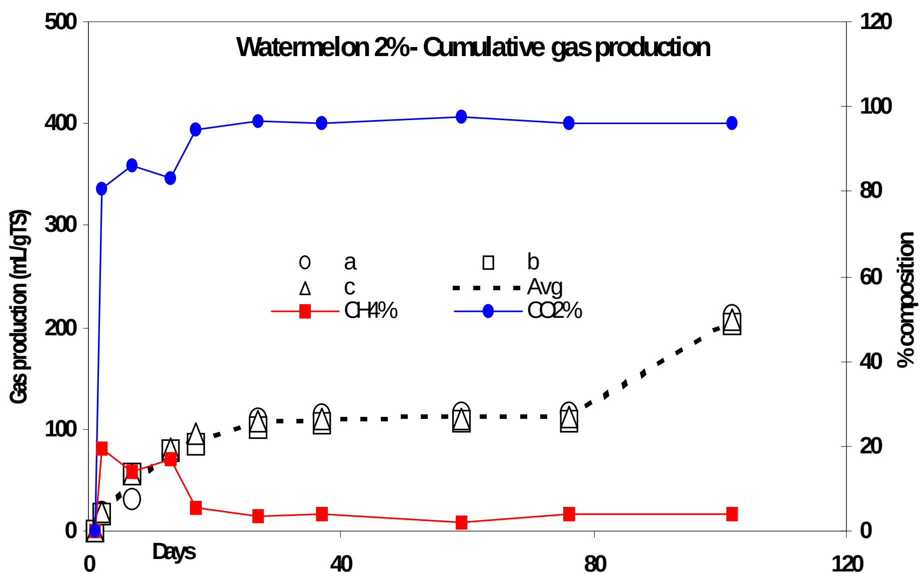


Fig 4.22. Cumulative gas production pattern of watermelon rinds.

4.2.10. Citrus fruits

Citrus fruits peel form a significant proportion of fruit waste component of USW and is dominant in wastes collected from nursing homes and hospitals. Citrus peels either as orange or sweet lime is largely pectic material with significant components of essential oils which have anti-microbial properties. There are reports that citrus peels inhibit biogas production and this form a major challenge to biogas production The BMP assay results for orange peel are presented in Fig 4.23. A rapid gas production pattern is seen and accompanied by a very high evolution of CO_2 at concentration in the range of 80%. While methane concentration remains around 20%. Such a pattern is characteristic of methanogenic inhibition. As a consequence of low methane production and high CO_2 it is suggestive of VFA accumulation. The BMP assay did not exhibit any steady state gas production phase either in 1 or 2% vials. Slowing down of gas production occurred rapidly and gas production did not recover during the BMP assay period of 100 days. The BMP values recorded are very low at 0.1 m^3 /kg TS and are the indicative of suppressed biogas production process. The level of inhibition is higher at 2%TS. From this data, ultimate BMP cannot be determined. Further studies are required to understand the suppression process. In previous studies, it ahs been found (Chanakya *et al.*, 1997) that up to a small fraction in the form of citrus peel has not affected biogas production in plug flow digesters. Similarly other research findings on citrus peels have shown biogas production is possible below a certain overall concentration of citrus peels in the feedstock.

The case of sweet lime (local name Mosambi) is similar to that of orange peels. The gas production is suppressed and the methane concentration remains around 20% and even lower at 2%TS concentration (Fig 4.24). This pattern is the suggestive of very high level of methanogenic suppression. At lower concentration of sweet lime peel is required to deduce the BMP and is inhibitory in nature at higher concentrations.

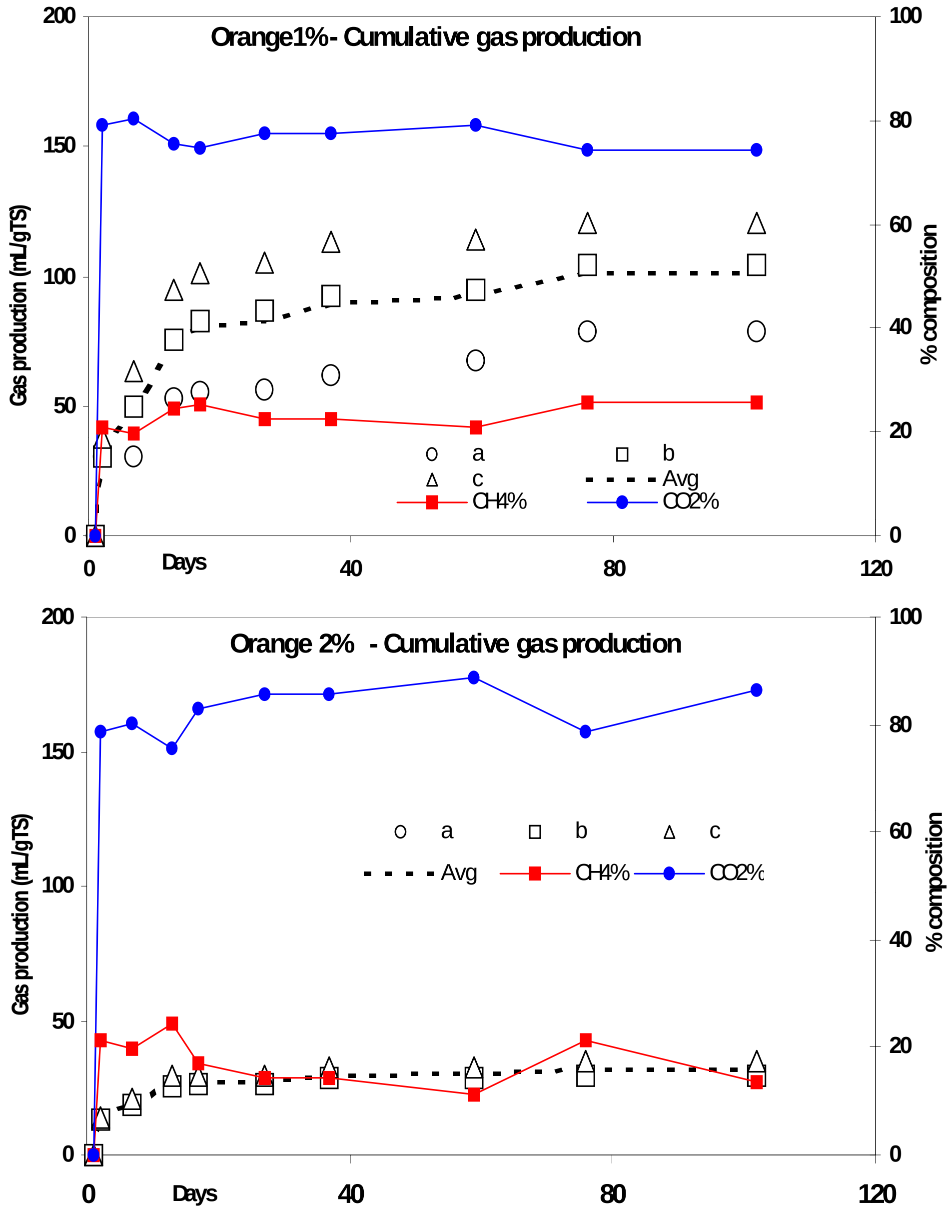


Fig 4.23. Cumulative gas production pattern of orange peel.

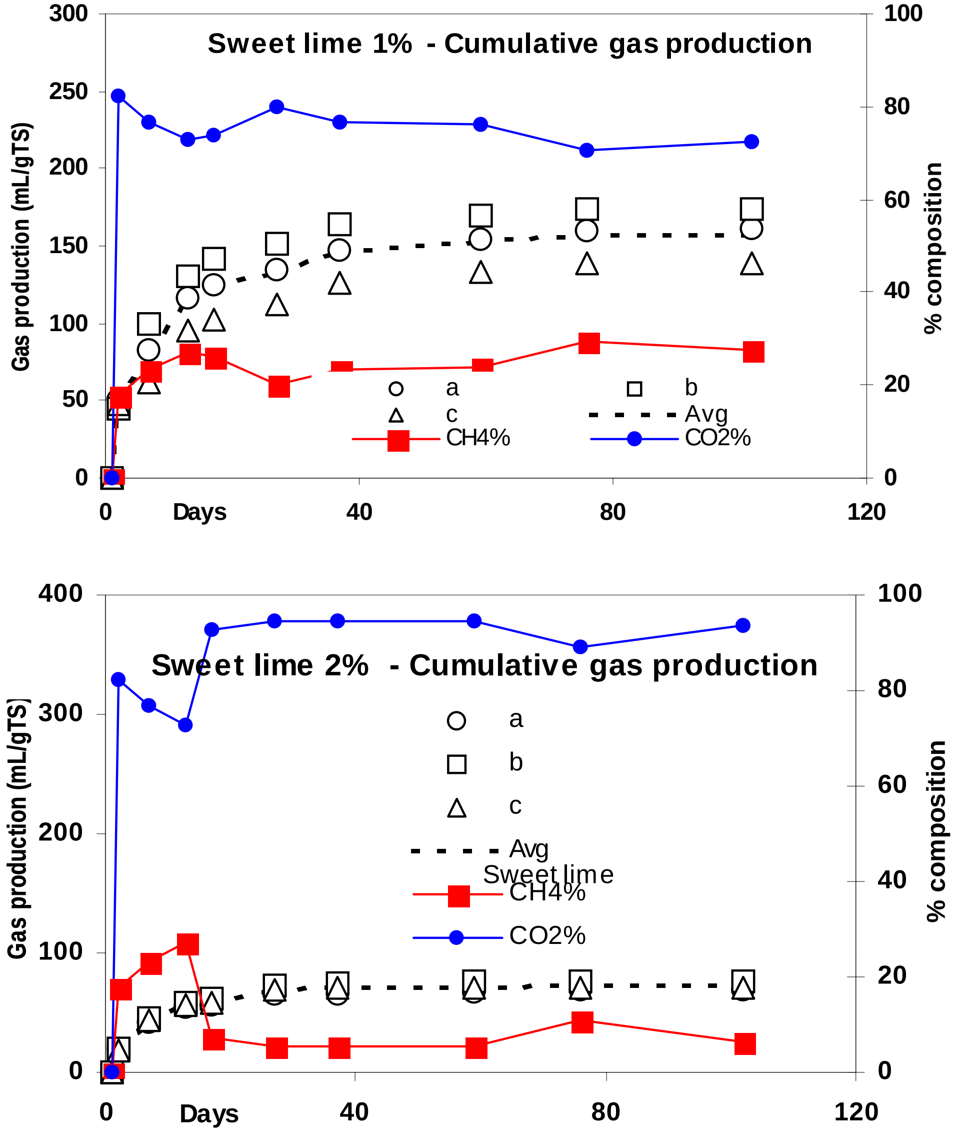


Fig 4.24. Cumulative gas production pattern of mosambi peel.

4.2.11. Mixed fruit wastes with sweet lime (mosambi)

The BMP assay results for mixed fruits with mosambi are presented in Fig 4.25. A rapid gas production pattern is seen and accompanied by a very high evolution of CO_2 at concentration in the range of 80%. While methane concentration remains around 20%, this is the characteristic of methanogenic inhibition. A low methane production and high CO_2 is the suggestive of VFA accumulation. The BMP assay did not exhibit any steady state gas production phase either in 1 or 2% vials. This was followed up by the leveling off phase lasted till 79th day. A sudden spurt after leveling off phase was detected clearly showed the presence of non-VFA induced inhibitory factors. Recovery of methane production was detected on 59th day. The BMP values recorded are very low at 204mL/gTS and are the indicative of suppressed biogas production process. The level of inhibition is higher at 2%TS. For this data, ultimate BMP cannot be determined. Further studies are required to understand the suppression process.

4.2.12. Mixed fruit wastes with orange

The BMP assay results for mixed fruits with 25% orange peel in mixture are presented in Fig 4.26. A rapid gas production pattern is seen and accompanied by a very high evolution of CO_2 at concentration in the range of 80%. Methane concentration remains around 20% and is characteristic of methanogenic inhibition. A low methane production and high CO_2 is the suggestive of possible VFA accumulation. The BMP assay did not exhibit any steady state gas production phase either in 1 or 2% vials. This was followed up by the leveling off phase lasted till 37th day. A sudden spurt after leveling off phase was detected clearly showed the presence of non-VFA induced inhibitory factors. Recovery of gas production in 1-2 replicates confirmed the same. Recovery of methane production was detected on 59th day. Yet, the BMP values recorded are very low at 336mL/gTS and are the indicative of suppressed biogas production process. The level of inhibition is higher at 2%TS. For this data, ultimate BMP cannot be determined. Further studies are required to understand the suppression process.

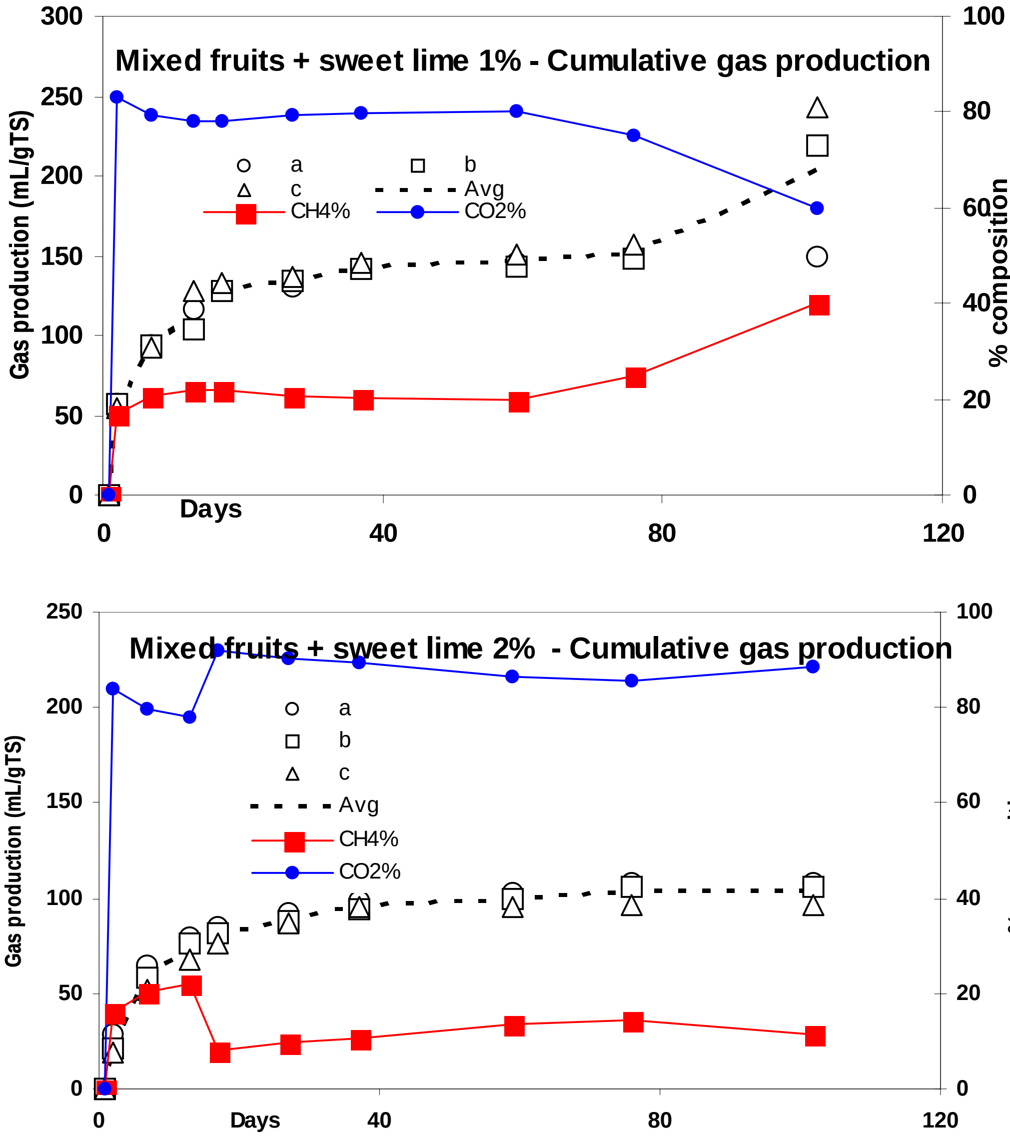


Fig 4.25. Cumulative gas production pattern of mixed fruits and mosambi mixture.

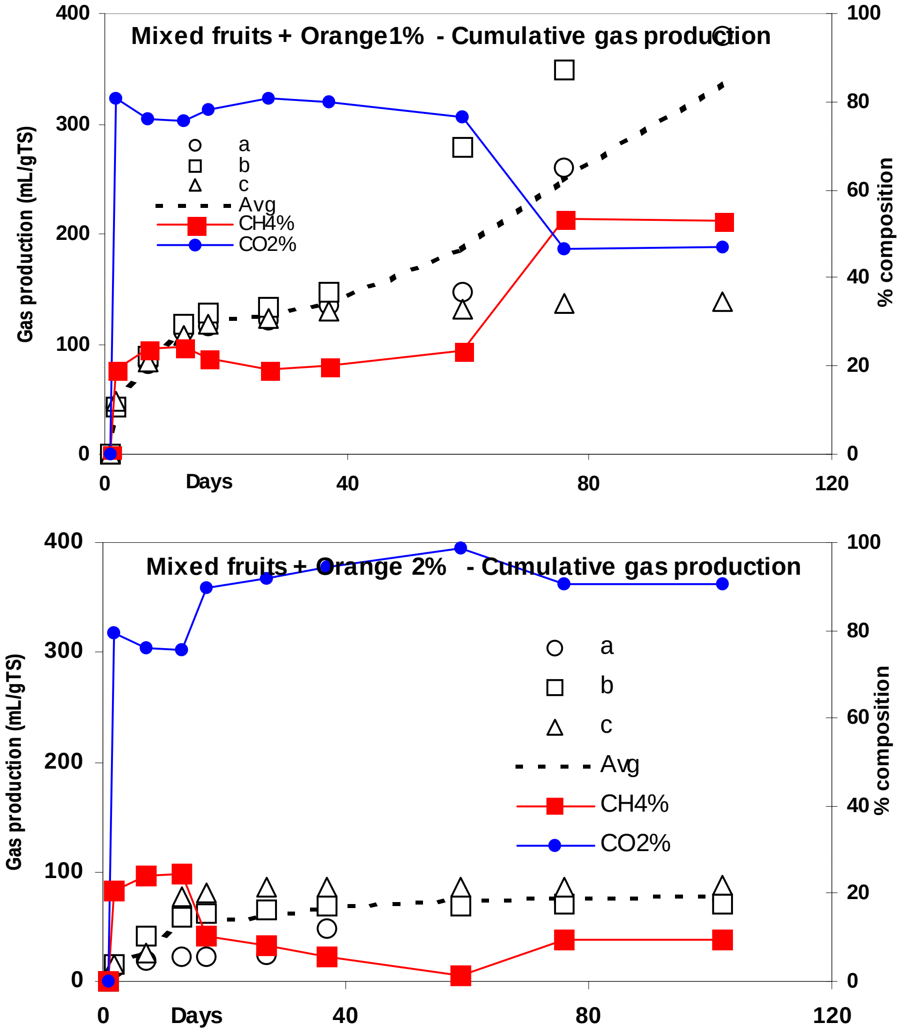


Fig 4.26. Cumulative gas production pattern of mixed fruits and orange mixture.

4.2.13. Water hyacinth whole plants

Water hyacinth fresh has been studied for its BMP. In spite of an early increase in gas production similar to the one found in dry water hyacinth. There is a high gas production accompanied by greater than 50% methane concentration in both 1 and 2% assay (Fig 4.27). A steady state gas production is found up to a period of 40d after with signs of leveling off of gas production. Methane concentration has remained higher than CO_2 suggesting a normal methanogenic process. After leveling off occurring, after period of 40d no rapid spurts in gas production has been found. In terms of composition, there is no significant difference between 1 and 2% BMP assay. Although rate of gas production is low in 2%, data suggests that no significant inhibition is likely at higher concentrations of this feedstock. The ultimate BMP is around 0.6 m^3 CH_4 /kg TS and around 0.35 m^3 CH_4 /kg TS. Fresh and dry water hyacinths have been a subject of study for energy recovery from aquatic weeds (Chynoweth,1982; Klass and Ghosh,1981; Mallik, 1990).

4.2.14. Fresh water hyacinth leaves

Fresh water hyacinth leaves has posed a challenge for biogas production in terms of its low bulk density, reaching levels as low as 30kgTS/m^3**.** This poses a challenge for biogas production in conventional reactors. In the BMP assay, these leaves did not exhibit a large initial gas production and accompanying indicators for high VFA flux (Fig 4.28). The methane concentration has remained in the range of 50% throughout the study period. 1 and 2% concentration suggesting that at higher concentrations of this feedstock, methanogenesis is unlikely to be inhibited by VFA fluxes. A steady state gas production continues throughout the study period and the absence of a leveling off suggests, a low gas production due to factors other than VFA induced inhibition. The ultimate BMP is in the range of 0.6 m^3 /kg TS or around 0.350 m^3 CH_4 /kg TS**.** There is a significant reduction in gas production levels between 1 and 2% assay. There is no indication of methanogenic inhibition. Water hyacinth leaves has been used previously as a feedstock to biogas production and the gas production levels achieved are similar to those found in literature (Gopalakrishna, 1989).

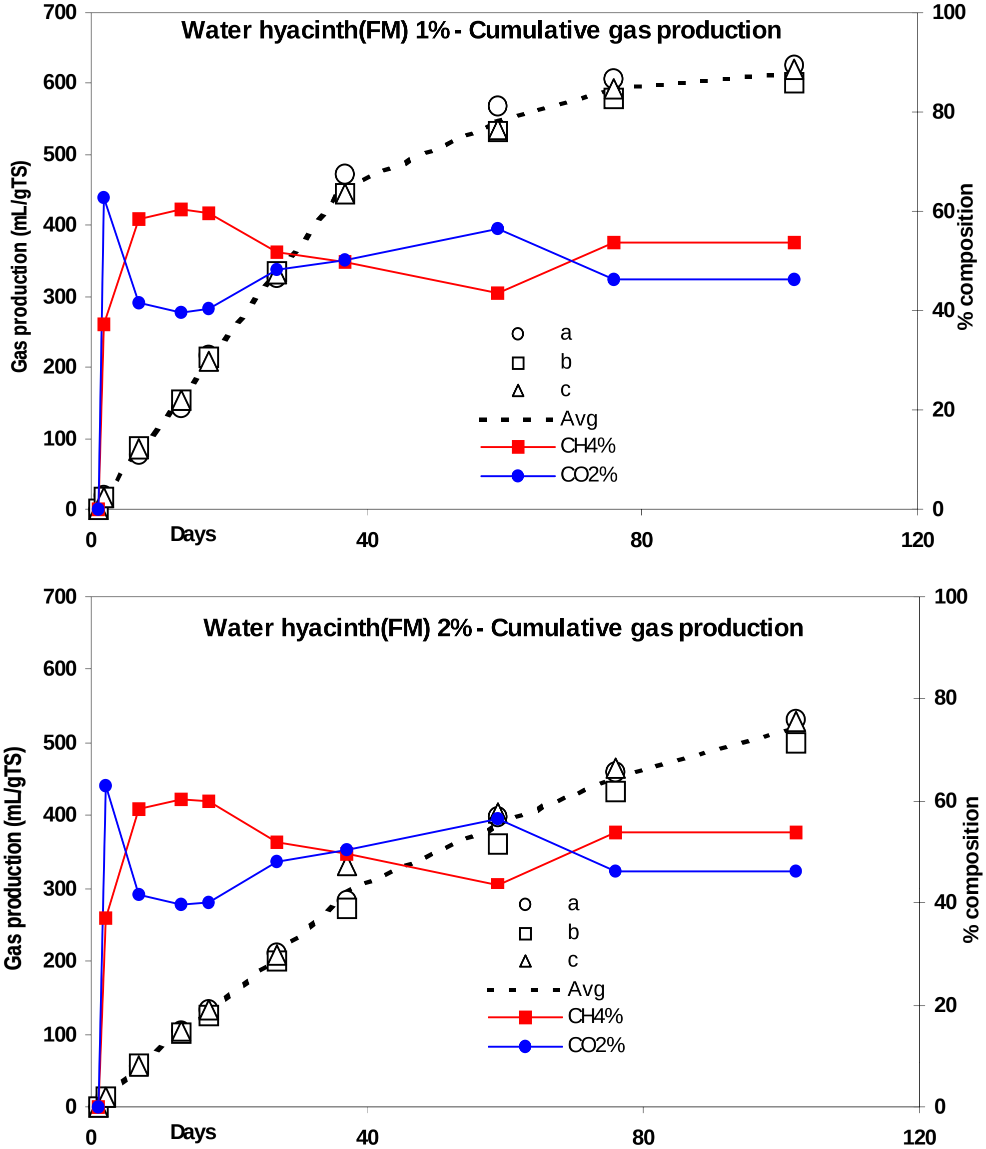
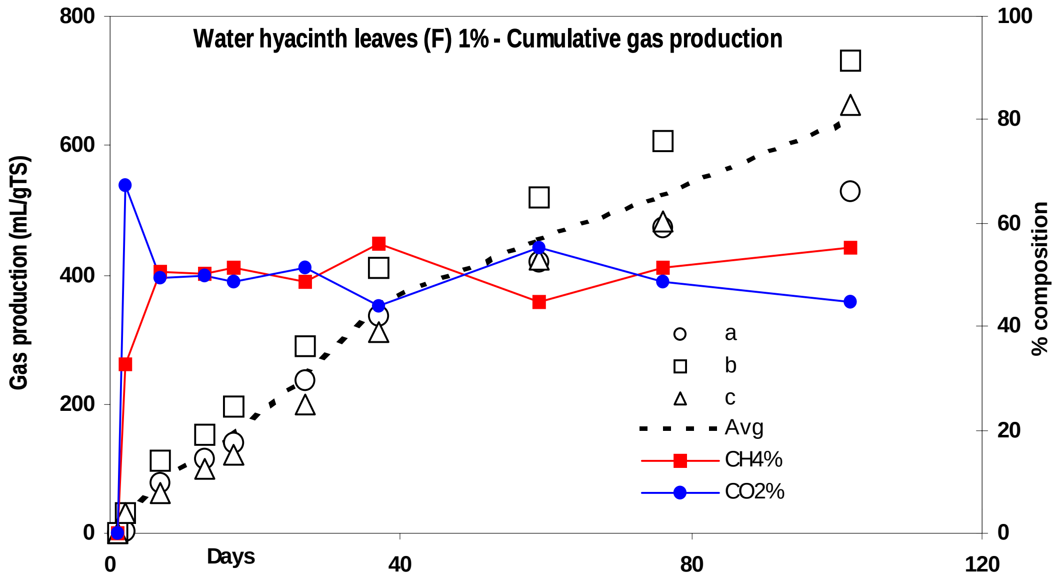


Fig 4.27. Cumulative gas production pattern of fresh water hyacinth whole plants



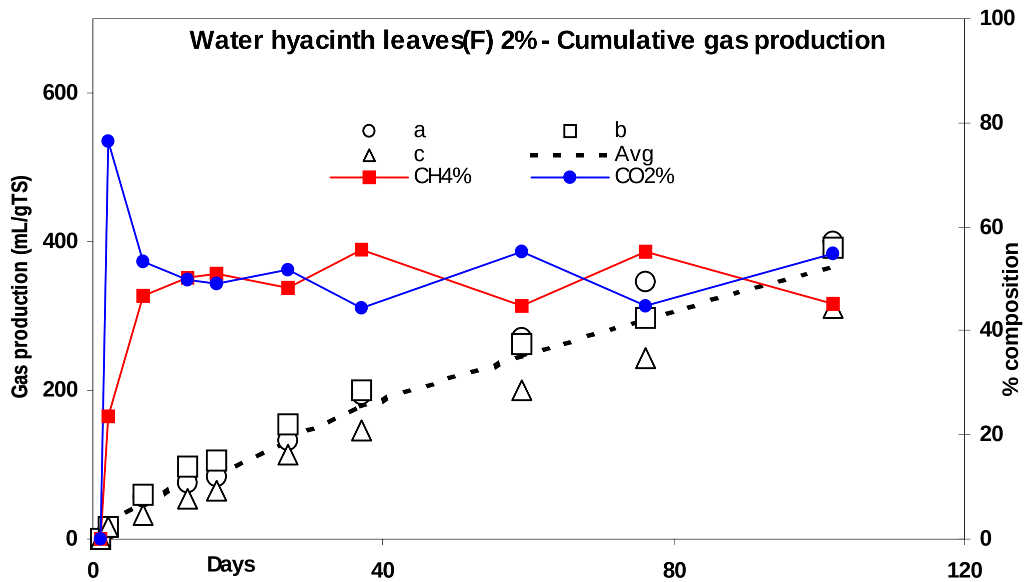


Fig 4.28. Cumulative gas production pattern of fresh water hyacinth leaves

4.2.15. Water hyacinth roots

Water hyacinth roots are recovered and removed for use in various other materials such as compost, microbial inoculants etc. They can be expected to form separate wastes around urban tanks taking water hyacinth tops away as cattle feed while roots are left behind and form a part of USW. There has been a significantly high methane concentration through out the study period and there is a total absence of rapid initial VFA production has been consistently low (Fig 4.29). A steady state gas production is found to occur until 30d period of which gas production seems to level off. There is no secondary recovery in gas production. The methane concentrations are roughly similar for 1 and 2% concentration feedstock of the assay and suggest that higher concentration of feedstock are unlikely to inhibit the biogas production process. The ultimate BMP was low at $0.27m^3$ CH_4 /kg TS and suggests this is a poor feedstock for biogas production. Previous studies have shown a low gas production from water hyacinth roots and the current study showed the same with that reported in literature.

4.2.16. Paper mulberry

It is a large tree-weed occurring on IISc campus. Its litter production is high and constitutes the significant component of litter component of USW collected on the campus. Paper mulberry has been previously studied for biogas production and has been found large quantities of biogas. It is of interest to determine the BMP of this feedstock in the form of litter. There is an initial gas production level accompanied by low methane and high CO_2 concentration. This is characteristic of initial VFA flux and short duration methanogenic suppression (Fig 4.30). A gradual steady state accompanied with rise in methane concentration occurred and lasted up to 59d. This recovery of methane is the suggestive of possible acclimatization by bacteria. This is also seen in 2% TS with recovery after 60^{th} day. A leveling off gas production was found. An early leveling off was seen in 2% lasts at 60d followed up by a recovery of gas production later and is the indicative of non-VFA induced inhibition. Further research is required to determine nature of this inhibition. No such increase was encountered in1% TS. The ultimate BMP for this feedstock was 679mL/gTS, suggests that this is a good feedstock for biogas plants with lower TS concentration. From the above results, it is clear that care is needed when using this feedstock at higher concentrations

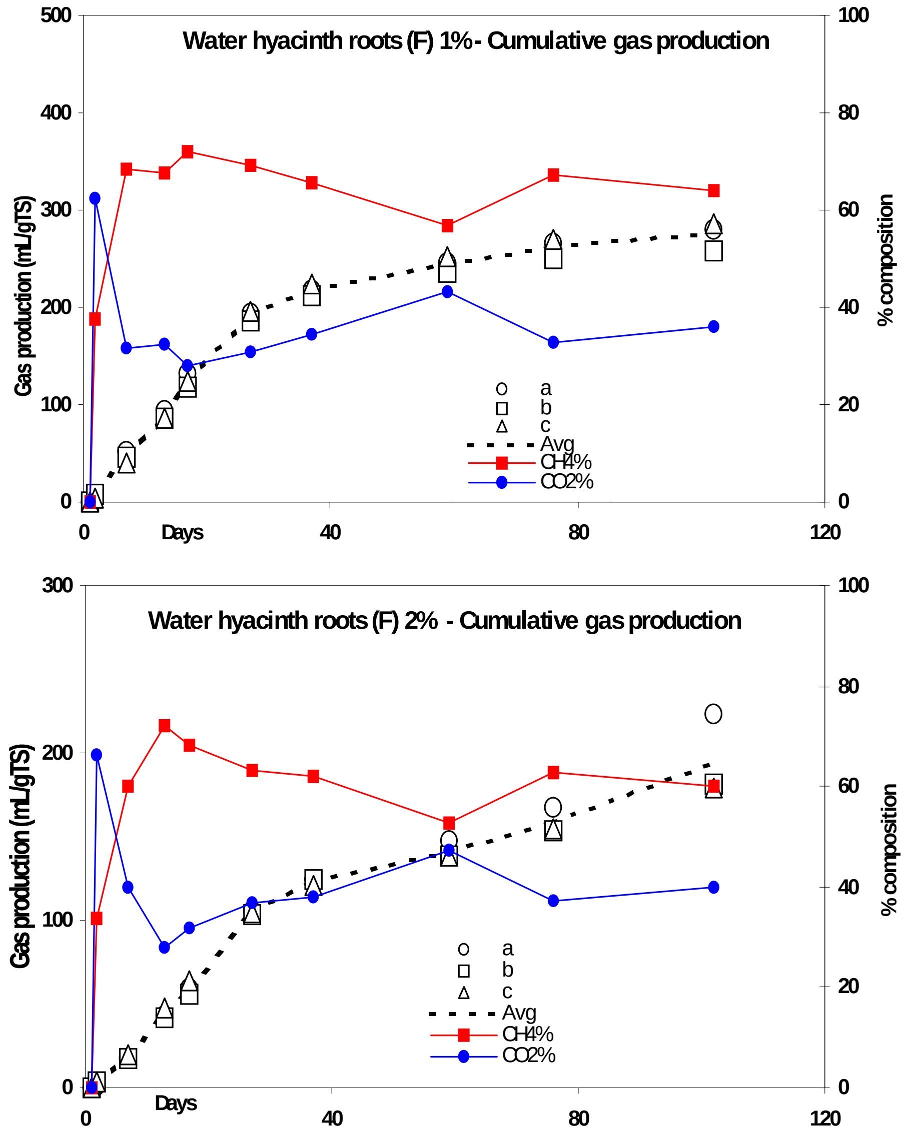
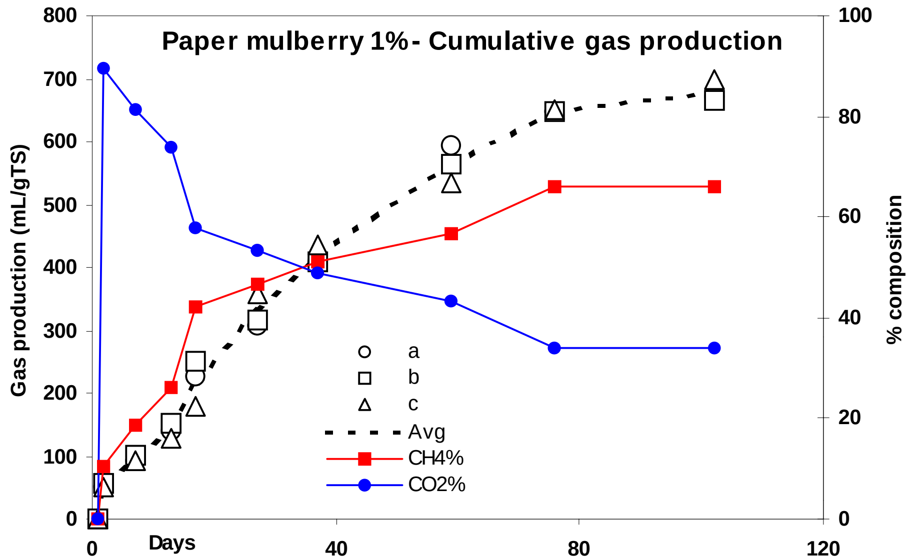


Fig 4.29. Cumulative gas production pattern of fresh water hyacinth roots.



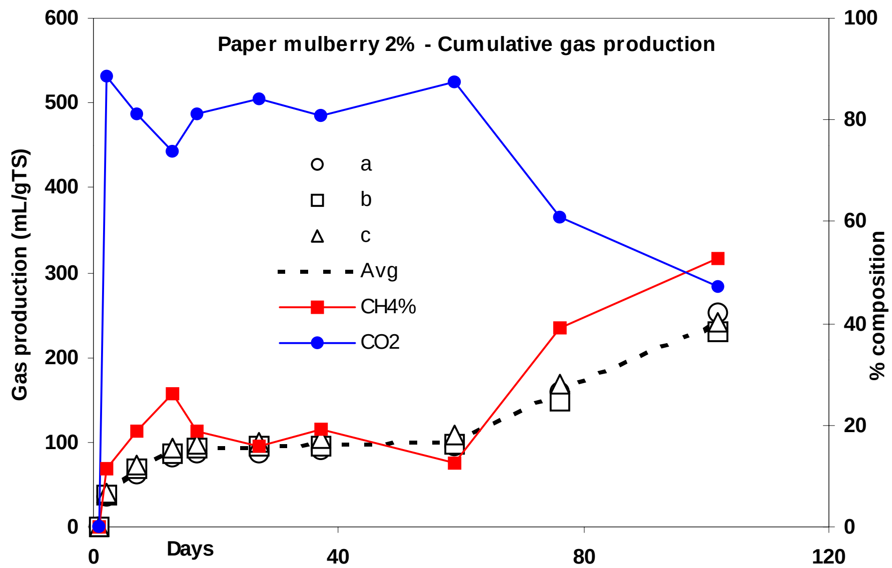


Fig 4.30. Cumulative gas production pattern of paper mulberry.

Thus from the BMP results of different feedstocks, water hyacinth and agro residues gave good biogas production potential, has not shown the same in the SSB digestion. This infers that under controlled condition VFA flux was avoided by the recovery of methanogenic bacteria in the initial lag period. Other feedstocks did not show any significant difference except fruit wastes and it was affected by rapid VFA flux, in turn needs careful start up procedure to avoid souring. Hence the proper start up and pretreatment procedure is needed to improve the gas yield in such lab study.

4.3. Reuse of digested biomass as methanogenic support in DFFBR

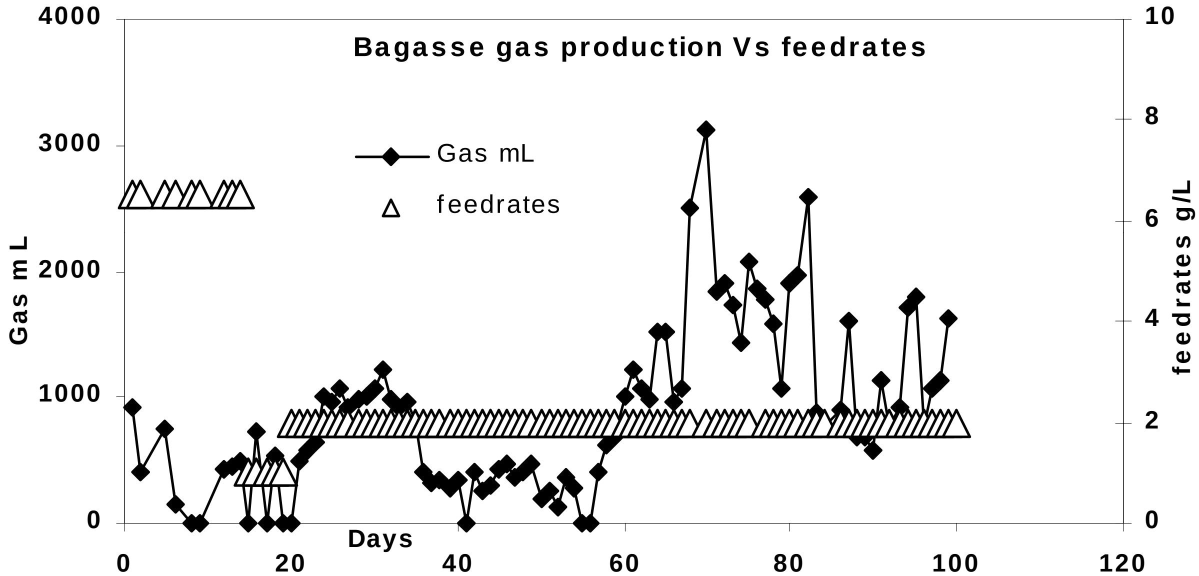
Methanogenic bacteria were found strongly adhered to several green biomass feedstocks digested in a solid phase biogas fermentor. Methanogenic activities measured on such biomass support material exhibited a potential to achieve much higher gas production rates (Chanakya *et al.,* 1998). Hence these digested feedstocks were examined for their potential in acting as a biofilm to convert the liquid waste in to biogas. In addition, reticulated spirals (synthetic support tested against naturally occurring material for their efficiency of supporting the methanogenic bacteria) and mixture of biomass with bagasse was also tested.

4.3.1. Daily gas production

The gas production pattern (Fig 4.31) in relation to stepwise changes in feed rates as well as a gradual replacement of the recycled effluent by anoxic water was studied. It was observed that up to a daily feed rate of 0.16-1g/L/d with 100% effluent recycling gave the gas production of 3L in the case of bagasse and PVC used as support. With a mixture of bagasse and spent biomass as a support material, gas production rose to maximum of 5.5L/d. These results suggest that a mixture of bagasse and biomass (digested in an anaerobic reactor) provides for a good support material for methanogenic biofilms to form and function. A combination of bagasse and biomass provided a long duration support compared to leafy biomass alone that has a half life in the range of 120d (Chanakya *et* al, 1998).

4.3.2. COD conversion Vs gas production rates

The COD conversion pattern was very well coincides with gas production pattern. Maximum of COD conversion in all the fermenters harboring bed materials was observed when it was recycled with 100% effluent. An attempt was made once in 15 days to reduce the dependence of on the extent of effluent recycled. When the extent of effluent reduced to 25%v/v, the fermentor became unstable and the effluent gradually became acidic (pH 5.6). At this stage, recycling with 50v/v of effluent was started. Then the gas production gradually picked up to the maximum levels. These results suggest that the practice of effluent recycling will be required under operating conditions followed. The reason for this dependence on recycling is not clear from data available. Hence at the startup of these fermentors, recycling plays an important role and will need to be understood better. Inlet and outlet COD of the synthetic effluent was given in the Fig 4.34.



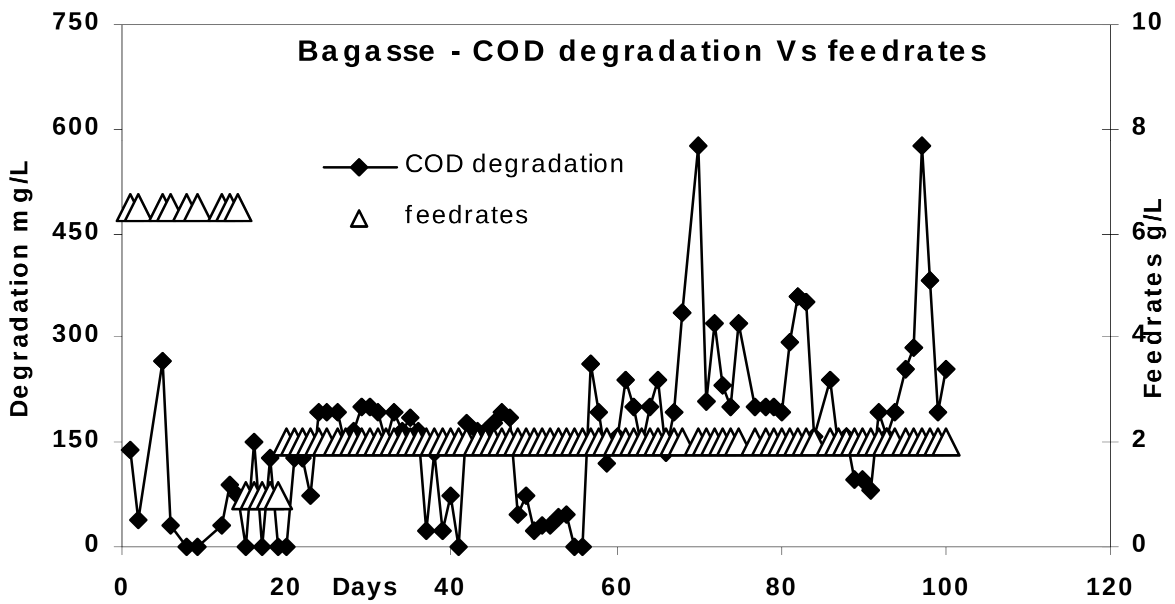
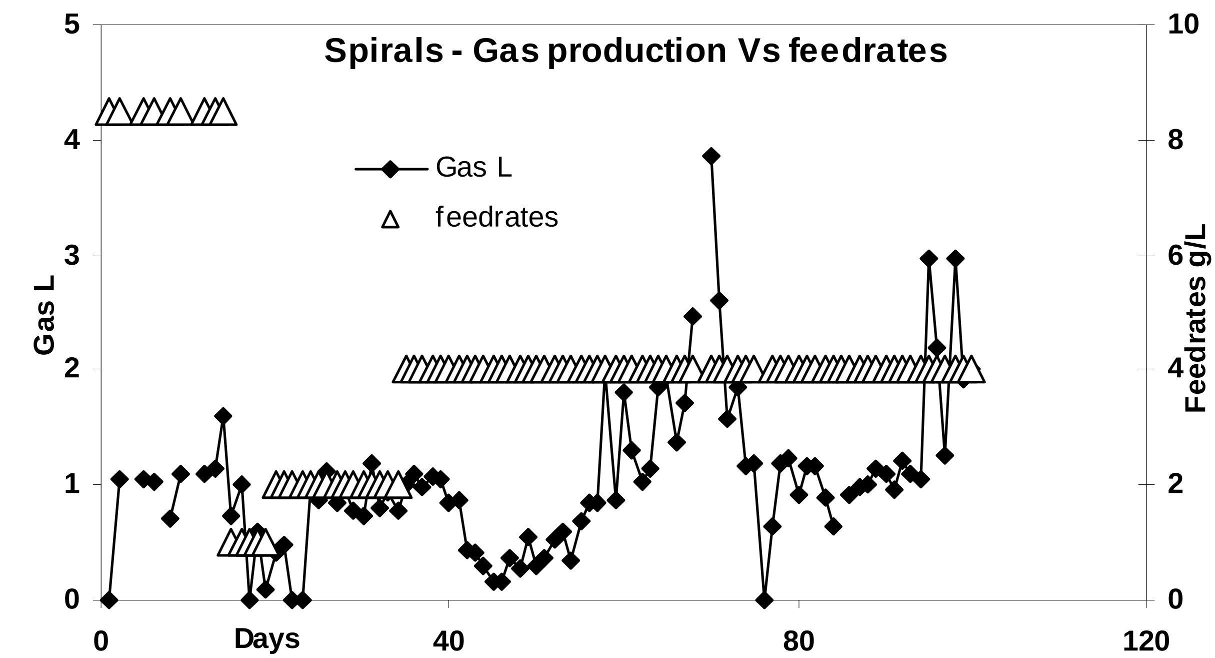


Fig 4.31. Feed rate Vs Gas production and COD degradation for bagasse



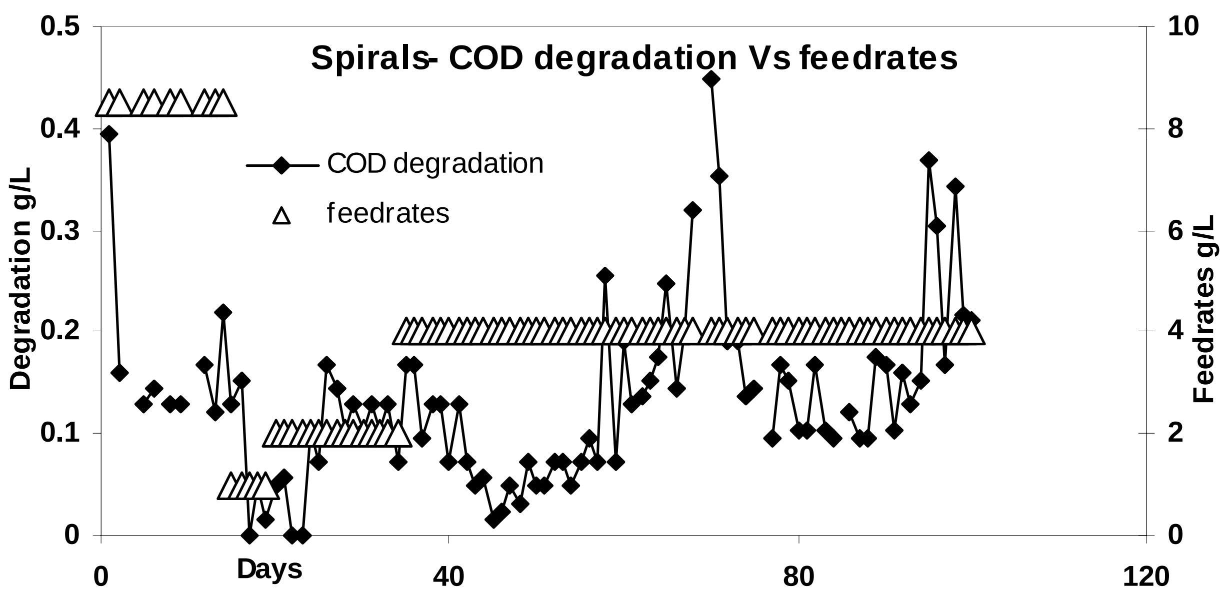
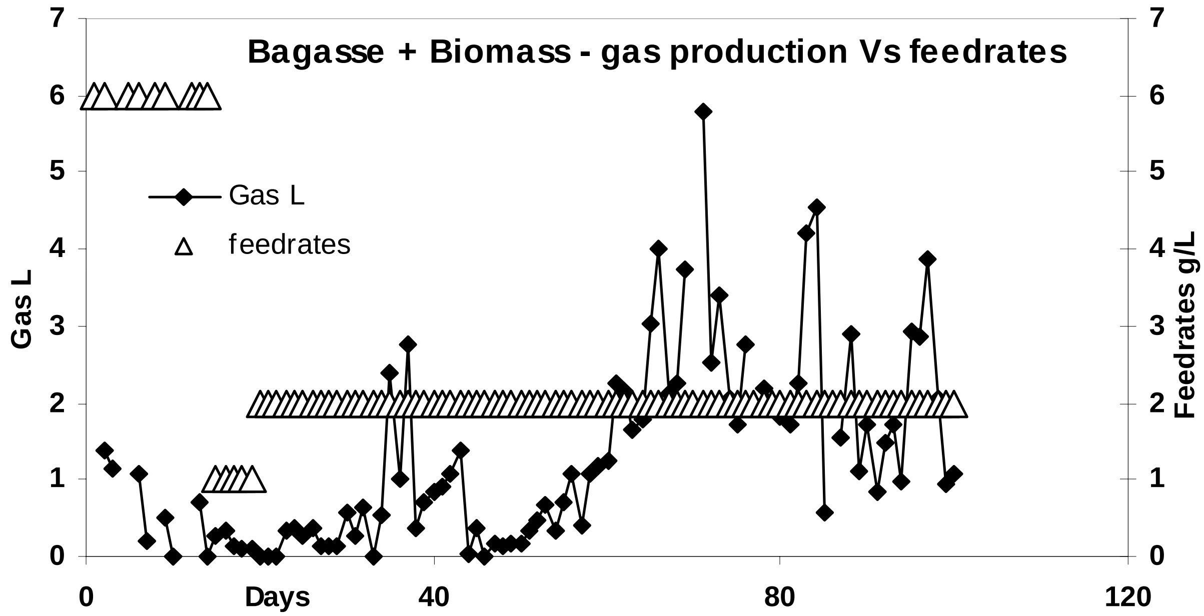


Fig 4.32. Feed rates Vs Gas production and COD degradation for spirals



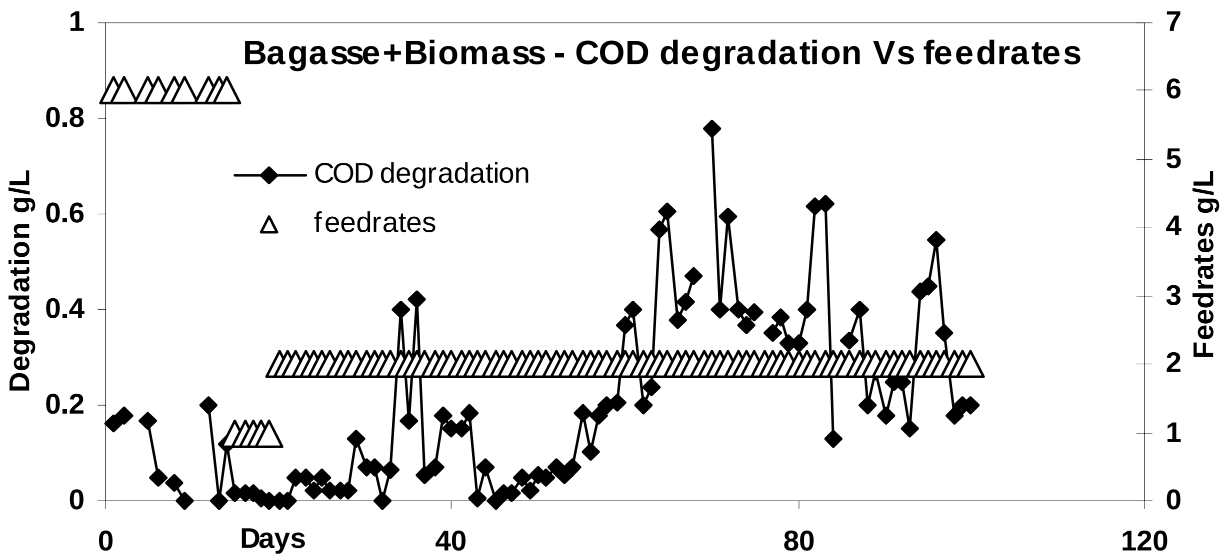


Fig 4.33. Feed rates Vs Gas production and COD degradation for bagasse + biomass

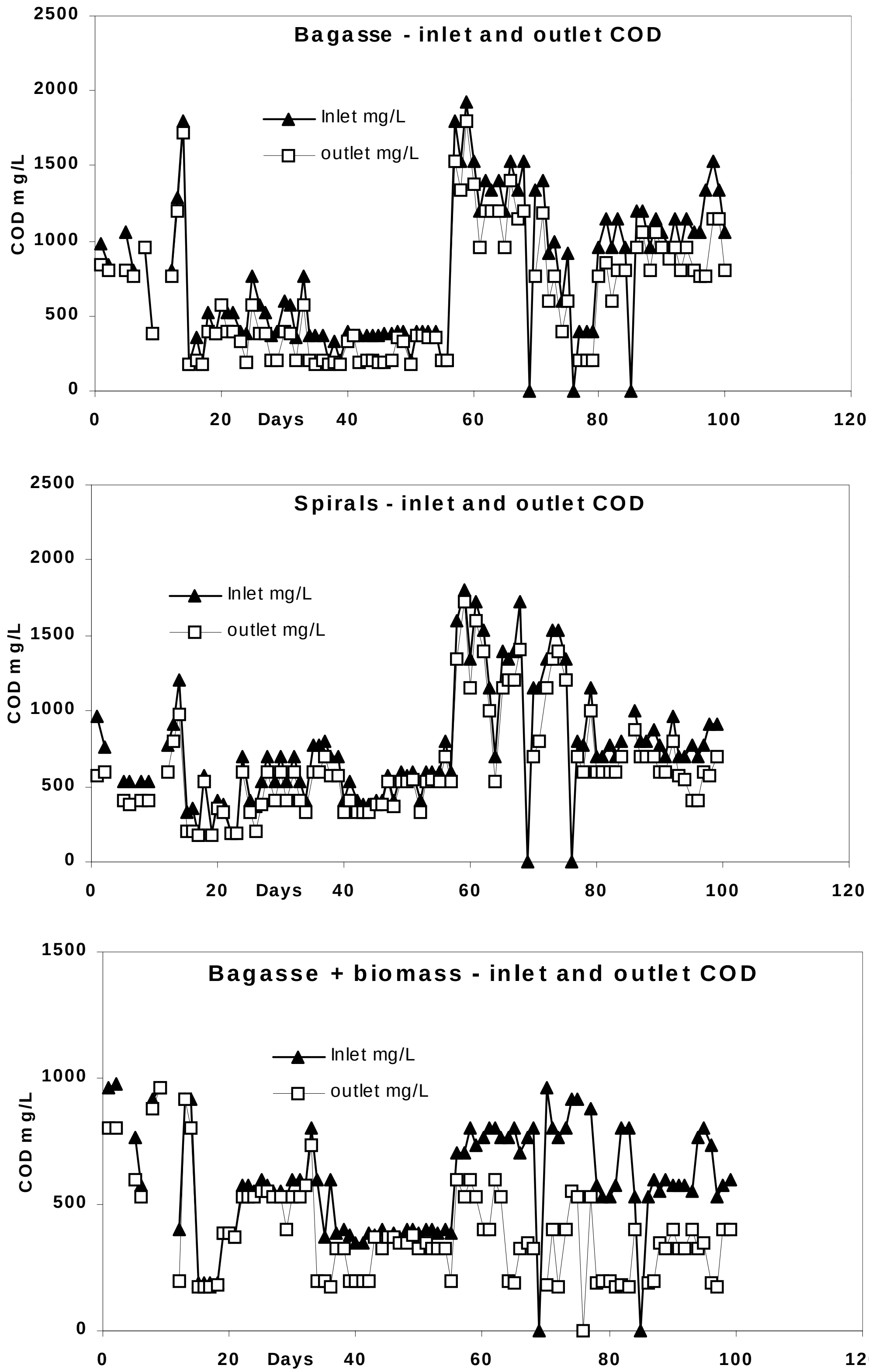


Fig 4.34. COD reduction in DFFBR reactor.

4.3.3. Gas composition

The biogas composition of fermentor with biomass support of bagasse, bagasse + biomass mixture and PVC spirals showed a good methane content of above 60-70%. This in turn suggests good methanogenesis. Yet, in spite of high methane content, various indicators of digester failure occurred. Such is situation is possible when digesters have regions of malfunction and regions of good conversion. Further studies are required to develop techniques that can overcome this problem before biomass is employed as methanogenic support in high rate digesters.

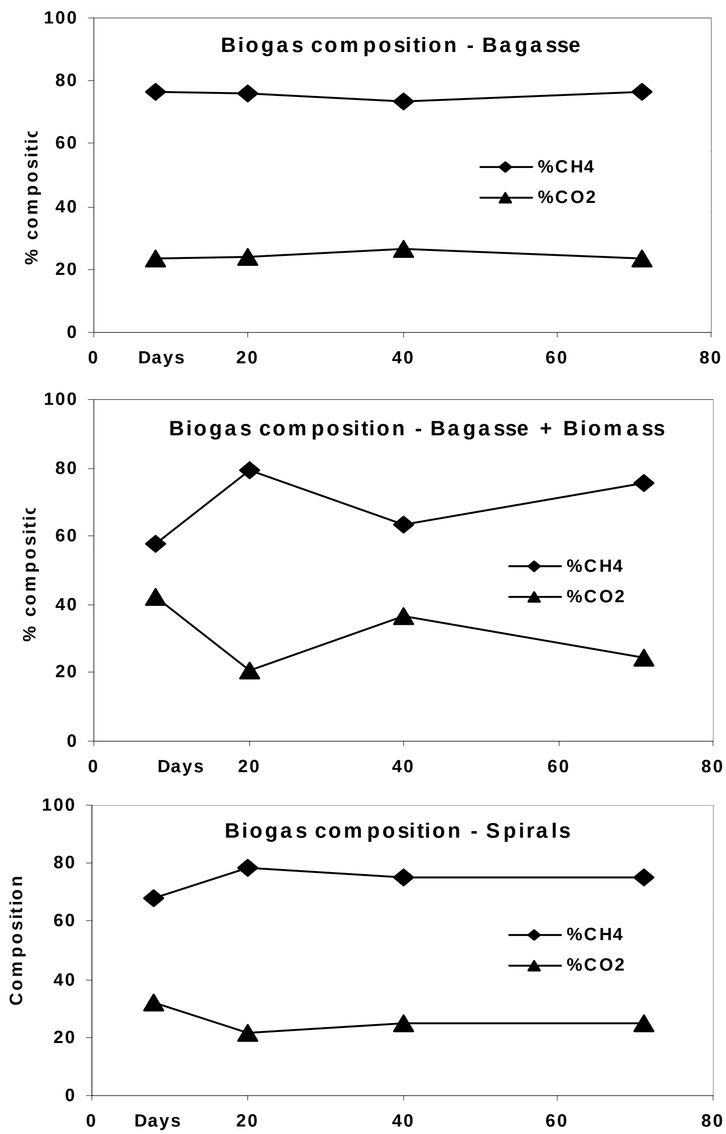


Fig 4.35. Composition of biogas in DFFB reactor.

Chapter 5: Conclusions and recommendations

Most of the OFUSW components tried out had good biogas production potential. They promise high gas yields at residence time similar to that of aerobic composting.
Solid-state stratified bed reactor approach can be used to ferment components of USW with small corrections for their fermentation pattern.

Under SSB fermentation conditions, following pattern was observed:

1. OFUSW will undergo >50% VS conversion. A greater VS destruction is also possible if the proper start up procedures employed.
2. A significant part of the VS lost was not accounted as gas production. Appropriate steps to raise efficiency are needed.
3. The liquid recycling rate adopted was high and did not uniformly leach the biomass bed. Its design needs to be improved.
4. A part of the methanogenesis occurred in the digester liquid outside the digester as seen from profuse bubbling.

Liquid waste treatment carried out under DFFBR mode shows:

That the bagasse and leaf biomass could form a long functioning biofilm support. The flow pattern through the support needs to be improved to harness a high conversion potential.

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Annexure 1:

Final destination of waste in Bangalore city

SWM option	%
Reuse	19
Recycling	43
Composting	7
Disposal	31

Source: Gerlagh *et al.*, 1999

Biogas Composition:

The gas obtained during anaerobic digestion comprises of methane, carbon dioxide, some inert gases and sulfur compounds. Usually 100-200 $m^3$of total gas are produced per ton of organic USW digested.

Typical biogas composition:

Methane	55-70% by vol.
Carbon dioxide	30-45% by vol
Hydrogen sulphide	200-4000 ppm by vol
Energy content of gas product	20-25MJ/standard m3
Energy content of CH4 per ton MSW	167-373MJ/Ton MSW

Source: Verma, 2002