ASSESSMENT OF PORTABLE BIOGAS PLANTS FOR THEIR ENERGY PRODUCTION AND EMISSION REDUCTION POTENTIAL

By

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(2011-20-107)

THESIS

Submitted in partial fulfilment of the requirement for the degree

B.Sc.-M.Sc. (Integrated) Climate Change Adaptation

Faculty of Agriculture

Kerala Agricultural University, Thrissur

ACADEMY OF CLIMATE CHANGE EDUCATION AND RESEARCH

VELLANIKKARA, THRISSUR – 680656

KERALA, INDIA

2016

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DECLARATION

I hereby declare that the thesis entitled **"Assessment of portable biogas plants for their energy production and emission reduction potential"** is a bonafide record of research work done by me during the course of research and the thesis has not been previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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ACKNOWLEDGEMENT

*I respectfully thank **Kerala Agricultural University** and **Academy of Climate Change Education and Research authorities** for providing all the support to complete this work.*

*With deep sense of gratitude, indebtedness and due respect, I express my heartfelt thanks to my respected advisor **Dr. Shaji James P.**, Professor, KCAET, Tavanur, for his exceptional guidance and relentless inspiration throughout the period of my M.Sc. thesis. It was a great honor and privilege working under his guidance.*

*I express my thanks **to Dr. E. K. Kurien**, Special officer, Academy of Climate Change Education and Research, KAU, Vellanikkara and member of my advisory committee for his scrupulous guidance, advices, valuable and timely suggestions given during my work.*

*I extent my thanks to **Dr. K. Surendra Gopal**, Professor, Microbiology, Department of Agricultural Microbiology, College of Horticulture, Kerala Agricultural University, Vellanikkara and member of my advisory committee for his valuable recommendation and help during the lab analysis and writing of thesis.*

*I express my heartfelt thanks to **Dr. Mary Regina F**. Professor (Soil and Water Engineering) Krishi Vigyan Kendra, Thrissur and member of my advisory committee for her scrupulous guidance, advices, valuable and timely suggestions given during my work and writing of thesis.*

*I also extent my sincere thanks to **Dr. Sunil K. M**. Assistant Professor, (Agricultural Meteorology) for his help offered during my thesis.*

*I also express my gratitude to **Mr. Sunil** (Managing director of green technology, Thrissur) for providing me with a portable biogas plant and also I express my gratitude to **head of KVK Thrissur, KVK Pattambi and ATIC Mannuthy** for providing me with different types of Portable biogas plants.*

I also extent my sincere thanks to ***Professor and Head of Tissue and Soil Analysis, RTL and Professor and Head of Department of Soil Science of Horticulture collage*** *for providing me with the lab facilities for the analysis.*

I gratefully acknowledge the help and support extended by the lab members of Microbiology especially ***Miss. Fasna P. K.*** *for their help during the thesis work*

I am short of words to extent my gratitude to my small family, ***SPARTANS-2011****, for their support given to me during the whole college days.*

I sincerely thank all the ***teaching and non-teaching staffs*** *of Academy of Climate Change Education and Research especially* ***Saju Sir, Unniyettan, Jineesh sir and Greeshma miss*** *for their support during my thesis work.*

With great pleasure I express my heartfelt respect to all my ***Seniors*** *especially* ***basilettan, niyaskka, athulettan and thoufeqettan*** *for their guidance during my thesis work.*

I am short of words to acknowledge the selfless helps offered by my ***Juniors*** *especially* ***Unnikkuttan, Vishnu, Yasir and Nidhish*** *during the research work.*

I sincerely acknowledge all my ***hostel mates and swami*** *for helping me during the research work.*

My thanks remain with all those who have helped me in one way or the other for the completion of the research work.

I am greatly indebted to my ***parents and brothers*** *for their blessings, prayers and support without which I could not have completed this work.*

Above all, I bow my head to God Almighty, whose blessings filled me with power to complete this work.

Iwin K. Augastian

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ABBREVIATIONS

APHA	American Public Health Association
BD	Bag Digesters
C/N	Carbon/Nitrogen
d	day
DBD	Domestic Biogas Digesters
EEA	European Environment Agency
EU	European Union
IARI	Indian Agricultural Research Institute
FRP	Fibre Reinforced Plastic
Gg	Gigagrame
GHG	Green House Gas
GWP	Global Warming Potential
h	Hour
ha	Hectare
HDPE	High Density Polyethylene
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
IPCC	Intergovernmental Panel on Climate Change
KAU	Kerala Agricultural University
kg	Kilogram
KSUDP	Kerala Sustainable Urban Development Project
KVIC	Khadi and Village Industries Commission
min	Minute
mL	Milli Litre
mW	Mill Watts
NBMMP	National Biogas and Manure Management Programme
MT	Metric Ton
PBP	Portable Biogas Plants
PE	Polyethylene

ppb	Parts Per Billion
PVC	Poly vinyl chloride
RCEP	Royal Commission on Environmental Pollution
Tg	Tera gram
TOC	Total organic carbon
TS	Total Solids
UNFCC	The United Nations Framework Convention on Climate Change
USA	United States of America
VS	volatile solids
yr^{-1}	Per year
OLR	Organic Loading Rate
CO_2e	Carbon dioxide equivalent
NEERI	National Environmental Engineering Research Institute
OECD	Organization for Economic Co-operation and Development
GtC	Gigatonnes of carbon

CHAPTER I

INTRODUCTION

Climate change is one of the serious issues faced currently by humanity. The uncontrolled emission of Green House Gases (GHGs) plays a major role in global warming, which eventually leads to climate change. Anthropogenic emission is the key factor of increasing GHG concentration in the atmosphere. It is estimated that 3-5% of the GHGs are emitted from the waste sector and is roughly one fifth of the total global anthropogenic emission. Even though the contribution is less, it needs serious actions of mitigation. Since, the world population is increasing day by day, per capita waste generation is also getting amplified, and gradually it leads to failure of waste disposal practices especially in developing countries.

The unscientific methods of waste disposal has serious environmental impacts by continuous emission of GHGs leading to global warming. Among the GHGs, Methane is the major one which is released largely from unscientific waste disposal sites. Methane emission from landfills are generally considered to represent the major source of climate impact in the waste sector. About one third of the anthropogenic emission of methane is from waste disposal itself, whereas only 1 % of N_2O and 0.5 % of CO_2 is emitted from the waste sector (IPCC, 1996). Methane emissions from landfill represent the largest source of GHG emissions from the waste sector, contributing around 700 Mt CO2-e (Bogner *et al.*, 2008). For this reason it is often assumed that reducing the amount of CH_4 emitted from landfills would have the greatest potential for reducing the overall climate change impacts of solid waste management. Hence, there is a great possibility in reducing GHG emissions and associated climate change impacts through appropriate waste management practices.

Management of organic waste is one of the most pressing environmental issues at the present time in most urban and semi-urban areas of the developing world. Unscientific land filling of municipal solid wastes (MSW) is one among the important causes for environmental degradation and many other health problems. According to World Bank statistics, 400,000 tonnes of waste is generated in each developing country every day and it will reach to a maximum of 1,400,000 tonnes per day in 2025. Among these, around 40-50% of the waste generated was organic itself (The World Bank, 1999). In majority of countries around the world, controlled and uncontrolled landfilling of untreated waste is the primary disposal method. Apart from methane emissions, uncontrolled and unscientific waste disposals also leads to problems like water pollution, unsustainable use of land and its degradation, air pollution and also cause serious health problems to humans. In most of the countries, there is no proper waste disposal mechanism at present, the only way for primary waste disposal is dumping. The studies carried out by the National Environmental Engineering Research Institute in Indian cities have revealed that quantum of MSW generation varies between 0.21-0.35 kg $capita^{-1} day^{-1}$ in the urban centres and it goes up to 0.5 kg $capita^{-1}$ day^{-1} in large cities (NEERI, 1996).

Households constitute the most basic unit in urban energy consumption and waste generation. Management of waste generation is very important in household level itself. Domestic sector contributes 49% of the MSW (SEUF, 2006). As household waste constitutes an important fraction in MSW, the management of waste in the household level is very important in the current situation. Collection and transportation of unsorted wastes containing a large organic fraction is often problematic and costly in Kerala. Apart from unscientific disposal of the waste at dump yards, it can be effectively utilized for energy production. Anaerobic digestion of the organic fraction of household wastes in a decentralised manner offers great scope in this situation. Incorporation of biogas plants in waste management will help to generate cheap renewable energy for domestic cooking in addition to the proper and safe management of domestic wastes.

Incorporation of biogas plants in waste management will help to reduce the emission of greenhouse gases to the atmosphere and it would act as a better climate change mitigation measure. This understanding has led to the installation of many community based biogas plants in India. Several models like fixed gas holder type and floating gasholder type biogas plants were installed by the government in different locations. In the initial stages, it acted as a better waste management practice. But when we look into the current working status, most of them are unproductive. As being a biological system, proper maintenance is very important for its sustained working. Due to the difficulties in segregating the wastes and improper feeding rate, many of the community biogas plants have become faulty.

In this context, household biogas plants have greater importance. Small household biogas plants would help to nullify the issues of waste disposal in the houses and it will serve as an alternative fuel source. Disposing the waste in the source itself will helps to reduce most problems. Different models of biogas plants are available for installation. Fixed gas holder type and floating has holder type are the two major category of biogas plants available. IARI Model and KVIC Model are the examples of floating gasholder type biogas plants. Chinese designs, like Janata model and Deenbandhu model are the examples of fixed gasholder type biogas plants. One of the disadvantages of fixed biogas plants is that, it requires a fair area for installation and they cannot be transported when the family is shifted. For most of the people in the urban and semi-urban areas, the space available is too less making the installation of biogas plants difficult. To avoid such problems 'Portable Biogas Plants' are designed.

In Kerala, MSW management being a serious issue, several studies have been conducted to investigate the waste generation pattern and its management practices. Lalur in Thrissur District is a best example to point out the issues due to improper landfilling. According to the study conducted by Varma *et al*. (2004), the per capita waste generation in Kerala is 0.178 kg day^{-1}. Since the population density is increasing day by day, the problems related to the disposal of waste is also increasing tremendously in Kerala. The problem is mainly concentrated in the municipalities and corporations because of limited land availability and high population density. Even though community biogas plants are installed at several places in Kerala, due to the improper management and maintenance, majority of them are not working efficiently. The segregation of the collected waste is the major problem while dealing with the management of MSW. It is highly warranted that the organic fraction of MSW is sorted and collected at the source itself in order to control the problems in waste disposal.

Portable biogas plants are easily movable biogas plants and requires less space compared to other fixed biogas plants. It is purely designed for small families and it will help them to reduce the use of commercial cooking fuel resources. Kerala is a state in India where urbanisation is much rapid. Number of municipalities are increasing and many grama panchayats are likely to be upgraded to municipalities in the near future. The main problem faced by them is waste disposal itself. Incorporation of portable biogas plants will help them to reduce the waste management problem in a better way. Due to its effective design it would not be a burden for them. Several models of floating gas holder type and fixed gas holder type portable biogas plants are available. But proper studies to compare the efficiency of these portable biogas plants are not held yet. Possibilities of effective utilization of the technology for kitchen waste in biogas plant also requires proper study in order to evolve guidelines.

In this contest, the present study was undertaken to assess portable biogas plants for their energy production and emission reduction potential with the following specific objectives:

- To investigate the biomethanation characteristics of household organic wastes and assess the potential for emission reduction.
- To assess different designs of portable domestic biogas plants for energy conversion of domestic organic wastes.

CHAPTER II

REVIEW OF LITERATURE

Biogas technology not only aids to provide renewable energy but also helps to reduce the problems of solid waste management and reduce the emissions from wastes. This chapter is a comprehensive review done on the work of various researchers on impacts of improper municipal solid wastes management on climate change, the relevance of anaerobic digestion technology as well as the means and mode of domestic waste management using portable biogas plants.

2.1 Climate Change and Waste Management

Intergovernmental Panel on Climate Change (IPCC) defines climate change as "any change in climate over time whether due to natural variability or as a result of human activity". The United Nations Framework Convention on Climate Change (UNFCCC) defined climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over a comparable period" (Easterbrook, 2011).

Climate change is caused by factors such as biotic process, variations in solar radiation received by Earth, plate tectonics, and volcanic eruption. Human activities also enhance the climate change, often referred to as global warming. It is a change in the statistical distribution of weather patterns that lasts decades to millions of years (Sagan and Chyba, 1997).

The global mean temperature has increased since 19th century. Each decade get warmer and warmer. In the period of 1901-2012, the combined sea and land surface temperature increased by 0.89 ^{0}C, while the increase for the period 1950-2012 was 0.72 ^{0}C. It is clear that, the maximum as well as minimum temperature over the land surface and sea surface has increased since 1950. It is also observed that the number of hot days and nights has increased while the cold days and nights have decreased globally from 1951-2010. The extreme precipitation events have increased in many regions of the world. The Greenland and Antarctic ice sheets had lost its mass, artic sea ice and the spring snow cover in the northern hemisphere had decreased in its extent and glaciers all over the world had been shrinking in the past two decades. Sea level was also rising due to the global warming, the rise on global sea level has been 0.19 m from 1901-2010 (IPCC, 2013).

Climate change is real. Several studies were done to find out the ill effects of climate change on various sectors like agriculture, socio- economy, health etc. Human activities are responsible for the changes in the composition of the earth's surface and atmosphere. These directly influence the heat energy of the earth and thus act as a driver of the climate change. Radiative forcing is a measure of the net change in the earths energy system in response to external perturbations, a positive radiative forcing indicates a warming trend while the negative radiative forcing indicates a cooling trend. There is a 7.5 % increase in radiative forcing from GHGs from 2005 to 2011. The latest IPCC report ascertains the fact that more than half of the increase in global mean temperature has been due to the anthropogenic activities from 1951 to 2010 (IPCC, 2013).

IPCC (2014) summarised the observed impacts of climate change in the Assessment Report 5 (AR5). The main impacts include, impact on natural and human systems on all continents and across the oceans; in many regions melting of ice and snow causes altered hydrological systems and also affects the water resources in quality and quantity. Many freshwater, terrestrial and marine species have shifted their seasonal activities, geographic ranges, mitigation patterns, abundance and species interactions in response to the changes in climate. More than positive impacts, many crops showed negative yield in the past decades. Extreme weather events and several health problems are found in many regions of the world and also the climate related hazards leads to negative outcomes for livelihoods, especially for the people living in poverty.

2.1.1 Green House Gases and Climate Change

Human influence on the climate system is very clear. The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in the last few decades. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. In 2011 the concentrations of CO_2, CH_4 and N_2O were 391 ppm, 1803 ppb and 324 ppb, and exceeded the pre-industrial levels by about 40%, 150% and 20% respectively. Concentrations of CO_2, CH_4 and N_2O now substantially exceed the highest concentrations recorded in ice cores during the past 8,00,000 years. Annual CO_2 emissions from fossil fuel combustion and cement production were 8.3 GtC yr^{-1} averaged over 2002–2011 and were 9.5 GtC yr^{-1} in 2011, 54% above the 1990 level. Annual net CO_2 emissions from anthropogenic land use change were 0.9 GtC yr^{-1} on average during 2002 to 2011. Greenhouse gases contributed to global mean surface warming in a range of 0.5 °C to 1.3 °C over a period of 1951 to 2011 (IPCC, 2013).

2.1.2 Methane and climate change

Methane emission from various sources contribute in a big way to global warming as the Global Warming Potential (GWP) of methane is 25 (IPCC, 2007) times that of carbon dioxide. Methane concentration has increased by a factor of 2.5 since preindustrial times, from 722 ppb in 1750 to 1803 ppb in 2011. Anthropogenic activities have influenced in triggering the methane emission during the industrial era. The massive increase in the number of ruminants, the emissions from rice paddy agriculture and fossil fuel extraction as well as the emissions from landfills and waste are the dominant anthropogenic methane sources. 50-60% of total emissions are accounted by anthropogenic emissions. In recent decades, CH_4 growth in the atmosphere was seen to be highly variable. In 1990s, the atmospheric methane concentration was relatively stable, but after 1990s the methane concentration started growing. The exact drivers of this renewed growth are still debated. Climate-driven fluctuations of CH_4 emissions from natural wetlands (177 to 284 ×1012 g (CH_4) yr^{-1} for 2000–2009 based on bottom-up estimates) are the main drivers of the global inter annual variability of CH_4 emissions, with a smaller contribution from biomass burning emissions during high fire years. Atmospheric methane (CH_4) was 1803.2 ppb (1801.2 to 1805.2) in 2011; this is 150% greater than that before 1750. CH_4 began increasing in 2007 after remaining nearly constant from 1999 to 2006 (IPCC, 2013).

IPCC (2013), calculated the net amount of CH_4 emissions in various sectors, among that methane emission from anthropogenic factors are listed below.

Table 1. Global CH4 budget for the past three decades (in Tg (CH_4) yr^{-1})

Anthropogenic sources	**1980-1989**	**1990-1999**	**2000-2009**
Agriculture and waste	185	187	200
Rice	45	35	36
Ruminants	85	87	89
Landfills and wastes	55	65	75
Biomass burning (incl. biofuels)	34	42	35
Fossil fuels	89	84	96
Total	**308**	**313**	**331**

(IPCC, 2013)

2.2 Municipal Solid Waste

EEA (2013) described municipal solid waste as "Municipal solid waste is mainly produced by households, though similar wastes from sources such as commerce, offices and public institutions are included. The amount of municipal waste generated consists of waste collected by or on behalf of municipal authorities and disposed of through the waste management system."

2.2.1 Generation pattern of MSW

The term municipal solid waste (MSW), refers to the solid wastes from domestic sources (household), hotel and restaurants, commercial establishments, school, markets, street sweepings and drain clean and other sources which include temples, parks, exhibition halls, marriage halls, hostels, institution and offices, which is very often the responsibility of municipal or other governmental authorities. Solid waste from industrial processes is generally not considered as MSW (Swarup *et al.,* 1992).

In a study conducted by The World Bank (1999), it was found that the urban areas of Asia generate 7, 60,000 tonnes of MSW per day, or approximately 2.7 million m^3 d^{-1}. It was projected that in 2025 the waste generation will increase to 5.2 million m^3 d^{-1}.

Due to the fast economic development and urbanization, the generation of municipal solid waste (MSW) has rapidly increased worldwide and the composition of MSW has also changed significantly. These changes bring more pressure on the existing environment, human health and also to the management of MSW system (Wang and Nie, 2001).

According to Varma *et al.,* (2004), per capita waste generation in Kerala is 0.178 kg d^{-1} and it's less compared to the national per capita waste generation of 0.35 kg d^{-1}. The survey results of Kerala Sustainable Urban Development Project (KSUDP, 2006) shows that, In Kerala, 1183 tonnes/day MSW was generated from 5 corporations, 758 tonnes d^{-1} from 53 municipalities and 4565 tonnes d^{-1} from 999 panchayats. In total 6506 tonnes d^{-1} MSW is currently generated in Kerala.

Babayemi and Dauda (2009) evaluated the waste disposal methods in Nigeria. They concluded that the MSW generation is increasing in alarming rate due to the lack of efficient and modern technologies. Only 35.8 % of population utilize the waste collection services. 31.3 % and 41.3 % were unaware about the waste collection services and waste management regulations respectively. Increased population growth and raising consumer demand lead to the increased production of MSW worldwide (Karak *et al.,* 2012). The characteristics and composition of MSW varied mainly with topography of the area, seasons, food habits and commercial status of the city (Thitame *et al.,* 2012).

Palanivel and Sulaiman (2014) studied about the per capita waste generation in Oman and they found that the daily generation of MSW worked out to be 0.97 kg $d^{-1}person^{-1}$ by weight, 3.113 x 10-3 m^3 $d^{-1}person^{-1}$ by volume with a density of 311.73 kg m^{-3}. The results revealed that the MSW stream has the largest proportion of biodegradable and recyclable waste. They also found that, food waste constitute 28.2 % of MSW generated within the city.

Gogoi (2013) investigated the generation and disposal pattern of MSW in Guwahati, Assam. She concluded that the major problem is improper waste disposal. 626.84 ton of solid waste was generated each day in the city. Only 40 % was properly disposed. Remaining 60 % was disposed in improper way and it made several environmental and health problems within the city.

Das and Bhattacharya (2014) forecasted the waste generation of Kolkata in 2035 and they found that, 8805 MT d^{-1} of MSW will be produced in 2035 which is approximately double of the MSW produced in 2011. The MSW generation in 2011 was 4939 MT d^{-1}. They reported that, apart from population increase, per capita waste generation and change of living standard leads to the increment in MSW in Kolkata. The per capita waste generation increased from 0.2 kg $capita^{-1}$ to 0.47 kg $capita^{-1}$ during the period 1981-2035. In Kolkata, MSW is still collected without any proper segregation and treatment facilities.

2.2.2 Households and MSW generation

The results from the study conducted by Dangi *et al.*, (2011) found that, per capita waste generation in Nepal from households was 0.4973 kg day^{-1} and the household waste constituents included 71 % organic wastes, 12 % plastics, 7.5 % paper and paper products, 5 % dirt and construction debris and 1 % hazardous wastes. He concluded that there was a greater potential of recovery of organic materials and it will help to reduce the MSW generation.

Gogoi (2013) studied the waste generation pattern in Guwahati city, India and reported that 2.66 kg of waste is generated from each household in each day. In total, 490.64 tonnes of waste was generated from the households in Guwahati, which was 78.27 % of the total MSW generated within the city.

Suthar and Singh (2015) conducted a survey at Dehradun city, India to study about the waste generation pattern of Indian households. They found that household waste generation rates in the city ranged from 24.5 to 4147.1 g day^{-1}. The average household waste quantity in households was estimated as 267.17 g day^{-1}. The food/kitchen waste was the major constituent ($\geq$80 % of total weight) of household waste in city followed by polythene and plastic ($\approx$7 %), paper ($\approx$6 %), cardboard ($\approx$2 %), glass/ceramic scrap ($\approx$ 1%) and other miscellaneous items (e.g. cloths, silt, dirt, rubber; all $\approx$ 4%). They also examined that, the amount of waste generated in different socio economic groups were also different. The highest amount of waste generation was observed in the high income groups followed by middle income groups and lower income groups. Food/ kitchen waste constituted about 75–80% of the total domestic waste and the average quantity was estimated as 267.17 g day^{-1}.

2.2.3 MSW Dumping problems

Unscientific dumping of MSW is being done in many developing countries resulting in environmental and health hazards.

2.2.3.1 Environmental problems

In a study conducted for the World Bank, Cointreau (2006) summarised the major environmental problems of MSW dumping in developing countries. The commonly reported environmental issues were: contaminated leachate and surface runoff from land disposal facilities affecting down gradient ground and surface water quality, clogging of drains leading to stagnant waters which encourage mosquito growth, methane and carbon dioxide emissions from land disposal facilities adding to global warming, vector-borne disease abundance and pathogen survival as a result of uncollected wastes providing food and breeding sites for insect, bird and rodent disease vectors.

Department for Environment, Food and Rural Affairs, United Kingdom (DEFRUK, 2014) studied about the major environmental problems of landfills. It was found that, the uncontrolled landfills have the potential for soil acidification due to the deposition of acid gases. The emission of oxides of nitrogen and sulphur dioxide can damage the vegetation. They also found that, MSW landfills have the potential for ground water contamination with metals ands organic compounds as the toxic materials will get accumulated to the ground water leading to poor ground water quality.

2.2.3.2 Health Problems

Nath (1980) conducted a comparative study of waste pickers and farmers who use organic solid waste as fertilizer at Calcutta and he found that waste pickers shows higher symptoms of respiratory diseases, diarrhoea, and protozoal and helminthic infestations.

Royal Commission of Environmental Pollution (RCEP, 1984) stated that, improper handling of MSW lead to dangerous risks of environmental and health problems. Direct contact to MSW will increase the hazard density, especially for those handling it. In general apart from direct effect, indirect effects arise from the breeding of disease vectors, primarily flies and rats which cause major health problems.

Huisman (1994) studied about the health problems of waste pickers in Bangalore, Manohar and New Delhi. He found that, they commonly suffered from tuberculosis, bronchitis, asthma, pneumonia, dysentery, parasites, and malnutrition.

Konnoth (1996) surveyed about 95 solid waste workers at Mumbai. He examined that 80 % had eye problems, 51 % had gastrointestinal ailments, 73 % had respiratory ailments, 40 % had skin infections or allergies, and 22 % had orthopaedic ailments. Based on clinical examination, 90% had decreased visual acuity. Most workers complained of eye burning, diminished vision, redness, itching, watering. Clinical examination showed 27 % had skin lesions, of which 30% were determined to be directly occupation related.

Social and Health Action Calcutta (SHAC, 1996) analysed 180 waste pickers at Calcutta. It was observed that, during the course of one year, 40 % had chronic cough, and 37% had jaundice. The average quarterly incidence of diarrhoea was 85 %, of fever was 72 %, of coughs and colds was 63 %. Eye soreness or redness occurred quarterly in 15 % and skin ulcers in 29 %.

Alam and Ahmade (2013) stated that, mixing of uncontrolled hazardous wastes from industries to municipal waste will create potential risks to human health. It may be leads to many dangerous problems to health from those toxic wastes. The mixture of MSW and liquid industrial effluents containing heavy metals will enter into the food chain and natural resources by leaching or by any other means and it will lead to problems like cancer, nausea, vomiting, low birth weight, congenital malformations, mercury toxicity by eating fish with high levels of mercury, chemical poisoning through chemical inhalation and neurological diseases. It will also result in higher algal population in rivers and sea and it will lead to degradation of water quality. Uncollected waste can obstruct the storm water runoff resulting in flood.

Selin (2013) studied about the health problems of residents' living near to an open MSW dump yard at Mutomo, Kenya. Identified diseases caused to them in past 10 years are listed below:

Table 2. Health problems of residents living near to an open MSW dump yard at Mutomo, Kenya

Sl. No	Type of disorder	Name of disease
1	Respiratory abnormalities	Bacterial upper respiratory tract infections Pharyngitis Laryngitis Rhinitis Chronic bronchitis Asthma Lung cancer
2	Skin disorders	Allergic dermatitis Fungal infection Pruritus Skin cancer
3	Dental disorders	Dental carries Dental pain
4	Abdominal and Intestinal Problems	Helminthiasis Bacterial enteritis Amoebiasis Liver cancer Kidney and renal failure
5	Muscular systems	Back pain
6	Ear infections	Otitis media Bacterial infections
7	Eye infections	Bacterial eye infections Allergic conjunctivitis
8	Central nervous system	Impairment of neurological development Peripheral nerve damage Headaches
9	Blood disorders	Iron deficiency, anaemia
10	Other diseases	Chicken pox Malaria Septic wounds Congenital abnormalities Cardiovascular diseases

Singh *et al.*, (2014) studied about the health problems of resident's living near to an open MSW dumping site at Agra. He found that those heaps were acting as a base of breeding grounds for flies causing typhoid, cholera, amoebic dysentery, tuberculosis and anthrax. He also point out that the heaps act as a feeding sites of large number of animal disease vectors causing plague, salmonellosis, trichinosis endemic typhus like diseases through direct bite.

2.2.4 MSW and greenhouse gas emission

UNFCC (2001) evaluated the GHG emissions in USA. It was found that waste management sector contributes ~4 % of total anthropogenic GHG emissions ((i.e., 260 out of 6750 Tera grams of CO_2 equivalents). They also concluded that uncontrolled emission of GHGs to the atmosphere through uncontrolled management of MSW should be minimized to reduce the impacts of climate change.

Jha *et al.*, (2008) studied the GHG emissions from Chennai MSW disposals. They found that the CH_4 emission was about 0.12 Gg y^{-1}. They also found that majority of organic waste materials is decomposed aerobically and it results in emission of about 1.16Gg y^{-1} of CO_2. They concluded that the lower emission of CH_4 was due to lower height of MSW deposits in landfill area, uncontrolled leaching of organic matter, climatic conditions and open burning of MSW in landfill.

Mohareb *et al.*, (2008) estimated the GHG emissions in Canada and found that 25 Mega tonnes of CO_2e was produced from the solid waste sector in 2001, and 23 mega tonnes of it was contributed from the land fillings. Beibei *et al.*, (2012) examined the emission from waste sector in Germany between 1990 and 2007. They found that the emissions in the field of waste accounted for only 3.33 % of Germany's total emissions and the reduction in the same field accounted for 11.18 % of total emission reductions. Germany achieved 94.12 % of emissions reduction in the waste sector through the processing of MSW.

Greenhouse gas emissions from MSW disposal in Africa was studied by Couth *et al.*, (2011) and found that 8.1 % of the total GHG emission in Africa was from MSW. They also calculated per capita emission using a multi-phase model and found that 0.064 t CO_2 e as the per capita emission.

Chen and Lo (2016) studied about the greenhouse gas emissions from different waste management practices in Taiwan. They evaluated the greenhouse gas emissions from five MSW treatment practices including land filling, waste to energy and material recovery. They found that land filling sites emits 1.10×10^6 to 4.39×10^6 kg CO_2-eq day^{-1} greenhouse gases to the atmosphere from 20,000 tonne day^{-1} of MSW.

Friedrich and Trois (2016) evaluated the greenhouse gas emissions from MSW in eThekwini Municipality, South Africa. They calculated that 1, 61,780 tonnes CO_2 e of GHGs are emitted every day from the landfills. They also projected that, if the current situation continues, the GHG emission will increase to 2, 07,056 tonnes CO_2e day^{-1} in 2020.

Lee *et al.*, (2016) identified that, the United States generated the most waste among OECD countries. Apart from the issues related to environmental and health problems due to the MSW dumping, those dumping's will emit huge quantity of GHGs to the atmosphere. The amount of waste generation is not likely to decrease as the recycling rate is lower in US compared to other OECD countries. They suggest recycling to reduce the major problems related to MSW as recycling not only reduce the waste, but also reduce the GHG emissions. They also suggested that apart from recycling, the breakage of casual relationship between MSW and GHGs will helps to reduce the GHG emissions. They advocated waste to energy technologies for better management of MSW.

2.2.4.1 Methane emissions from MSW

IPCC (2006) stated that, decomposition of waste does not begin immediately after the disposal of waste but with a typical time delay. Therefore, the methane emission from the decomposition of waste will last for a period of time (roughly 50 years) after the MSW is land filled. Methane (CH_4) is the second largest driver of climate change behind CO_2 and one of the six greenhouse gases (GHGs) listed in the Kyoto Protocol, with global warming potential of 25 over 100 years. CH_4 is also a short-lived climate pollutant with an average life-time around 12 years in the atmosphere. The total CH_4 emissions and those from MSW management accounted for 14.3 % and 2.8 % respectively, of the global GHG emissions in 2004 (IPCC, 2007).

Mor *et al.,* (2006) estimated the methane emission from Gazipur landfill site at Delhi. They used first- order decay model for the estimation of methane emission and it was found that 1.5Gg y^{-1} methane is being emitted from that landfill. They also estimated the total methane emission from all landfills in India and was in the order of 1.25 Tg y^{-1} to 1.68 Tg y^{-1}.

Chakraborty *et al.,* (2011) estimated the methane emission from 3 landfills namely, Ghazipur, Bhalswa and Okhla in Delhi using different methodologies. They used IPCC 1996 Default Methodology (DM), Modified Triangular Method (MTM) and first order decay method for the estimation of methane emission. By using DM method, the methane emissions from Ghazipur, Bhalswa and Okhla were found as 14.6, 23.6 and 7.5 Gg y^{-1} respectively. By FOD method the methane emissions from these landfills were 13.3, 10.6 and 7.2 Gg y^{-1} respectively. Finally by using MTM method, the respective values were 17.0, 13.7 and 10.7 Gg y^{-1}.

Ishii and Furuichi (2013) studied the methane generation potential of food waste and it was found that 126.7 mL of methane per gram of wet waste was produced.

Monster *et al.,* (2015) quantified methane emission from 15 Danish landfills using the mobile tracer dispersion method. They choose different stages of the life time of landfills including open, active, closed covered as well as landfills with and without gas extraction and utilization system. It was found that methane emission rates ranged from 2.6 to 60.8 kg h^{-1}, corresponding to 0.7-13.2 g m^{-2} d^{-1}. The largest emission rates per unit area was found to be from landfills with malfunctioning gas extraction system where as the smallest emission rates were from landfills closed years ago and those with an engineered biocover. They also found that the gas collection and recovery systems had a recovery efficiency of 41-81% and the average methane emission from a landfill was 154 tonnes year^{-1}. They concluded that newly deposited shredded waste produce the largest amount of methane and the total emission from the Danish landfills were 20,600 tonnes y^{-1}.

2.2.5 MSW management

Proper segregation of MSW would lead to better options and opportunities for scientific disposal of waste (Sharholy *et al.*, 2008). They suggested house-to-house collection of MSW, organized through methods like collection on regular pre-informed timing and scheduling and placement of bins at appropriate locations. The collection bins must be appropriately designed with necessary features like lids, provision for mechanical loading and un-loading and should have a large enough capacity to accommodate 20 % more than the expected waste generation in the area. Proper maintenance of the MSW transportation vehicles must be conducted, and the Dumper Placer should replace the old transportation vehicles in a phased manner. Currently, at the level of waste generation and collection, there is no source segregation of compostable waste from the other non-biodegradable and recyclable waste.

Scheutz *et al.,* (2011) studied about the management practices to reduce the methane emission from Fakse landfill, Denmark where 'biocover technology was adopted. It helped to enhance the biological oxidation of methane. A full scale biocover system to reduce methane emission was installed in the Fakse landfill using composted yard waste active material supporting oxidation. In the 12 ha site, ten bio-windows with a total area of 5000 m^2 were integrated into the existing cover. The results showed that, there was a decrease of 28 % of CH_4 emission at the end of one year monitoring period.

EEA (2013) evaluated the management practices established for the year 2001-2010 at European Union. EU formulated a waste hierarchy for the better management practices. According to EU waste hierarchy, prevention is the best method for the waste management. Re-use, recycling, other recovery (eg. energy recovery) and disposal (eg. landfill) are the other management practices coming under waste hierarchy. They found that recycling trend increased in almost all the countries. Statistics showed that landfilling decreased by 41 million tonnes, incineration increased by nearly 15 million tonnes and recycling and composting increased by 28 million tonnes. The target set was 50 % recycling by 2020.

Ministry of urban development, India (2014), described the integrated solid waste management hierarchy. According to them, the most preferred management practice was source reduction and reuse. It includes waste minimization and sustainable use/multi use of products (eg. reuse of carry bags/packaging jars). After source reduction and reuse, recycling was the most preferred one. It includes the processing inorganic waste to recover commercially valuable materials (eg. plastic, paper, metal, glass recycling and e-waste recycling). The next preference was composting, which includes the processing organic waste to recover compost (eg. windrow composting, in-vessel composting, vermi composting). Waste to energy was the next option of waste management. It included energy recovery before final disposal of waste. Landfilling was the least preferred method of waste management, which includes safe disposal of inert residual waste at sanitary landfills.

2.2.6 Biogas from landfills and MSW

Recovery of methane from landfills has huge potential. The organic components of landfills breakdown in anaerobic condition and produces methane and carbon dioxide.

Chandra (1986) described about the India's first major attempt to produce biogas from landfill at Timarpur in Delhi. Biogas was recovered by drilling a series of eight wells drilled at a spacing of 60.96 m. The recovered gas was used for power generation. As per the design criterion, one well was found adequate to produce 100 kilowatts of electricity from a landfill area of one acre. In other words, landfill covering an area of 10 acres can produce 1000 kW or equivalently one megawatt of electricity. Considering that the landfill at Timarpur covers an area of 80 acres, it has the potential to produce 8 mW of electricity. The cost of electricity generation from landfill gas was estimated as 10 paisa per unit which is nearly one tenth of the power generated by conventional sources.

Nadalotti *et al.,* (2015) conducted a study on potential use of landfill biogas in urban bus fleet in Brazilian states. According to their study Brazil generates about 16,131,857 m^3h^{-1} biogas, which could supply fuel for around 107000 vehicles. The use of methane derived from sanitary landfills substitute the mineral diesel and guarantees the minimization of environmental impacts providing a significant reduction in the emission of greenhouse gases. They also found that the effective utilization of biogas from landfill sites lead to socio economic benefits like reduced fuel cost and decreased the spread of many diseases.

2.3 Biogas plants for anaerobic digestion of organic wastes

Biogas is popularly known as gobar gas, marsh gas, swamp gas, sewer gas, wet gas, and fuel gas. It is produced by the anaerobic decomposition of organic materials. In India, researches related to biogas production started in the early 19^{th} century. In the past years, most of the families in rural areas utilized wood and cow dung cake as their source of fuel. As agriculture is the major source of livelihood in rural India, incorporation of biogas plants was highly effective in providing a clean fuel, simultaneously providing good quality organic manure in the form of biogas slurry. The addition of biogas plants helped to reduce the use of both wood and cow dung cake and aided in improving the health of women and reducing deforestation (Chawla, 1986).

The composition of biogas is 50-70 % CH_4, 30-40 % CO_2, 5-10% hydrogen, 1-2 % nitrogen and traces of H_2S (Yadev and Hesse, 1981). The biogas produce gas in three steps, which are, hydrolysis, acidification and methane formation. The enzyme mediated transformation of insoluble organic material and higher molecular mass compound is the first step. In acidogensis another group of microorganisms fragment the breakdown products into acetic acid, hydrogen, CO_2 and other lower weight simple volatile organic acids. In third step, acetic acid, hydrogen and CO_2 are converted into a mixture of CH_4 and CO_2 by the methanogenic bacteria (Mclenerny and Bryant, 1981).

Chawla (1986) estimated the replacement values for different fuels with biogas. One meter cube of biogas can replace 0.620 L of kerosene, 3.474 kg if fire wood, 12.296 kg of cow dung cake, 1.458 kg of charcoal, 1.605kg of soft coke, 0.433kg of butane, 0.417 L of furnace oil, 1.117 m^3 of coal gas, 0.45 kg of LPG and 4.695 kWh of electricity.

2.3.1 Biogas production from different organic wastes

Biogas production potential was different for different types of feed materials. It varies according to the composition in the feed material. Biogas production from different feed materials are described in this section.

2.3.1.1 Biogas production from dairy wastes and cattle dung

Schulte *et al.,* (1976) studied about the biogas yield from diary waste under varying loading rates. They examined the biogas yield when the loadings rates were 2.56-3.53, 2.41-4.01, 2.08-3.53, 1.92-3.85 and 1.60-2.89 kg VS $m^{-3}day^{-1}$ and the results were found as 0.12-0.19,0.26-0.90,0.07-0.16,0.06-0.10 and 0.04-0.06 m^3 kg VS^{-1} added.

Ranade, *et al.,* (1979) examined the possibility of producing biogas from dung cake. Experiments were carried out in two sets. In the first set, wet dung was diluted with an equal quantity of water to obtain slurry with 10 per cent total solids concentration. The same slurry with 10 percent TS concentration was also used for preparing dung-cake samples. These dung-cakes were later fermented by preparing their slurry at (i) two months and, (ii) eight months intervals after they were formed. In another set of experiment, about eight months old dung cakes purchased from market were used. Anaerobic fermentation was carried out separately with wet manure, two and eight month old cake samples prepared in laboratory and ready-made dung cakes purchased from market, and the results of biomethanation compared. Average gas yield with wet dung as feed was 3.68 litres day^{-1}, total gas generation over a period of 54 days being 204 litres with methane content as 55 and carbon dioxide content as 42 per cent. In the experiment with dry dung cakes purchased from the market, the average gas production was 2.78-3.68 litres day^{-1} and total gas produced over a period of 54 days was 150 litres with methane content as 47 and carbon dioxide also 47 per cent. This means in relation to wet dung case, gas yield declined by 24.3 per cent and methane content less by eight per cent. In the experiment with two month old dry dung prepared in the laboratory, mean gas production was 3.2 litres d^{-1} and total gas yield over a period of 54 days was 172.3 litres with methane and carbon dioxide content being 67 and 28.5 per cent, respectively. When compared with wet dung case, this shows that mean gas production declined by 13 per cent and total yield was less by 32.3 litres but methane content went up from 55 to 66 per cent. In the experiment with eight months old dry dung cakes prepared in the laboratory, average gas yield was 2.72 litres/day with total gas production over a period of 54 days as 147.2 litres and methane content as 58.7 per cent. This shows that in relation to the wet dung case, daily gas yield declined by 26 per cent and total yield for the same period was less by 57 L. Comparative results of these experiments shows that one to two months old dung cakes can be harmlessly used for biomethanation without any appreciable decline in gas yield and also with some improvement in calorific value following somewhat higher methane content.

UN (1980) calculated biogas yield from different feedstocks which includes both agriculture and animal wastes. Their findings shows that, biogas production from cattle waste, pig waste and pig waste were 260-280,561 and 200-300 m^3 ton^{-1} of dry matter respectively. Biogas production from different agriculture wastes such as fresh weeds, hemp stalks, wheat straw, green leaf, rice husks, sewage waste and liquid waste from wine or spirit making factory were estimated as 600, 369, 432, 210-294, 615, 640, 300-600 $m^3 ton^{-1}$ of dry matter respectively.

Singh *et al*., (1985) studied about the anaerobic digestion of cattle waste at various retention times. The study was conducted in 2.5 m^3 vertical, daily fed floating drum biogas plants of the type recommended by Khadi and Village Industries Commission. They selected HRTs as 12, 25, 36, 50 and 62 days and the daily kilograms of waste fed in to the biogas plants per cubic meter was 40, 20, 14, 10 and 8 kg respectively. Kilogram of TS added per cubic meter per day was calculated as 6.81, 3.40, 2.38, 1.70 and 1.36 respectively. They found the biogas production as 933, 727, 610, 434 and 383 Lm^{-3} per day in respective HRT periods.

Surendra *et al.*, (2013) quantified the biogas production potential of various manures and other feedstocks. They found that, Cattle manure: 200-300 m^3 ton dry $solids^{-1}$, Pig manure: 250-500 m^3 ton dry $solids^{-1}$, Chicken manure: 310 m^3 ton dry $solids^{-1}$, Sheep manure: 300-400 m^3 ton dry $solids^{-1}$, Human excreta: (night soil) 380 m^3 ton dry $solids^{-1}$, Vegetable wastes: 400 m^3 ton dry $solids^{-1}$, Grass lawn cuttings: 700-800 m^3 ton dry $solids^{-1}$, Rice straw: 550-620 m^3 ton dry $solids^{-1}$, Maize silage: 600-700 m^3 ton dry $solids^{-1}$, Maize straw: 400-1000 m^3 ton dry solids $^{-1}$, and Kitchen waste: 400-1000 m^3 ton dry $solids^{-1}$.

2.3.1.2 Biogas production from poultry wastes

Hobson *et al.*, (1981) studied about the biogas production from a 150 L continuously stirred single staged digester with poultry excreta/ waste as the substrate. They found TS of the slurry as 6% and the methane content as 70%. Biogas production from that digester in a 15 day retention time was found as 362 L $kgTS^{-1}$ and that of 20 day HRT period was 380 L $kgTS^{-1}$.

Field *et al.*, (1985) quantified the biogas yield from poultry manure at 30 day HRT period. Average daily biogas production was found as 752 Lm^{-3}. The average biogas production from the TS added was found as 390 L $kgTS^{-1}$. Alfa *et al.*, (2014) conducted a Comparative evaluation of biogas production from Poultry droppings, Cow dung and Lemon grass. The three substrates were pre-fermented according to standard methods. 6 kg of each pre-fermented substrate was mixed with water in ratio 1:1 v/v to form slurry and digested for 30 days. A total of 0.125 m^3, 0.191 m^3 and 0.211 m^3 of biogas were respectively produced from the Lemon grass, Cow dung and Poultry droppings. The cooking test carried out revealed that the scrubbed gas had higher cooking rates for water (0.12 L min^{-1}, 0.085 L min^{-1} and 0.079 L min^{-1} for Lemon grass, Cow dung and Poultry droppings respectively) while the cooking rates for un-scrubbed gas were 0.079 L min^{-1}, 0.064 L min^{-1} and 0.06 L min^{-1} respectively.

2.3.1.3 Biogas production from composite wastes and food wastes

Mandal and Mandal (1995) conducted a study on the potential of five different kitchen waste residues to produce biogas. The results showed that banana peels have higher potential for biogas production followed by potato peel, tea leaves, mixture of kitchen waste and orange peel.

Bardiya *et al.*, (1996) estimated the biogas yield from banana peels and pineapple waste. They found that, on 40 day HRT period specific biogas production from chopped banana peel, powdered banana peel and pineapple waste was found as 219, 231 and 413 L $kgTS^{-1}$ respectively. They also estimated the methane content and found as 57, 55 and 50 % respectively.

Li *et al.,* (2009) conducted a comparative study on kitchen waste, cattle manure and mixture of kitchen waste and cattle manure to find out their efficiency in biogas production. Each biogas plants were fed with equal quantity of volatile solids with a 30 day HRT. It was found that co-digestion of kitchen waste and cattle manure shows 44% increased yield compared to the plants working on kitchen waste and cattle manure alone.

Estoppey (2010) conducted a case study at Kochi on a biogas plant working on kitchen waste. He found out that with an average feed of 2.9 kg of solid kitchen waste (mainly rice leftovers and slaughtered chicken waste) and 11.7 L of liquid waste (mainly organic waste water) per day, the plant produces 684 L of gas per day.

2.2.2 Evolution of biogas plants in India

Chawla (1986) described about the developments of biogas technology in India. According to him, the first attempt to produce methane from biological decomposition was made at Bombay in 1900. In 1937, Dr. S. V. Desai, a senior microbiologist of Indian Agricultural Research Institute (IARI), New Delhi started investigations with Dr. S. C. Biwas, on the anaerobic fermentation of cattle dung and they identified the effect of temperature, pH and substrate concentration on biogas production. In 1951, Shri. Jashbhai J. Patel developed a simple model of cow dung gas plant called Gramlaxmi. After few years, Dr. C. N. Acharya at IARI developed a model called IARI design to meet the energy requirements for an average village home of 5-6 family members. In 1960, The Planning, Research and Action Division of Government of Uttar Pradesh, Luknow established a permanent research station called Gobar Gas Research Station at Ajitmal. They introduced the Chinese model 'Janata biogas plant' by installing 7000 units in Uttar Pradesh. The Structural Engineering Research Centre, Roorkee, introduced the Ferro cement gas holders and digester, which resulted not only in substantial reduction in cost, but also had high durability and easiness in installation. Around 1980s, The Department of Science and Technology, Government of India started a project on biogas plant, All- India Co-ordinated Project on Biogas Technology with the collaboration with different institutes within India and worked about various aspects of the problem relating to biogas plants in rural areas.

2.2.3 Major factors affecting biogas production

Biogas production is purely a microbial process, so factors affecting microbial activities also affect production of biogas. Activities of microorganisms are mainly influenced by pH, temperature, substrate/carbon source, nitrogen and C/N ratio.

2.3.3.1 pH

Jones *et al.,* (1987) identified that most methanogens have pH optima near to neutrality. Jain and Mattiaasson (1998) studied about the efficiency of methane production in varying pH. They found that, at pH 5.0, 4.5, 4.0 the methane production obtained as 67, 37 and 34 % respectively. Above pH 5.0, the efficiency of methane production was 75 % and 100 % yield was obtainable at the neutral pH.

Zhou *et al.,* (2016) conducted an experiment to find out the performance of anaerobic digestion in varying pH. They used pig manure with 7.8 % total solids as the inoculum. The found that the performance of anaerobic digestion was strongly dependent on pH value. Biogas production and methane content at neutral pH 7.0 were significantly higher (16,607 mL, 51.81 %) than those at pH 6.0 (6916 mL, 42.9 %) and 8.0 (9739 mL, 35.6 %).

2.3.3.2 Temperature

According to the studies conducted by Hansen (1977), optimum temperature for the better productivity was 35^0 C. He concluded that, rapid digestion of raw materials and efficient biogas production occurs within narrow range of temperature and temperature variations of 2.7^0 C could inhibit methane forming bacteria.

Ward *et al*. (2008) found optimal growth temperatures for some methanogenic bacteria. It includes, 37–45° C for mesophilic *Methanobacterium*, 37–40° C for *Methanobrevibacter*, 35–40° C for *Methanolobus, Methanococcus, Methanoculleus, Methanospirillum* and *Methanolobus*, 30–40° C for *Methanoplanus* and *Methanocorpusculum* and 50–55° C for thermo-philic *Methanohalobium* and *Methanosarcina.*

2.3.3.3 C/N ratio

Nitrogen is essential for protein synthesis and primarily required as a nutrient by the microorganisms in anaerobic digestion. The C/N ratio in the organic material plays an important role in anaerobic digestion. The unbalanced nutrients are regarded as an important factor limiting anaerobic digestion of organic wastes. For the improvement of nutrition and C/N ratios, co-digestion of organic mixtures is employed (Cuetos *et al*., 2008). Lee *et al*. (2009) reported that the optimal C/N ratio for anaerobic degradation of organic waste was 20–35.

2.3.3.4 Substrate/carbon source

Anaerobic digestion rate was strongly affected by the type, complexity and availability of the substrate. Different groups of microbes are supported by different types of carbon sources. Before starting a digestion process, the substrate must be characterized for carbohydrate, lipid, protein and fibre contents. In addition, the substrate should also be characterized for the quantity of methane that can potentially be produced under anaerobic conditions. Carbohydrates are considered the most important organic component of municipal solid waste for biogas production. However, starch could act as an effective low cost substrate for biogas production compared to sucrose and glucose. It was identified that the initial concentration and TS content of the substrate in the biogas plant can significantly affect the performance of the process and the amount of methane produced during the process (Su *et al.*, 2009; Lesteur *et al.*, 2010).

2.3.3.5 Ammonia concentration

Proteins are the nitrogenous compounds in the organic waste which are converted to ammonium by anaerobic digestion. The amount of ammonia in the digester may also affect the production of hydrogen and removal of volatile solids. Total biogas production was unaffected by small increases in ammonia nitrogen while higher increases reduces biogas production by 50 % of the original rate. In the fluidized-bed anaerobic digester, the methane formation decreased at ammonium concentrations of greater than 6000 mg NH_4–N/l. It was reported that methanogenic activity is decreased by 10% at ammonium concentrations of 1670–3720 mg NH_4–N/l, while by 50% at 4090–5550 mg NH_4–N/l, and completely zero at 5880–6000 mg NH_4–N/l (Sawayama *et al.*, 2004).

2.3.4 Types of biogas plants

Shilpkar and Shilpkar (2009) described about different types of biogas systems. According to them, biogas plants are categorized as, floating gas holder type biogas plants, fixed dome type biogas plants, vertical biogas plants, horizontal biogas plants, movable biogas plants, digester and gas holder separate type biogas plants, plug flow reactors, anaerobic filter reactors, anaerobic baffled reactors, anaerobic contact reactors, anaerobic fluidized and extended bed reactors and down flow stationary reactors. They also identified the commonly used fixed and floating gasholder type biogas plants in India. Floating gasholder types include; IARI model, KVIC model, Nepal model, Bureau of Indian Standards model, ASTRA model, NEERI model, Bajwa-KVIC/ Ganesh model, Jyoti model, Kachra model, Pragati model and Jwala model. Fixed dome biogas plants include; 2047 design GGC fixed dome model of Nepal, Chinese model, Janata model, Deenbandhu model, Deenbandhu- 2000 model, Gayatri model, Krishna model, Manipal model, Surahi model and Spherical model.

2.3.4.1 Domestic biogas plants

Domestic biogas digesters (DBDs) have been effectively implemented worldwide, and governments and institutions have become involved in subsidy schemes, planning, design, construction, operation, and maintenance of biogas plants. Several countries in Asia and Africa, particularly China, India, Nepal, Bangladesh, Cambodia, Vietnam, Kenya, Rwanda, and Tanzania, have launched massive campaigns to promote biogas technology (Bond and Templeton, 2011).

According to National Advisory Board for Energy estimates India got a potential to have 16 million to 22 million domestic biogas digesters producing $2m^3$ biogas day^{-1}. But up to 2011, India had only 4.25 million domestic biogas digesters (Kaniyamparambil, 2011).

Austin and Morris (2012) examined the level of biogas technology use for household purposes in African countries. Some of the first domestic biogas digesters (DBD) in the continent were set up in the 1950s in South Africa and Kenya. Application scales of DBDs in African countries, unlike in Asia, have been ambiguous. An analysis revealed that the exact number of plants installed in Africa is not known but that most units were installed in Tanzania (more than 4,000), Kenya, and Ethiopia. The number of units ranges from a few to hundreds in other countries. "Biogas for a Better Life: An African Initiative" set up the ambitious target to install two million DBDs (90% operation rate) by 2020. National programs in Africa are currently implemented in Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin, and Burkina Faso. Gwavuya *et al.,* (2012) conducted a cost benefit analysis of domestic biogas plants at Ethiopia. The results showed that households gain much financial benefits from replacing their energy source with biogas and the slurry was utilized effectively as a manure to reduce the use of other fertilizers. The net benefit showed a positive trend for the use of biogas plants in households.

Laramee and Davis (2013) concluded that the development of rural household biogas systems is an important strategy to promote agricultural structural adjustment because it simultaneously reduces greenhouse gas emissions, increases rural incomes, improves sanitation, enhances ecology in rural areas, optimizes rural energy consumption structure, and improves the quality of both rural life and agricultural products.

Rajendran *et al.,* (2013) investigated on the productivity of domestic biogas plants and found that the productivity of domestic biogas plants was 570 L $kg^{-1}day^{-1}$. They also concluded that a 2 m^3 digester could supply the fuel needed for cooking for a family of 4–6 people. Minimizing the energy needs of households would help to reduce the total energy demand of the country itself.

Most domestic biogas digesters in developing regions are constructed onsite and made of bricks and concrete. The poor construction of digesters, however, may cause leakages after a short period of operation. Once broken, digesters cannot be repaired easily for normal operation. Moreover, construction is often time consuming, lasting for as long as several months because of a dependency on weather conditions. Appropriate plant models are required to adapt to various geological, topographical, and climate conditions, such as those in regions where the groundwater table is high, soils are rocky, and temperatures are relatively low during winter. Traditional domestic biogas digesters currently being promoted are not particularly efficient, especially in hilly regions (Wang *et al.,* 2012).

2.3.4.2 Portable biogas plants

Pound *et al.,* (1981) described about portable biogas digesters called bag digesters (BD). BDs were developed to solve problems experienced with brick-and-metal digesters and were the most popular prefabricated biogas digesters that have been widely applied successfully because of their low cost, handling and easy installation. A BD is a sealed tubular structure made of soft plastic that may vary in size and thickness. BDs are also referred to as balloon digesters, tube digesters, ball-type digesters, bladder digesters, and sausage-type digesters, in different regions of developing countries. The BD design was first developed in Taiwan in the 1960s and subsequently introduced to other countries. A BD consists of a long cylinder made of polyvinyl chloride (PVC), polyethylene (PE), or red mud plastic.

A portable –split biogas plant was developed at Krishi Vigyan Kendra Palakkad by Shaji James during 2008-09. The developed system consisted of a sealed digester with a hand operated stirrer attached with a separate floating type gas holder unit. The digester unit could be placed near to the waste generation point and the gas holder unit could be placed near to the gas use point. The system offered better hygiene along with increased gas production and was included in the package of Practices – Recommendations of the Kerala agricultural University (KAU, 2011).

Nguyen *et al.*, (2012) described about the advantages of composite material biogas digesters (CMD). They concluded that compared to conventional biogas digesters, this type of portable biogas plants were highly gas-tight, watertight, saves construction area and have, simple operation and maintenance. As they can be moved to another location when necessary and installed very easily without the requirement of a trained mason they are suitable for popularisation.

Jyothilakshmi *et al.*, (2013) conducted a case study at Bangalore on the installation benefits of portable biogas plants in households. Due to paucity of sufficient space at house premises, waste management was a major issue in the households of Bangalore. That problem was managed in a better way by the installation of a portable biogas plant. Apart from waste management, substituting of commercial energy with biogas helped to improve their economy.

Cheng *et al.*, (2014) described the suitable cases where prefabricated biogas digesters could be extremely suitable. They listed that they are highly suitable for sites where (i) the quality of digester construction cannot be controlled while guaranteeing gas and water tightness, (ii) the groundwater level is high, such as in coastal areas where constructing onsite brick, stone, concrete, or moulded digesters is difficult, (iii) sites located in remote and/or mountainous areas where conventional construction materials are difficult to acquire and transport, (iv) sites with inadequate supply of conventional construction materials and limited availability of specialized labour force, which results in increased construction cost and sites where residential areas are modified and rebuilt, which affects the permanent locations of conventional digesters. They also explained about the major models of prefabricated biogas plants in India.

Table 3. Major models of prefabricated biogas plants in India

Major models of prefabricated biogas plants in India
Family-Type Biogas Fertilizer Plants under the NBMMP
Shakti Surbhi FRP based KVIC type floating gas holder
Prefabricated HDPE-based complete/dome Deenbhandhu model
Prefabricated BIOTECH made FRP
Prefabricated RCC fixed dome model
Prefabricated RCC digester KVIC model
Prefabricated HDPE-based KVIC-type floating dome model
Sintex-made plastic-based floating dome KVIC type and bag type (flexi model)

They concluded that, for expanding modern energy services, low cost household digesters could be considered an appropriate technology in many developing countries. Portable biogas digesters had advantages, such as low cost, high mobility, high durability, high insulation, and high resistance to corrosion and hence could stabilize and optimize the operational status of domestic biogas digesters.

2.3.5 Comparison of biogas plants

Pareek and Nagarsheth (2016) conducted a comparative evaluation of performance of High Density Polyethylene (HDPE) and Fibre Reinforced Plastic (FRP) biogas digesters. They found that FRP digesters are considered an appropriate technology compared to HDPE digesters in expanding use of biogas as an alternate energy resources in developing countries like India. Advantages, such as highly adaptable to design change and high strength to weight ratio compared to HDPE, make FRP much reliable as a construction material for biogas digester.

2.3.6 Batch biomethanation studies

Trevelyan (1975) stated that batch digestion was the quick and inexpensive method of testing comparative yield from different waste materials in terms of concentrations and digestion characteristics.

Sharma and Paul (1976) conducted a batch biomethanation studies at the National Dairy Research Institute, Aarey Milk Colony, Bombay on comparative biogas yield and composition from different animal manures. In case of poultry droppings, gas production was very quick which started within three hours of supplying feed whereas in case of cow and buffalo wastes it took from one to two weeks for biogas generation to begin. Biogas production from cow wastes, buffalo wastes, horse wastes, sheep wastes, camel wastes, goat wastes, pig wastes and poultry droppings were estimated as 60, 65, 91, 91, 100, 106, 107 and 126 L kg^{-1} of dry matter respectively.

Kalra and Panwar (1986) carried out experimental studies to investigate biodegradability of rice-straw which caused biogas yield of 200 L kg^{-1} of dry matter under batch digestion from experimental digesters of 190 litre capacity. Rice-husk did not undergo complete digestion following its high lignin content and unfavourable non-lignin carbon-to-nitrogen ratio. A mixture of rice-straw and cattle dung in equal proportion on dry weight basis yielded 9.1 per cent more gas than rice-straw alone.

2.3.7 Biogas slurry as fertilizer

Gupta (1991) estimated the nitrogen phosphorous and potassium (NP&K) content of biogas slurry. He found NPK content of biogas slurry as 1.03, 0.82 and 1.07 % respectively.

Gurung (1997) estimated the average increase in yield of different crops due to the application of biogas slurry. His findings are listed below:

Table 4. Percentage of increase in yield of different crop in slurry treated plot compared to untreated plot

Crop	Percentage of increase in yield over untreated plot (%).	Crop	Percentage of increase in yield over untreated plot (%).
Paddy	31.95	Chillies	24.25
Wheat	24.69	Tomato	126.10
Maize	40.46	Banana	4.69
Millet	40.46	Groundnut	23.99
Turmeric	27.05	Brinjal	103.23
Potato	30.85	Sugar cane	6.29

Yi *et al.*, (2002) studied about the effect of biogas slurry on production of tomato and physiological activity index of tomato plant he found that applying the fertilizer of biogas slurry or the mixed fertilizer of chemical fertilizer and biogas slurry together with biogas slurry sprayed on the tomato leaves could have a significant role in the aspects of increasing the yield of tomato and promoting the physiological activity of tomato plant: Chlorophyll content has increased 11 percent, Polyphenol oxidase and ascorbic acid oxidase of the tomato plant has improved 114.7 and 206.4 percent, respectively, production of tomato has increased 51.7 percent compared with that of the control.

CHAPTER III

MATERIALS AND METHODS

The procedure adopted for the assessment of kitchen waste as a feed stock for biogas plants and the methodology for assessment of different portable biogas plants are outlined in this section.

3.1 Characteristics of kitchen waste

The following methods were adopted for estimating different characteristics of kitchen waste which are relevant in anaerobic digestion.

3.1.1 Total solids (TS)

The total solid were determined by the procedure developed by American Public Health Association (APHA, 1989). A measured volume of well mixed sample was transferred to a pre- weighed and evaporated to dryness in a drying oven. The evaporated sample was dried for one hour in the oven at 103-105 ^{0}C. The dish was then cooled in a desiccator and weighed. The process of drying, cooling and weighing was repeated till concordant weighs were obtained.

$$TS = \left\{ \frac{W_1 - W_2}{\text{Sample volume, mL}} \times 1000 \right\} gL^{-1}$$

W_1 = Weight of the dried residue with dish, g

W_2= Weight of dish, g

3.1.2 pH value

pH of the samples were determined using the method prescribed by APHA, (1989). The pH meter used was Eutech instruments make, model- WD-35617-00 (Fig. 1), pH range 0.00 to 14.00 with an accuracy ±0.01 pH.

3.1.3 Total Kjeldahl Nitrogen (TKN)

From the collected sample, 0.5 g of sample was grinded and sieved using 0.25 mm sieve. Grinded sample was then transferred to the digestion tube. 10 ml of concentrated H_2SO_4 and 2 tea spoon of digestion mixture ($CuSO_4$+ K_2SO_4 in 1:10 ratio). Place the mixture for digestion over one day at room temperature. After one day, digested sample in the test tube will mix with distilled water and place in the distillation tube. At the end of delivery tube place 20 ml 4% boric acid containing mixed indicator. After adding 25 ml 40% NaOH in distillation tube distillation will start. During distillation NH_3 evolved will be trapped in Boric Acid Containing mixed indicator and the mixture will became blue. This process will take about 12 minutes. After distillation the sample will titrate against 0.1 N NH_2SO_4. At the end point the colour of sample will turn from blue to reddish brown due to the regeneration of boric acid.

$$N\% = \frac{\text{Titrate value x 0.1 x 0.014}}{\text{Weight of sample}} \text{ X } 100$$

3.1.4 Estimation of Carbon

Carbon was estimated using the instrument called "Elemental analyser, multi EA, 4000" (Fig. 2). The working principle behind the elemental analyser is as follows: carbon present in the sample is compressed inside the compressor tube present in the furnace module at a temperature of 1200 ^{0}C and pressure of 6 bar. The sample will then move to the dust trap. Here all the impurities are removed and the halogen absorber absorbs all other gases except CO_2 and the drying agent in the furnace module absorbs the moisture. At the final step, CO_2 enters into detector module. In the detector module, carbon non-dispersive infrared tube absorbs the CO_2 and converts it into signals and transfers to the monitor attached with elemental analyser.

Figure 1. pH meter

Figure 2. Elemental analyser, multi EA, 4000

3.2 Components in kitchen waste

This investigation was carried out to find out the components in organic waste produced from household kitchen as well as community level kitchen.

3.2.1 Components of domestic kitchen waste

The samples were collected from houses of 5 member family in the study area. 5 families were selected randomly from the study area and the waste generation data was collected. Kitchen waste from each house hold was collected at random intervals over a period of 2 months. The family members were requested to sort different types of wastes such as vegetable peels, cooked food waste, liquid wastes and other organic wastes with low biodegradability and keep them in separate collection bags. Skeletal parts from meat and fish were considered as organic wastes with low biodegradability. Collected samples are weighed in-situ using weighing balance.

3.2.2 Components of Community level kitchen waste

The sample was collected from a kitchen of 40 member hostel. Hostel mess had a weekly food menu during the study period and hence the samples of wastes were collected for one week for assessment. Different types of wastes were sorted, collected in separate collection bags and weighed as described in section 3.2.1.

3.3 Preliminary biomethanation studies

The biomethanation study of domestic waste was carried out to find out the methane generation potential of domestic waste.

3.3.1 Experimental setup

This experimental setup and the methodology adopted to assess the biomethanation potential of domestic organic waste were as described below:

3.3.1.1 Initial setup

The preliminary trial was conducted using a 25 capacity digester attached with a water displacement meter (Fig. 6). The volume of feed material was 10 L and the trial was replicated twice as given below:

T_0R_1- 10L inoculum + 10Lwater

T_0R_2- 10L inoculum + 10Lwater

T_1 R_1- 10L inoculum + 10Lkitchen waste

T_1 R_2- 10L inoculum + 10Lkitchen waste

Slurry from an existing biogas plant working on cow dung was taken as inoculum. The kitchen waste and slurry was taken in a ratio of 1:1 and they were mixed well. Initial pH and TS of kitchen waste were 3.23 and 60 gL^{-1}, respectively and the pH and TS of inoculum were 6.9 and 56 gL^{-1} respectively. The pH of the feed material was corrected to 7 with NaOH before starting the experiment. Another blank treatment with 10 L of slurry mixed with 10 L of water was also run simultaneously in a similar manner. The pH and methane content of biogas was taken in a 2 day interval.

3.3.1.2 Major items of observations

Daily gas production, methane content of biogas and digester pH were the main items of the observation.

3.1.3 Gas Measurement

The volume of gas in preliminary biomethanation studies was measured using water displacement method (Lo and Liao, 1986; James and Kamraj, 2004). A 5- liter graduated jar was used for the purpose (Fig. 3).

3.1.4 Methane content of biogas

Methane content was estimated using a sacharometer (Bovas, 2009) (Fig. 4). 5ml biogas was collected using a syringe (Fig. 5) from the gas holder and injected carefully into the sacharometer filled with saturated KOH solution. As CO_2 is absorbed by saturated KOH, the remaining volume of injected biogas was taken as methane. The methane content was calculated as follows.

$$\text{Methane content, \%} = \frac{\text{Volume of gas collected at the top}}{\text{Total volume of gas injected}} \times 100$$

Figure 3. Water displacement meter

Figure 4. Sacharometer

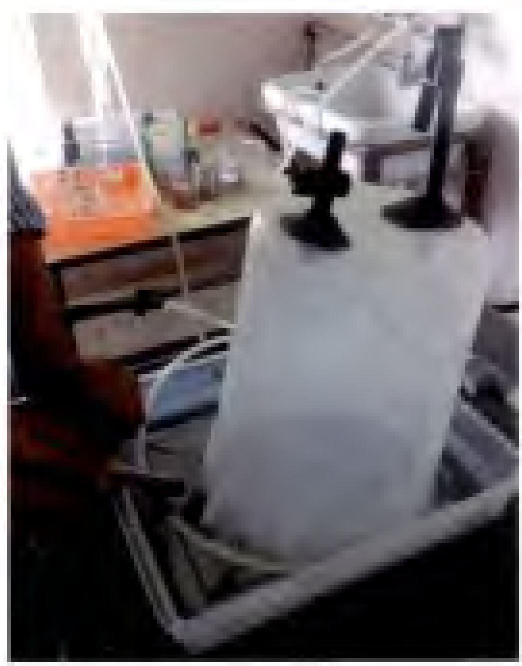


Figure 5. Collection of biogas using syringe

3.3.2 Isolation and characterization of methanogenic bacteria from slurry samples

To find out the presence of methanogenic bacteria in the samples, the slurry samples were collected from the slurry of T_0 and T_1 in a closed test tubes to avoid the exposure of samples to atmosphere.

Ten ml of each sample was mixed with 90 ml of sterilized distilled water and serially diluted from 10^{-1} to 10^{-4} (Park and Williams, 1905). The suspension of 0.1 mL from each dilution was spread on an anaerobic thiogycollate agar media which was kept in an inverted position in a desiccator for maintaining anaerobic condition at 37 ^{0}C for 48 hrs. The colonies exhibiting the characters of methanogenic bacteria were characterized using key characters for identification (Edwards and McBride, 1975).

3.3.3 Biomethanation study with modified feeding schedule

Biomethanation studies for domestic organic waste was conducted in lab-scale anaerobic plastic digesters of 25 litre capacity (Fig. 6). The digesters consisting of an inlet, gas outlet and a facility to mix the components were fabricated. The gas outlet was connected to a water displacement meter with a capacity of 5 L. Slurry from an existing biogas plant was used as the inoculum. The ratio between slurry and kitchen waste was taken as 5:1. Initial pH and TS of kitchen waste as 3.41 and 82 g L^{-1} respectively. The experimental set-up is shown in Fig. 7.

The following treatments were adopted for the study.

T_0- 20 L inoculum + 4Lwater (Feeding rate: 1L water for 4 days)

T_1- 20 L inoculum + 4L kitchen waste (Feeding rate: 500 ml kitchen waste for 8 days)

T_2- 20 L inoculum + 4L kitchen waste (Feeding rate: 666 ml kitchen waste for 6 days)

T_3- 20 L inoculum + 4L kitchen waste (Feeding rate: 1 L kitchen waste for 4 days)

T_4- 20 L inoculum + 4L kitchen waste (Feeding rate: 2 L kitchen waste for 2 days)

Figure 6. Arrangements of batch digesters for study

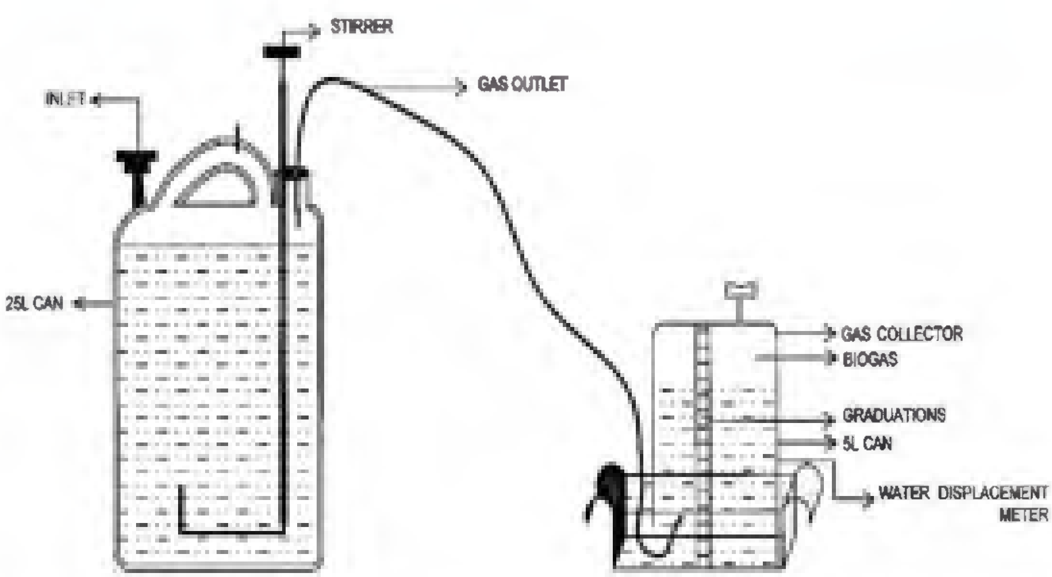


Figure 7. Experimental setup of batch digester

3.3.3.1 Observations recorded

Daily biogas production, methane content of biogas and the pH of digester were estimated as explained in section 3.1.4. Corrected gas production was calculated by subtracting the biogas production of T_0 from the quantity measured in other treatments.

3.4 Evaluation of portable domestic biogas plants

The experimental procedure adopted to compare the four different types of portable biogas plants are described below.

3.4.1 Different models used in the study

The four types of models used in this study are fixed gas holder type, floating gas holder type, floating gas holder type with water seal and KAU portable split biogas plant.

3.4.1.1 Floating gas holder type without water seal

The locally manufactured PVC floating gas holder type portable biogas plant (PBP1) used in the study is shown in Fig. 8. The biogas plant had a digester volume of 240.8 L. The height of the digester was 56 cm and diameter was 74 cm. (Fig. 9)

3.4.1.2 Floating gas holder type with water seal

This model (Fig. 10) consisted of a water seal to avoid escape of gas through the annular space between the digester wall and the floating gas holder (PBP2). This water seal arrangement was also useful in preventing the exposure of slurry to atmosphere and hence more hygienic. The total volume of the digester was 313.5 L and digester height was 77 cm and it had a diameter of 72 cm (Fig. 11).

3.4.1.3 Fixed gas holder type

Fixed gasholder type biogas plant, PBP3 (Fig. 12) constructed by a local manufacturer (Green Energy) was used for this study. It has a total volume of 232.1 L and the digester height and diameter were 60 cm and 70 cm respectively (Fig. 13).

3.4.1.4 KAU split biogas plant

The 'Split Biogas' model (PBP4) was developed by Kerala Agricultural University at Krishi Vigyan Kendra – Palakkad, Pattambi and included in the Package of Practices- Recommendations (2011) of Kerala Agricultural University. The biogas plant had separate gas holder and digester and the digester had a stirring arrangement (Fig. 14). Total volume of the digester was 474.4l L. The digester height and diameter were 78 cm and 88 cm respectively (Fig. 15).

3.4.2 Setting up of PBPs and observations

The 4 portable biogas plants were laid out adjacent to the hostel so as to enable easy daily feeding from the food wastes from the mess. Digesters were initially filled with slurry from an existing biogas plant. Initially for 3 days no feeding was done in the PBPs and the 4^{th} day onwards feeding was started with 60 day HRT. Arrangement of PBPs are shown in Fig. 16.

The observations recorded were, Daily biogas production, pH, methane content of biogas as well as TS of input and output.

3.4.2.1 Daily gas production

Daily gas production was measured using a gas flow meter with mechanical totalizer (Model SI-2.5) (Fig. 17). A dry type gas flow meter manufactured by Siya instruments, Rajasthan was used. The observations were taken twice per day at fixed times.

3.4.2.2 Total Kjeldahl Nitrogen (TKN)

Estimation of the nitrogen content is as explained in section 3.1.3

3.4.2.3 Estimation of Phosphorous and Potassium (P&K)

Phosphorous and potassium was estimated using flame photometer. Flame photometer was a traditional and simple method for determining sodium and potassium which involves the technique of emission flame photometry. This relies on the principle that an alkali metal salt drawn into a non-luminous flame will ionise, absorb energy from the flame and then emit light of a characteristic wavelength as the excited atoms decay to the unexcited ground state. The intensity of emission is proportional to the concentration of the element in the solution. A photocell detects the emitted light and converts it to a voltage, which can be recorded. Since Na^+ and K^+ emit light of different wavelengths (colours), by using appropriate coloured filters the emission due to Na^+ and K^+ (and hence their concentrations) can be specifically measured in the same sample (Siebers and Maling, 1988).

Figure 8. Floating gas holder type PBP without water seal

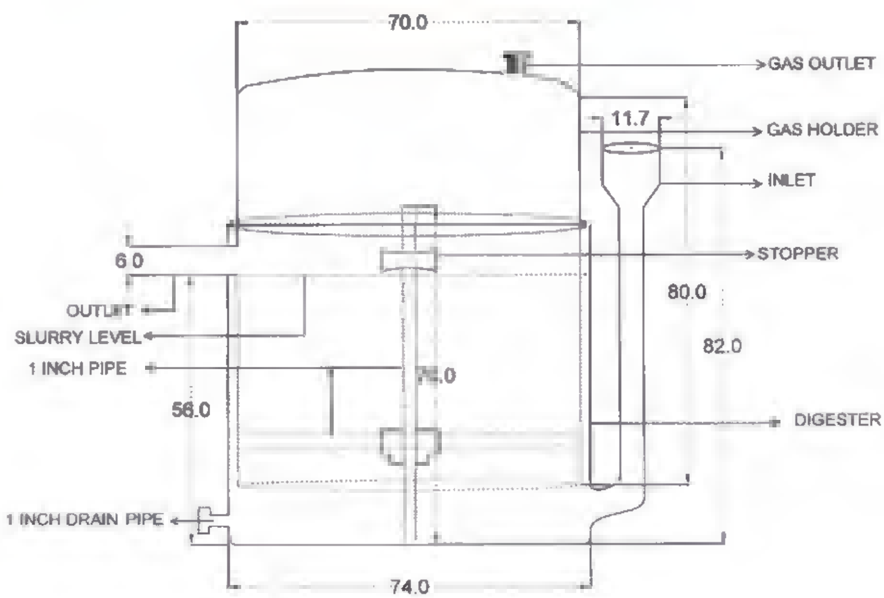
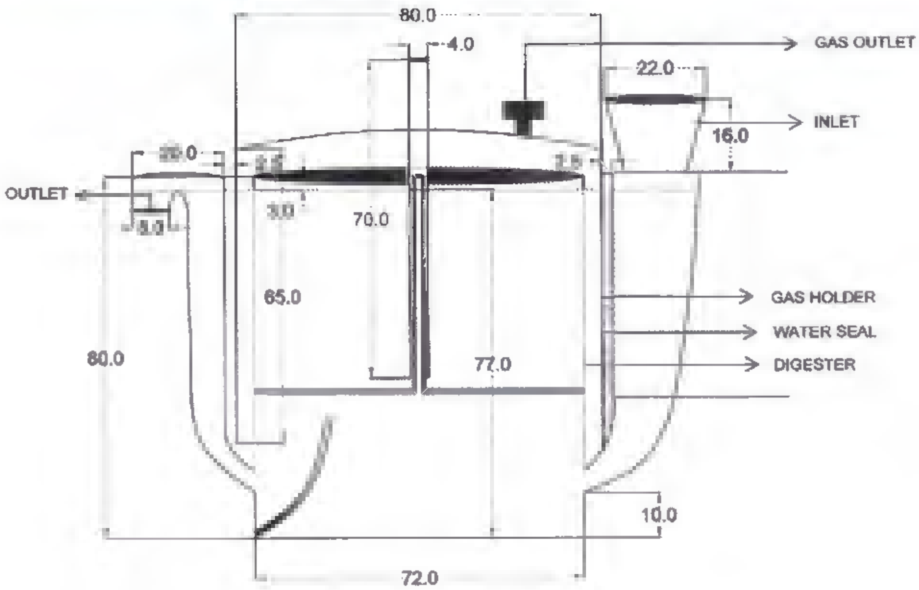


Figure 9. Schematic diagram of PBP1

Figure 10. Floating gas holder type PBP with water seal



ALL DIMENTIONS ARE IN CENTI METERS

Figure 11. Schematic diagram of PBP2

Figure 12. Fixed gasholder type PBP

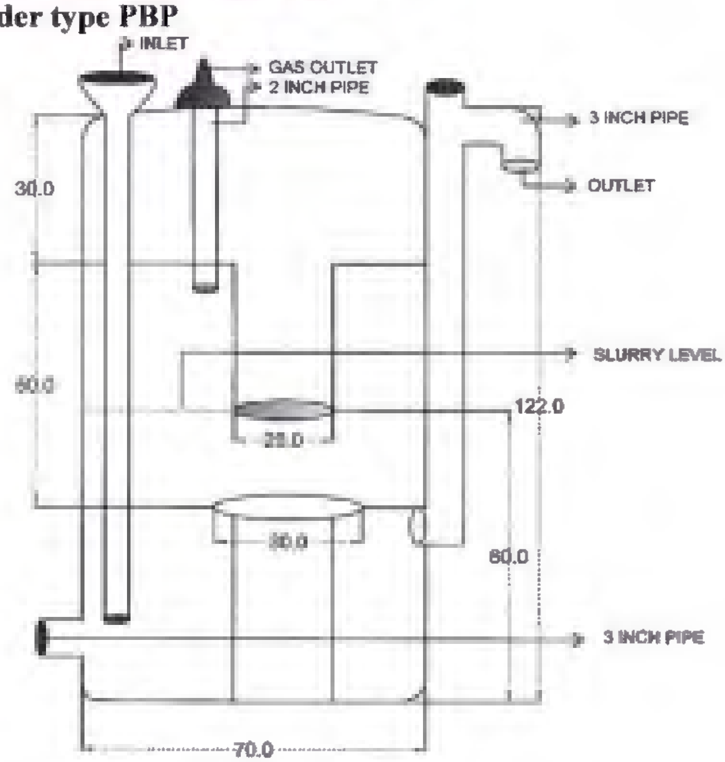


Figure 13. Schematic diagram of PBP3

ALL DIMENTIONS ARE IN CENTIMETERS

Figure 14. KAU split biogas plant

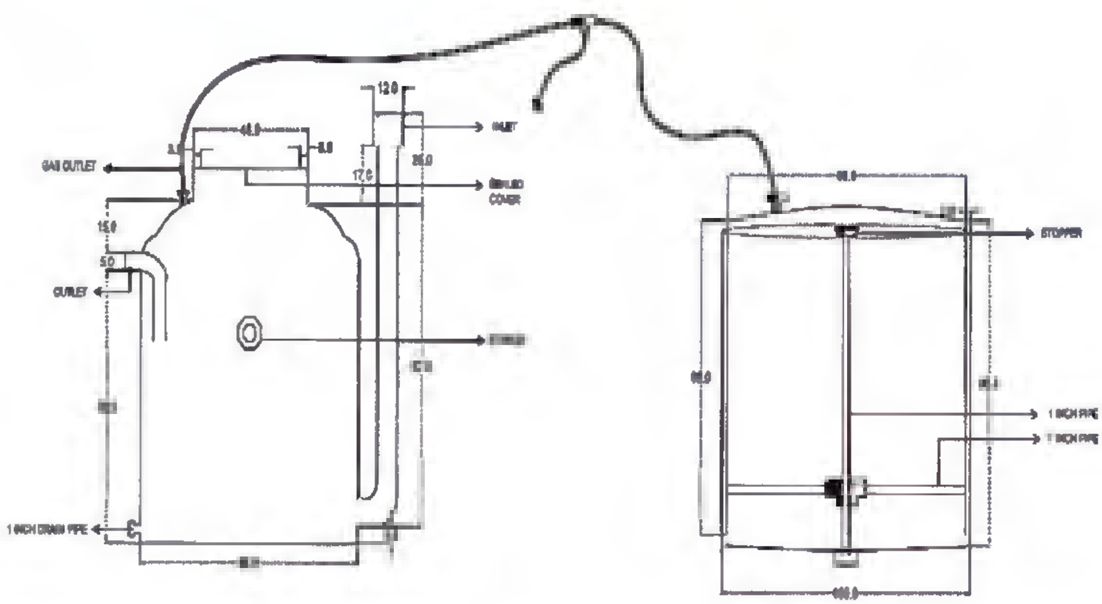


Figure 15. Schematic diagram of PBP4

Figure 16. Layout of Portable Biogas Plants

Figure 17. Biogas flow meter

3.4.3 Operating parameters

Feeding of the PBPs were done at a particular time of the day with kitchen waste collected from the hostel mess after mixing thoroughly so as to ensure uniformity. Materials with low biodegradability were separated from the collected waste and mixed well before feeding.

3.4.3.1 Hydraulic retention time (HRT)

The Hydraulic retention time is a measure of the average length of time that the feed material remains in the digester of an anaerobic system. The digesters were started-up at 60 day HRT for 10 days. The assessment was then done at HRTs of 50 and 40 days.

3.4.3.2 Hydraulic loading rate (HLR)

The HLR is the daily feed volume (L) per unit volume of digester and was constant for all PBPs at a given HRT. The daily feed volume was obtained by dividing the digester volume with HRT, which varied depending on the volume of digester in different models.

3.4.3.3 Organic loading rate (OLR)

The OLR is the kilogrammes of dry solid added per m^3 of the digester volume. OLR varies according to the TS of feed material and the TS of feed material was same for all PBPs in a day.

3.4.4 Parameters for Assessment

Different parameters used for the analysis of PBPs are explained in this section.

3.4.4.1 Specific biogas production

Specific biogas production is the biogas produced from a unit dry mass (TS) of the feed material expressed as L $kgTS^{-1}d^{-1}$. The Specific biogas production was obtained from the corrected gas production calculated by subtracting the corresponding volume of gas produced from inoculum determined from the blank treatment (T_0) in section 3.3.1.1.

3.4.4.2 Volumetric Biogas production

Volumetric biogas production is the biogas produced per unit volume of the digester and it's expressed as $Lm^{-3}d^{-1}$.

3.4.4.3 Biogas productivity

Biogas productivity is the volume of biogas produced from one litre of input. It's expressed in $LL^{-1}d^{-1}$.

3.4.5 Statistical analysis

Specific biogas production, Volumetric biogas production and biogas productivity was statistically analysed. Daily values in a biogas plant for a week was taken as different replications and values from a biogas plant was taken as a treatment. In every week a total of 4 treatments and 7 replication was taken and it was statistically analysed using completely randomized design (CRD). In a completely randomized design, combinations are assigned to experimental units at random. This is typically done by listing the treatment combinations and assigning a random number to each. By sorting out the random number, a random order for application of the treatments to experimental units are produced and the analysis will be carried out.

Wasp 2.0 developed by Central Coastal Agricultural Research Institute, GOA was used for the CRD analysis in the present study.

3.4.6 Emission reduction potential of Portable Biogas Plants

In order to assess the emission reduction potential the maximum biogas productivity of the experimental PBPs was considered. The conversion factors suggested by Chawla (1986) were used to obtain the equivalent quantities of popular cooking fuels in urban households. Accordingly, one cubic metre of biogas was equivalent to 0.620 L of kerosene, 0.45 kg of LPG and 4.695 kWh of electricity.

1 m^3 of CH_4= 0.662 kg of CH_4 at NTP (Holmgren *et al.*, 2015)

CO_2 emissions from 1 kWh of electricity, 1 kg of LPG and 1 L of kerosene were taken as 0.91 kg (Average of emissions from thermal power plant and hydroelectric power plants), 3 kg and 2.68 kg (EPA, 2014; Sun earth tools, 2016) respectively.

CHAPTER IV

RESULTS AND DISCUSSION

An analysis on the biomethanation potential of domestic organic wastes as well as investigations carried out to assess the performance of four different types of portable domestic biogas plants in energy conversion of wastes are described in this chapter.

4.1 Characteristics of domestic organic wastes

The characteristics of domestic organic wastes relevant to anaerobic digestion were as given in Table 5.

Table 5. Characteristics of domestic organic waste

Sl. No.	Parameters	Mean values
1	Total Solids (TS), gL^{-1}	82
2	pH	3.86
3	Total Carbon (%)	6.725
4	Total Nitrogen (%)	0.126
5	C:N ratio	53.88:1

Average TS of kitchen was found as 82 gL^{-1} and the pH was found as acidic. Average carbon content in kitchen waste was found as 6.725 % and the nitrogen content was found as 0.126%. Cuetos *et al*., (2008) found out that, C/N ratio in the organic material plays an important role in anaerobic digestion and the unbalanced nutrients are regarded as an important factor limiting anaerobic digestion of organic wastes. According to the study conducted by Lee *et al*. (2009), the optimal C/N ratio for anaerobic degradation of organic waste was 20–35:1. Here C: N ratio was found as 53.88:1. Which means the C: N ratio was quit high for kitchen waste. By reducing the C: N ratio to the optimum level, the biogas yield can be increased from kitchen waste.

4.1.1 Components of domestic organic kitchen wastes

The kitchen waste from households consisted of vegetable peels, food waste and liquid wastes. The constituents of the wastes varied with respect to houses and depended on the food preferences of the inhabitants on each day. The cooked food wastes and vegetable peels were considered as easily biodegradable whereas skeletal parts from meat and fish were having low biodegradability.The mean per capita waste generation in household was estimated to be 1.056 kg $person^{-1}day^{-1}$ and the average amount of organic waste generated per household was 5.28 kg. Average values of different components were as shown in Table 6.

Table 6. Components in domestic organic kitchen wastes

Sl. No.	Components	Amount (kg)
1	Vegetable peels	0.75
2	Cooked food waste	0.21
3	Liquid wastes	4.25
4	Organic wastes with low biodegradability	0.071
	Total	5.28

As rice being a common food item in Kerala, and the cooking method produced considerable amount of rice water, due to which the liquid fraction of the total organic waste from kitchen was very high. When we look into the per capita generation of cooked food waste, on an average only 42 grams were wasted. According to the study conducted by Suthar and Singh (2015) in Dehradun city, food/kitchen waste constituted about 75–80% of the total domestic waste and the average quantity was estimated as 0.2672 kg day^{-1}. In the present study the food/kitchen waste except liquid waste consisted of 1.031 kg day^{-1} and was quite high compared to the values reported for Dehradun. In Kerala vegetables are a major part of food menu and preparation of many dishes such as *sambar* and *avial* produces considerable quantities of vegetable peels. It was observed that on an average, 0.75kg day^{-1} of vegetable peals are generated in the households of the study area.

The percentage contribution of individual components are depicted in Fig. 18. More than 80 percentage of the generated wastes in the households were liquid wastes and cooked food waste was seen to be very low.

4.1.2 Components in Community level organic kitchen waste

The daily variation of individual waste components over a period of one week is shown in Table 7. Even though the proportion of different components varied according to the food menu, the quantity wise ranking of individual components was found to be same. Similar to households, major solid components in the hostel mess was food waste followed by vegetable peels. Liquid wastes was mainly constituted by the drained rice cooking water. Fraction of vegetable peels were less.

Table 7. Components in community level kitchen waste

Day	Vegetable peels	Cooked food waste	Liquid wastes	Organic wastes with low biodegradability	Total
Day 1	4.01	6.28	15.95	0.68	26.92
Day 2	2.85	5.92	11.09	0.54	20.40
Day 3	5.59	6.58	15.95	0.64	28.76
Day 4	4.62	6.23	14.93	0.42	26.19
Day 5	2.51	6.41	13.46	0.63	23.01
Day 6	3.45	5.88	14.26	0.4	23.99
Day 7	3.95	5.82	14.68	0.69	25.14
Average	**3.85**	**6.16**	**14.33**	**0.57**	**24.9**

Average organic waste generated in the hostel mess was 24.9 kg and the per capita waste generation was 0.622 kg $day^{-1}person^{-1}$. When we look into the per capita food waste, 153 g was wasted by one person.

Comparison between cooked food waste generation pattern of household and hostel mess (Fig. 18 and Fig. 19) showed that, per capita cooked food waste generation was higher in hostel mess (154 $gday^{-1}person^{-1}$). Households had a value of 42 $gday^{-1}person^{-1}$. This variation is due to the fact that households are constituted by few members when compared to hostel mess and the food consumption dynamics of a household are less complicated and more manageable compared to hostel mess.

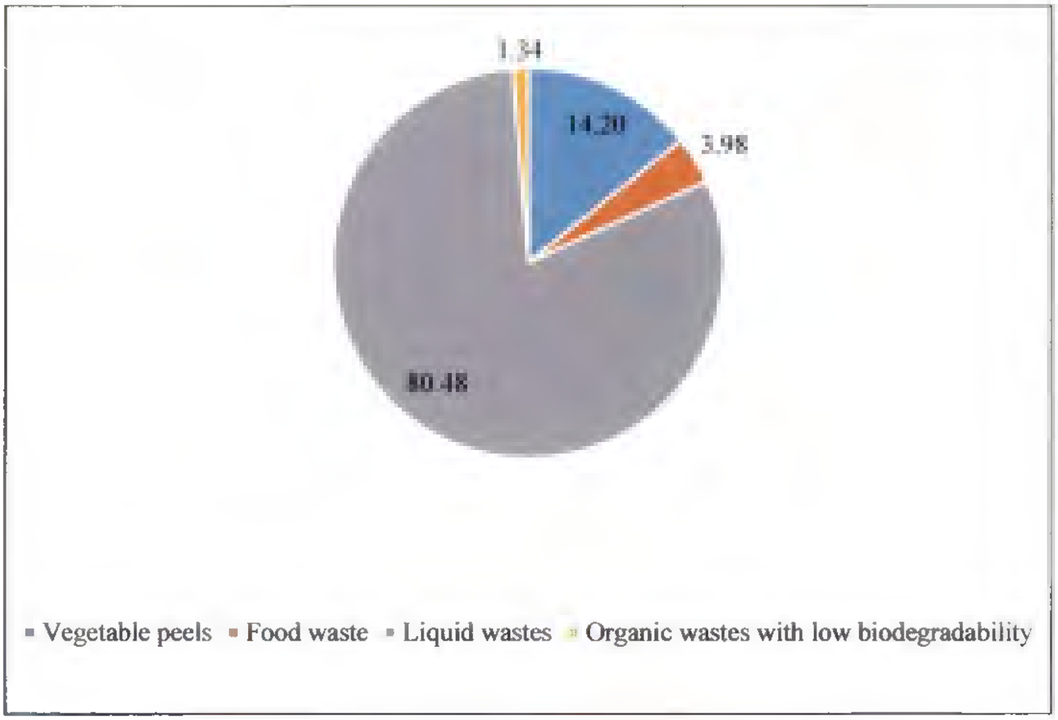


Figure 18. Waste generation pattern in household kitchen

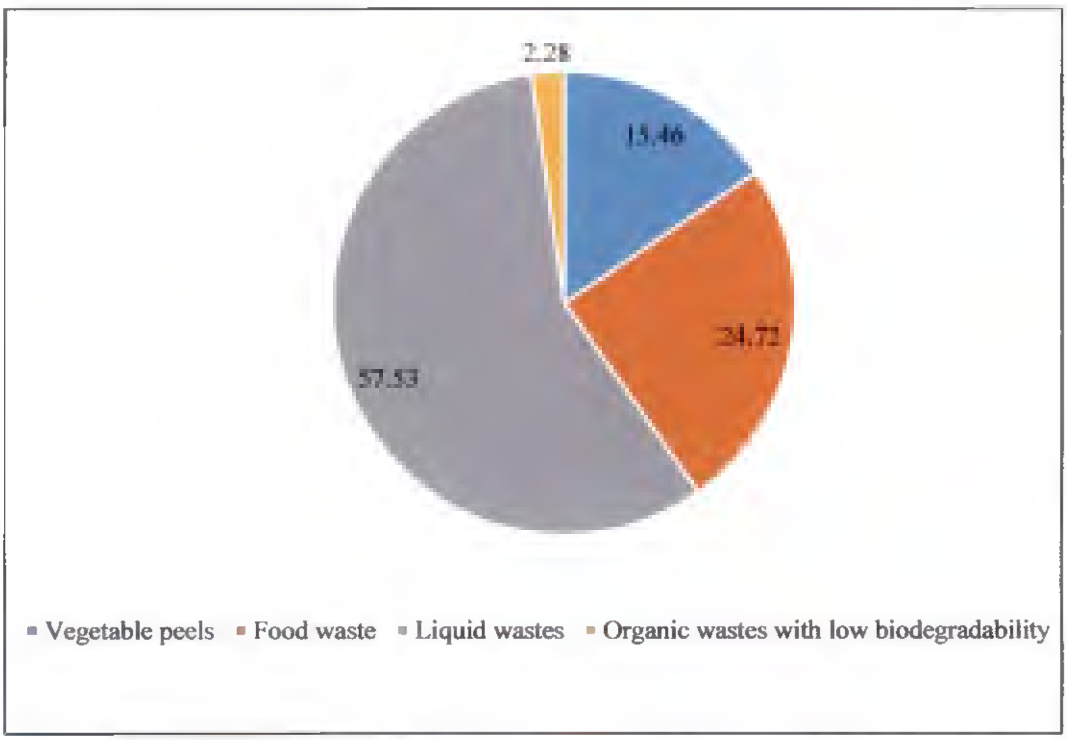


Figure 19. Waste generation pattern in community level kitchen

4.2 Preliminary biomethanation studies

Preliminary biomethanation studies were conducted to assess the potential of kitchen waste for generation of biogas through anaerobic digestion.

4.2.1 Initial Trial

In general the trial with kitchen waste (Treatments T_1) could not proceed satisfactorily. The failure to start-up of the anaerobic system was evident as the pH progressively declined with simultaneous reduction in the methane content of the biogas produced. The blank trials with biogas slurry (T_0) was performing satisfactorily with respect to the digester pH as well as the methane content of biogas. Efforts to restart the system by correcting the pH also could not succeed. The relevant observations of the trial are described in the following sections.

4.2.1.1 Biogas production

Fig. 20 shows the biogas production during the experimental period. In the initial 4 days the production was too low in T_1. Consequent to first neutralisation on the 4th day, biogas production improved slightly. But, subsequently it declined as the pH also declined to acidic ranges. Second neutralisation also lead to increased production of biogas for a few days. Then gas production started to decline steeply and on 36th day it ceased completely. The initial biogas production in T_0 was high and gradually declined day by day showing the gradual reduction of feed material in the digester. Biogas production was seen to be directly dependant on pH in T_1. When the pH was low, bio gas production was also found to decline. When the pH was corrected on the 4th day as well as 12th day, biogas production showed an increasing trend, even though for a short period.

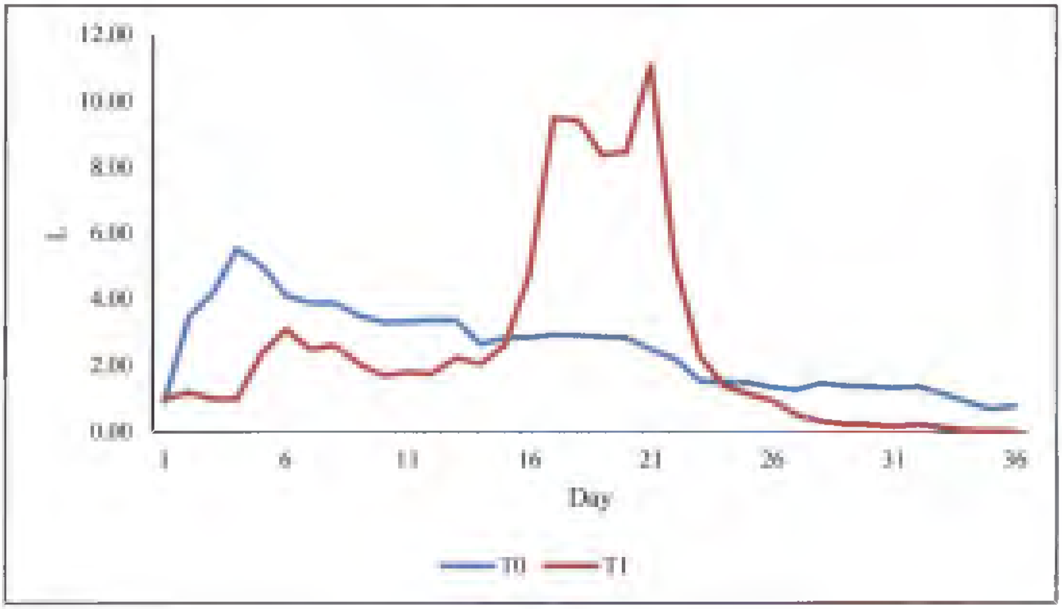


Figure 20. Biogas production from kitchen waste in the initial trial

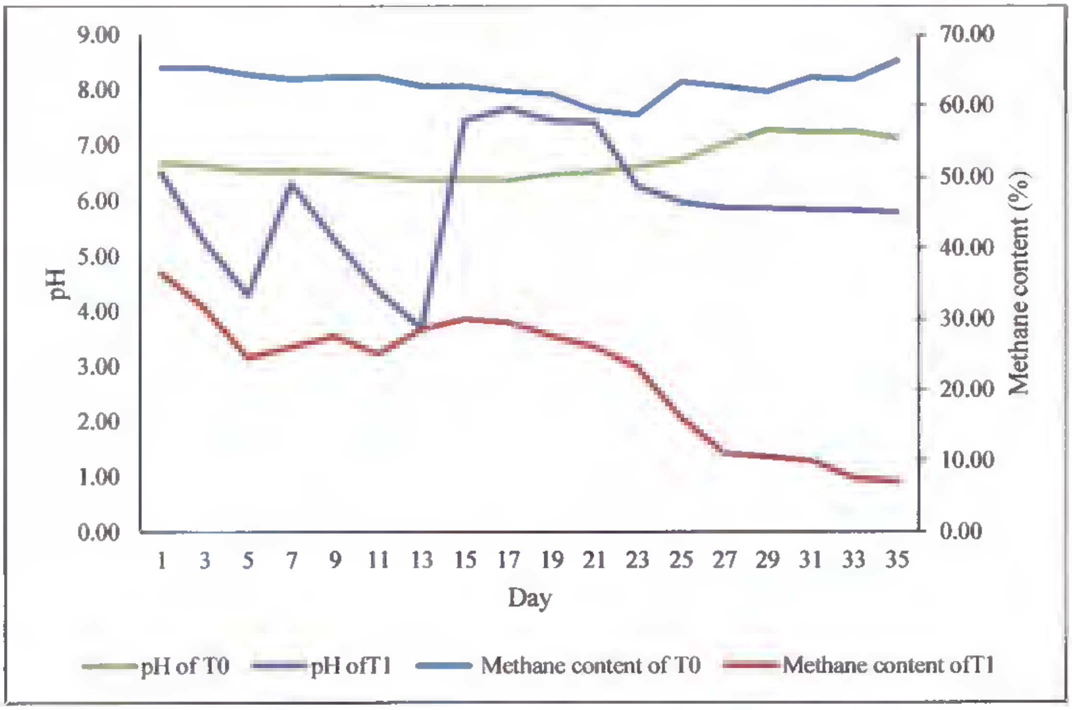


Figure 21. Variation in pH and methane content in T_0 and T_1

Fig. 21 shows the variation in pH and methane content of biogas during the experimental period. In the fourth day itself pH of T_1 was found reduced to 4.24. Then it was corrected using NaOH. But again the system could not sustain and the digester liquor became acidic. On 12^{th} day the pH was once again corrected. But the system couldn't maintain the neutral pH and started declining to acidic levels. The blank trial with biogas slurry always kept its pH at neutrality. Jones *et al.*, (1987) identified that most methanogens have pH optima near to neutrality. In the present trial, the pH progressively declined and intermediate neutralisation with alkali also could not promote favourable pH for sustaining the methanogenic activity. This was a clear indication that the methanogens were inhibited and could not survive due to the drop in pH.

Initial methane content of biogas in T_0 was 36%. There was no significant improvement even when the pH was corrected. Methane content showed a decreasing trend throughout the experimental period. Methane content in T_1 varied within the range of 58-67 %.

According to Jain and Mattiasson (1998), at pH 5.0, 4.5, and 4.0 the methane production obtained as 67, 37 and 34 % respectively. The present experiment also exhibited a similar trend in the case of T_1. Methane production was observed to be declining with the reduction in pH. This is evident from the observed values on the 6^{th} day, on which the pH was 4.26 and the methane content was 24%.Variation in methane content and pH were not very significant in T_0. Due to the decrease in pH, anaerobic bacteria became inactive. It lead to the decrease in methane content. Even if the pH was corrected, methane content did not increased. It reduced to a minimum value. The last few days, pH was almost stabilized, but methane content reduced continuously.

In T_1, pH and methane content shows a similar trend. Variation in both are negligible. The values of both undulated in a small range.

4.2.1.4 Standardization of inoculum ratio

Consequent to the failure of the first trial in successfully starting up the batch anaerobic digestion, the experiment was repeated by changing the ratio of slurry and kitchen waste into 2:1, 3:1 and 4:1. But a successful start-up of the system was not obtained.

The reason for the failure of start-up during these four trials was possibly due to the inhibition of methanogenic bacteria. It was likely that the population of methanogenic bacteria were insufficient to consume the acids produced by the acidogensis, the reason being the higher initial quantity of raw kitchen waste used. This is a clear indication that sufficient quantity of inoculum is required for start-up of domestic biogas plants working on kitchen waste.

4.2.1.5 Identification of methanogenic bacteria

Presence of methanogenic bacteria (Gram positive, short rod shaped and chain structured) was identified in both treatments (Fig. 23). In T_1, even though methanogenic bacteria were present, they were not active so as to generate biogas, due to the high concentration of substrate. This indicated that when the substrate concentration were high, it affected the overall biogas production in anaerobic digesters. Lesteur *et al.*, (2010) identified that, the initial concentration and TS of the substrate would affect the methane content of biogas. In the present study, T1, with higher concentration of substrate, recorded methane content which reduced gradually.

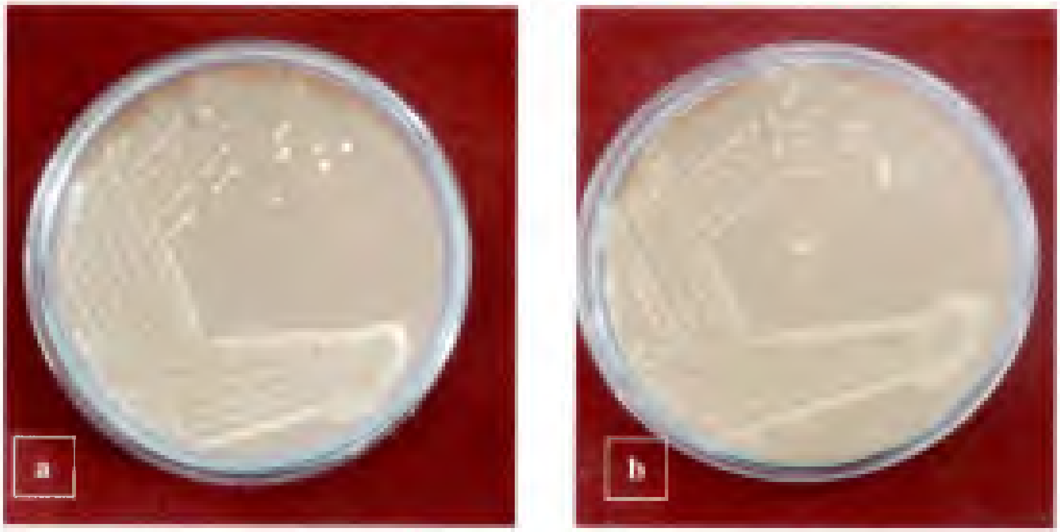


Figure 22. Methanogenic bacteria on the anaerobic thiogycollate agar media (Hi media laboratories)

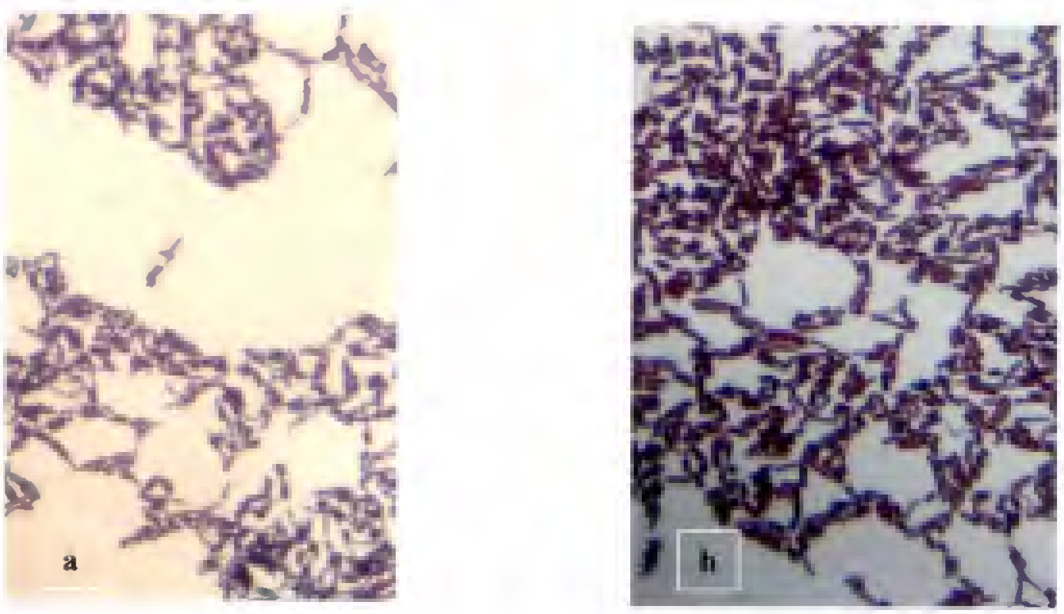


Figure 23. Isolated methanogenic bacteria from biogas slurry under microscope (40x)

4.2.2 Biomethanation study with modified feeding schedule

In subsequent experimentation, ratio between inoculum and kitchen waste was changed into 5:1. To avoid the problems due to acidification of digester liquor, wastes were fed into the digesters in increments as detailed in section 3.3.3 making the total quantity of food waste added per digester to 4 L. Table 8 shows the average daily biogas production during the stabilisation period.

Table 8. Average daily biogas production during the stabilisation period

Period	Mean biogas production (L)				
	T_0	T_1	T_2	T_3	T_4
1-3 days	7.17	7.23	7.07	7.03	7.17
4-6 days	10.50	10.30	10.60	10.73	10.53
7-9 days	7.51	7.53	7.54	7.52	7.53

The average daily biogas production over the three time periods was observed to follow a similar trend in all the digesters. This indicated that the digester liquor as well as the microbial population in all the digester units were almost identical. This also gave an assurance that the gas production after introducing different feeding schedules will be the effect of the feeding treatments. The uniformity in the digester status before the onset of feeding with kitchen waste was further confirmed by the fact that no significant difference between them was noticed in the mean biogas production data during all the three 3 –day time periods. Feeding of kitchen waste to digesters was started on the 10th day as per the schedule.

4.2.2.1 Daily biogas production

The daily biogas production after adding the feed material to the four different treatments in comparison with the blank treatment, T_0 (biogas plant slurry used as inoculum) is depicted in Fig. 24.

T_0 shows the daily biogas production from the blank starting from the 0^{th} day to 90^{th} day. The effect on daily biogas production due to the difference in feeding schedules are evident from Fig. 24. The biogas production on the first day after feeding was maximum in T_4, in which 2 L of feed was added on the first day itself. The quantity of biogas produced was in the order, T_3, T_2 and T_1. The feeding schedule was completed for all the digesters on the 8^{th} day. Even though changes were observed in the daily biogas production during the initial 15 days of operation, the variations were found to narrow down from the 10^{th} day onwards. From the 15^{th} day onwards biogas production from all treatments were observed to be following a similar trend.

The weekly average daily corrected biogas production from the treatments are shown in Fig. 25. Maximum biogas production occurred in the 1^{st} week itself during which average values were 6.82, 7.53, 7.70 and 7.99 L in T_1, T_2, T_3 and T_4, respectively. Even though maximum average biogas production was seen in T_4, there was no significant variation among the weekly average values for different treatments. A decreasing trend was observed in the average values for all the units from week 1 to week 12. In the 11^{th} week biogas production in T_3 seemed to be slightly higher than others, but towards 12^{th} week it followed the general trend.

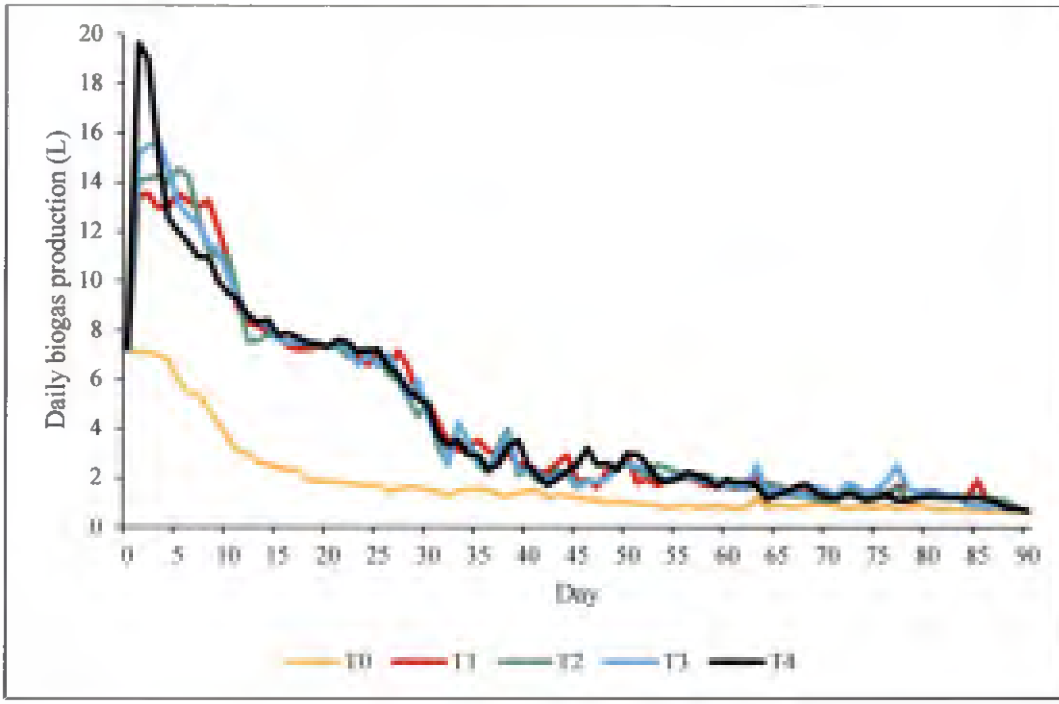


Figure 24. Daily biogas production from different treatments

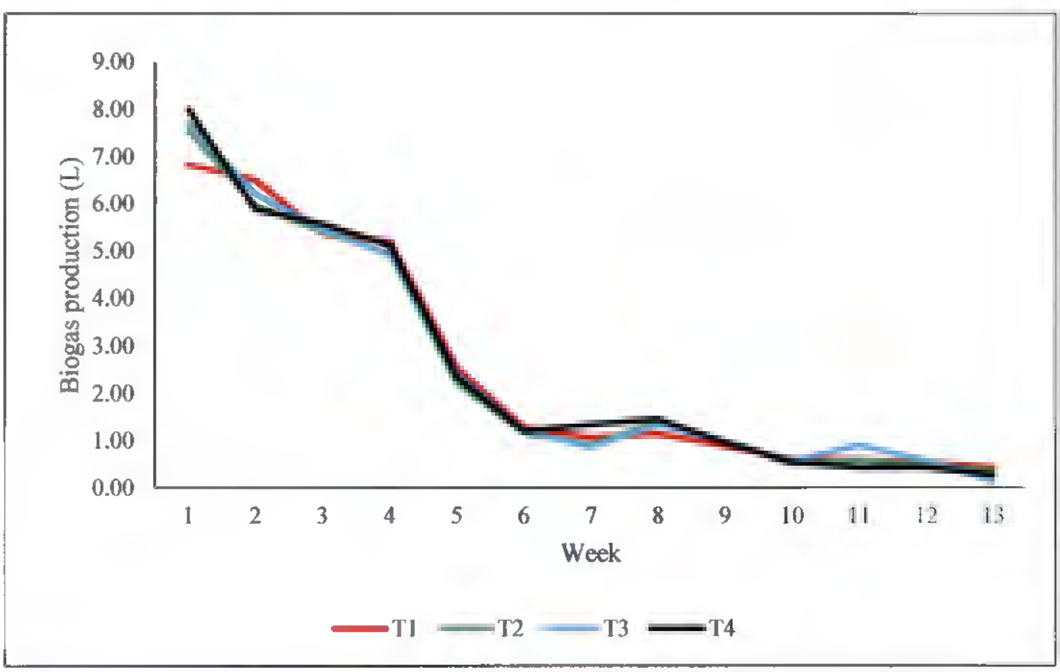


Figure 25. Corrected weekly average biogas production

On further examination of the trends of daily corrected biogas production over the entire period, it was observed that there were distinct time periods which exhibited a particular trend and all the treatments behaved in a comparable manner during these periods. The fig. 26 depicts the trend of mean daily biogas production over different time periods. The first period extended from day 1 to day 30 and there was a declining trend throughout the period (Fig. 26a). The gas production was high in the initial one week period showing that the readily biodegradable fraction of food wastes have already been subjected to acidification and these volatile acids have been quickly subjected to methanogenesis. During the second period (31-50 days), the less biodegradable fraction was possibly subjected to microbial action and there seems some irregularity in the production of biogas. There was no specific trend observed as clear from Fig. 26b. Finally, during the third period which extended from 51st day, the biogas production was seemingly stabilised to lower values but showing a gradual decline (Fig. 26c). Well defined trends were seen during the first period as well as the third period, whereas the second spell was unsteady with respect to biogas production.

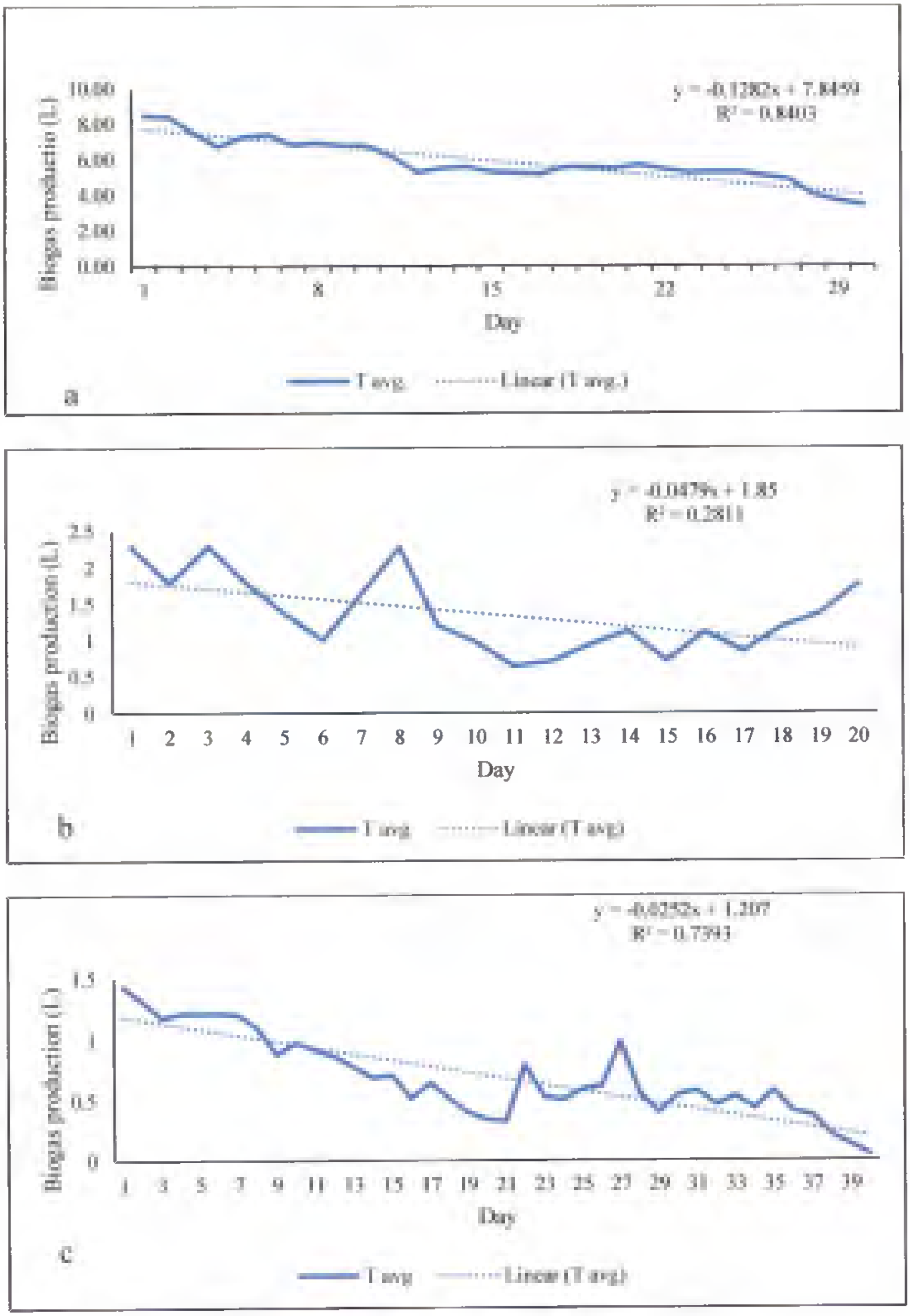


Fig 26. Trends of daily corrected biogas production over the entire period

4.2.2.2 Cumulative biogas production

Cumulative biogas production from the different treatments are shown in Table 9. At the end of 90[th] day biogas produced from 4 L of kitchen waste in T_1, T_2, T_3 and T_4 were 225.2, 221.6, 229.2 and 230.1 L respectively. Biogas productivity from the above treatments were calculated as 57.46, 56.39, 58 and 58.42 LL^{-1} respectively. On an average, 57.57 L of biogas can be produced from 1 L of kitchen waste if retained for a period of 90 days. The average specific biogas production from 1 kg of dry kitchen waste was estimated as 989.05 L $kgTS^{-1}$. For practical purposes, this quantity may be taken as the ultimate biogas production from kitchen waste. The results indicated that household kitchen waste had a good potential to generate biogas in comparison with other feed materials like cow dung. Maximum production was observed in T_4 and minimum in T_2.

Figure 27 shows the mean cumulative biogas production as percentage of the final value. Up to 35[rd] day, 80% of the total biogas production occurred and 88% of the biogas could be realised during the first 50 days of the experimental period. Hence, if 50 day is the selected HRT period, 88% of the biogas can be recovered from kitchen waste. If the HRT is 40 days, nearly 84% of the biogas yield can be obtained. It is also noteworthy that even in a short HRT of 30 days 76% of the biogas can be recovered. It is evident that there is not much advantage in having an HRT longer than 50 days with respect to biogas production. But, when we assign very short HRTs such as 30 for the biogas plants working on kitchen waste, it is likely that the out coming digested slurry is not fully stabilised. As the digester volume required is proportional to the HRT period, a shorter HRT is advantageous for cost reduction in constructing domestic biogas plants. Considering all these factors it is preferable to have an HRT in the range 40-50 days for domestic biogas plants working on kitchen wastes.

Table 9. Cumulative biogas production over the experimental period

Cumulative biogas production														
Day	T_1	T_2	T_3	T_4	Day	T_1	T_2	T_3	T_4	Day	T_1	T_2	T_3	T_4
1	6.3	6.9	8.0	12.5	31	177.0	175.0	179.2	181.0	61	213.5	211.6	215.0	220.9
2	12.7	13.9	16.4	24.4	32	179.3	176.3	180.6	183.1	62	214.5	212.4	215.8	222.0
3	18.7	21.2	25.0	32.5	33	181.0	179.1	183.3	185.1	63	215.3	212.9	217.1	222.4
4	24.9	28.3	32.7	38.3	34	182.7	181.1	185.3	186.5	64	216.2	213.8	217.6	222.8
5	32.4	36.8	39.9	44.3	35	184.7	182.0	186.4	187.9	65	217.1	214.7	218.4	223.2
6	40.1	45.5	47.0	50.3	36	186.3	182.8	187.3	188.7	66	217.6	215.1	218.7	223.8
7	47.7	52.7	53.9	55.9	37	187.9	184.7	189.0	189.9	67	218.3	215.6	219.4	224.6
8	56.2	59.1	60.6	62.1	38	189.7	187.5	191.6	191.9	68	218.8	216.0	219.7	225.4
9	64.0	65.8	67.5	67.8	39	190.8	188.2	192.5	194.0	69	219.2	216.1	220.4	225.8
10	71.2	73.2	74.1	73.7	40	191.9	189.1	193.3	195.1	70	219.4	216.3	221.0	226.2
11	77.0	79.6	80.3	79.8	41	192.7	189.5	194.1	195.7	71	219.8	216.6	221.3	226.5
12	82.3	84.2	85.9	85.4	42	193.7	190.1	194.8	196.2	72	220.4	217.5	222.4	227.1
13	87.9	89.1	91.6	91.1	43	194.9	191.1	195.6	196.8	73	220.9	217.8	223.1	227.5
14	93.3	94.5	97.3	97.0	44	196.6	192.0	196.6	197.8	74	221.5	218.4	223.7	227.8
15	98.6	99.7	102.6	102.4	45	197.2	192.4	197.1	199.1	75	222.2	218.9	224.4	228.2
16	103.7	104.9	107.7	108.0	46	198.0	193.2	197.8	201.2	76	222.6	219.5	225.5	228.7
17	108.6	110.1	112.9	113.4	47	198.6	193.9	198.5	202.7	77	223.5	220.4	227.2	229.1
18	113.9	115.7	118.6	119.0	48	199.8	194.9	199.4	204.2	78	224.3	220.7	228.0	229.4
19	119.4	121.2	124.2	124.5	49	201.1	196.4	200.8	205.5	79	224.8	221.0	228.5	229.7
20	124.9	126.7	129.7	130.1	50	203.0	197.9	202.4	207.5	80	225.2	221.6	229.2	230.1
21	130.6	132.2	135.4	135.9	51	203.8	199.3	203.9	209.5	81	226.3	222.5	230.4	231.1
22	136.1	137.3	140.8	141.6	52	204.9	200.5	205.3	211.1	82	226.8	223.0	231.0	231.6
23	141.3	142.8	145.7	147.0	53	205.7	202.1	206.5	212.2	83	227.3	223.5	231.2	232.1
24	146.2	148.3	150.9	152.4	54	206.8	203.7	207.6	213.2	84	228.5	224.0	231.4	232.5
25	151.6	153.7	155.7	157.9	55	207.9	205.1	208.9	214.3	85	229	224.6	231.5	233
26	156.4	158.5	161.3	163.0	56	209.1	206.1	210.2	215.6	86	229.5	224.9	231.7	233.4
27	162.1	163.0	166.0	167.7	57	210.1	207.4	211.3	216.9	87	229.7	225.4	231.8	233.5
28	167.0	166.6	169.6	171.6	58	211.0	208.7	212.3	218.1	88	229.8	225.5	231.9	233.6
29	170.6	169.5	174.0	175.3	59	211.9	209.6	213.3	218.8	89	229.9	225.6	232	233.7
30	174.2	173.2	177.0	178.7	60	212.7	210.8	214.1	219.9	90	226.3	222.5	230.4	231.1

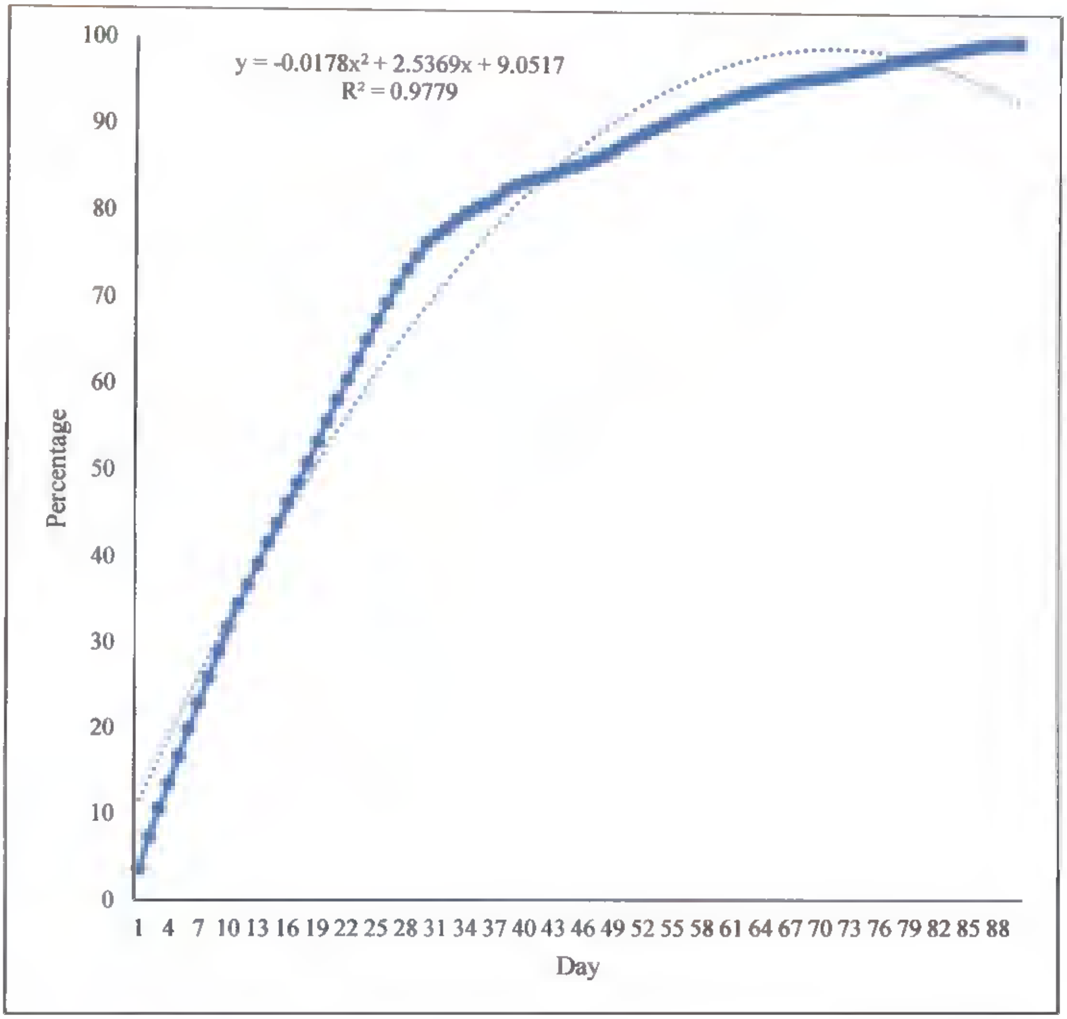


Figure 27. Cumulative biogas production

4.2.2.3 Variation of methane content of biogas

The variation of the methane content of biogas is depicted in Fig. 28. Initial methane content in T_0, T_1, T_2, T_3 and T_4 were 66, 60, 60, 62 and 60% respectively. At the end of 90th day, methane contents were found slightly varied to 63, 62, 63, 62 and 62% respectively, for the above treatments. The mean methane content of biogas from all the treatments which fed with kitchen waste was found as 62.18% during the experimental period.

4.2.2.4 Variation of pH

The pH of the experimental digesters were near neutral throughout the experimental period as depicted in Fig. 29. But they were found to increase slightly from the initial values of 6.98, 6.50, 6.58, 6.35 and 5.85 to 7.18, 7.11, 7.16, 6.96 and 7.17 for the treatments T_0, T_1, T_2, T_3 and T_4 respectively. As pH was near to neutrality in all the treatments no acidification problems occurred during the experimental period.

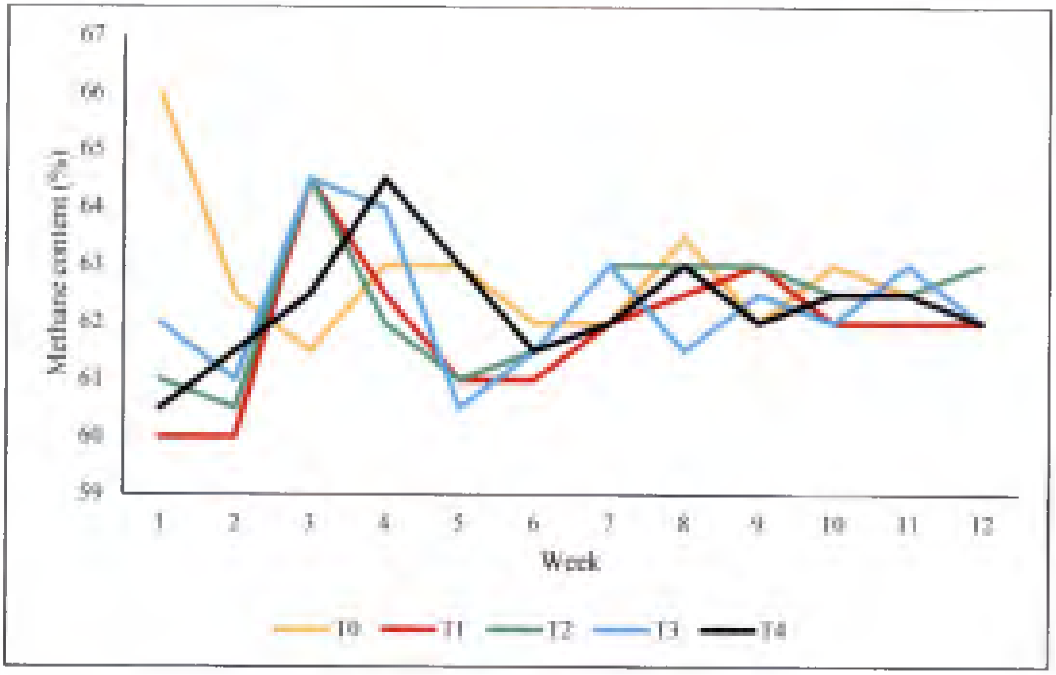


Figure 28. Weekly variation of methane content

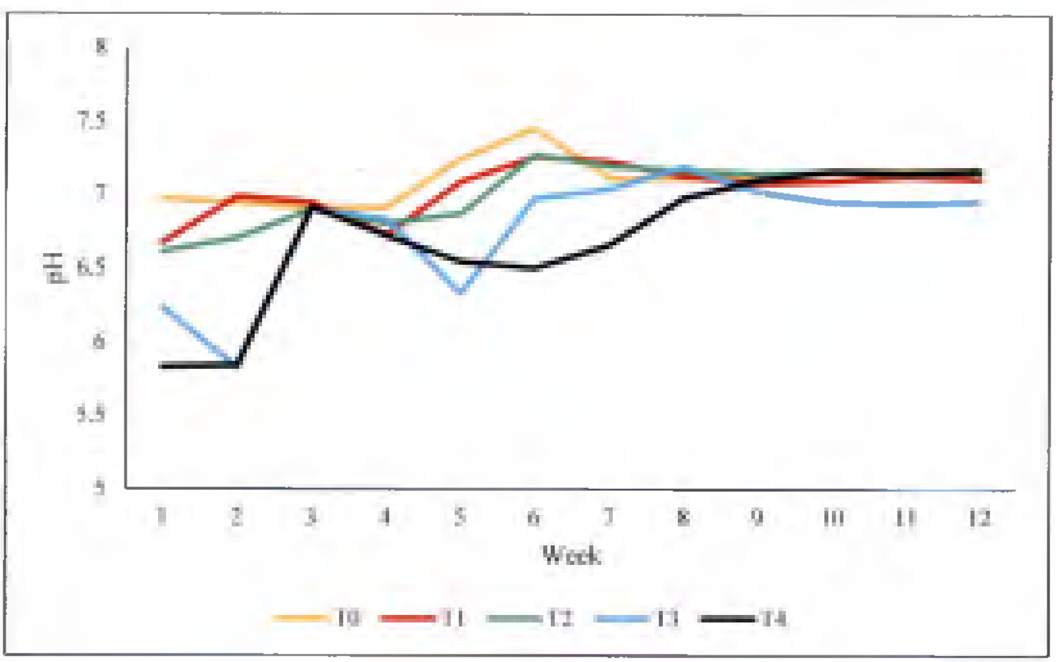


Figure 29. Weekly variation of pH during the experimental period

4.3 Assessment of portable biogas plants

The salient results of the studies conducted to evaluate the four different portable biogas plants are described in this section.

4.3.1 Start-up of portable biogas plants

Start-up of digesters were done as described in section 3.4.2. As the slurry from a biogas plant fed on cow dung was filled in the digesters for easy start up, the observations on gas production was readily available. Performance of portable biogas plants at start-up is shown in Table 10. Consequent to initial feeding, the feeding schedule was fixed at the rate corresponding to 50-day HRT and was run for 3 weeks. The gas production was monitored and was observed to be stabilised by the end of third week. The gas production and other major observations during the start-up period during which the biogas plant was run on 50-day HRT is shown in Table 10.

On 1st week mean volumetric biogas production was maximum in PBP1 and minimum in PBP4. The volumetric biogas production in PBP1 was on par with PBP2, whereas PBP2 was on par with PBP3. On the 2nd week, there was no significant difference in biogas production between the PBPs. On 3rd week, maximum biogas production was observed in PBP2 and the biogas production was on par with PBP1. The gas production of PBP1 was again on par with PBP4. Minimum biogas production at the end of 3rd week was in PBP3.

Specific biogas production was maximum in PBP1 during the 1st week of start-up period and the biogas production in PBP2 and PBP3 were on par with PBP1. Minimum specific biogas production was in PBP4. On 2nd week maximum biogas production was in PBP1 while on the 3rd week, maximum production was in PBP2. There was no significant difference observed in specific biogas production between the PBPs during second and third week of start-up period.

Table 10. Performance of portable biogas plants during start-up period

Parameter	Week	PBPs			
		PBP1	PBP2	PBP3	PBP4
Volumetric biogas production, $Lm^{-3}d^{-1}$of Biogas plant	1	862.35^{a}	796.07^{ab}	775.68^{b}	439.65^{c}
	2	1027.55	903.39	913.92	846.79
	3	1003.6^{ab}	1064.16^{a}	856.94^{c}	903.22^{bc}
Specific biogas production, L $kgTS^{-1}d^{-1}$	1	748.89^{a}	713.25^{a}	693.56^{a}	474.21^{b}
	2	775.11	706.93	713.43	655.23
	3	589.6	625.41	511.82	528.27
Biogas productivity, $LL^{-1}d^{-1}$ of daily feed	1	59.17^{a}	56.32^{ab}	55.06^{b}	37.71^{c}
	2	62.53	56.79	57.08	53.12
	3	56.09^{a}	59.64^{a}	48.94^{b}	50.73^{b}
TS reduction, %	1	47.24^{b}	42.21^{c}	47.24^{b}	54.77^{a}
	2	50.80^{b}	48.34^{c}	49.5^{bc}	58.18^{a}
	3	65.20^{a}	62.13^{b}	58.03^{c}	65.20^{a}
Average methane content of biogas	1	65	65	65	65
	2	64	64	63	64
	3	63	63	63	64
Digester pH	1	6.89	6.9	7	6.9
	2	6.95	6.95	7.02	7
	3	6.93	6.9	7.07	7.01

On 1st week biogas productivity was maximum in PBP1. The biogas productivity in PBP1 was on par with and PBP2, whereas PBP2 was on par with that of PBP3. On second week, maximum biogas productivity was observed in PBP1 and there was no significant difference observed between the biogas productivities. On the 3rd week maximum productivity was observed in PBP2. The biogas productivity in PBP2 was on par with PBP1. Minimum biogas production was observed in PBP3 at the end of 3rd week and was on par with PBP4.

TS reduction was observed to be maximum in PBP4 during all the 3 weeks and at the end of 3rd week it was on par with PBP1. In general, minimum TS reduction was observed in PBP3.

Methane content in biogas was similar in all PBPs during the 1st week of start-up period. On the second week, all the PBPs showed similar methane contents except in PBP3. On the 3rd week, methane content was observed maximum in PBP4.

Initial pH for all biogas plants except PBP3 (neutral pH) was slightly below neutral (6.89, 6.9 and 6.9) whereas the pH was found to progressively improve to values above 7 in PBP4 (7.04) at the end of 3rd week.

4.3.2 Performance of portable biogas plants at 50-day HRT period

The performance of portable biogas plants at 50-day HRT period could be assessed on the basis of biogas production and reduction of TS. The pH and methane content of biogas were also regarded as the indicators for active microbial degradation of the feed material to methane and other components.

4.3.2.1 Biogas production potential of portable biogas plants at 50-day HRT

The biogas production potential of the biogas plants were assessed based on different parameters as described in section 3.4.3.

The mean volumetric biogas production from the different PBPs at quasi-steady state condition of 50 day HRT are shown in table 11.

Table 11. Mean volumetric biogas production at 50-day HRT ($Lm^{-3}d^{-1}$)

Week	Biogas plant			
	PBP 1	**PBP 2**	**PBP3**	**PBP4**
1	1084.91[b]	1260.33[ab]	841.51[c]	1297.40[a]
2	1195.37[b]	1403.28[a]	932.96[c]	1248.27[b]
3	1116.98[b]	1498.01[a]	867.19[c]	1208.49[b]
4	1120.92[b]	1379.92[a]	895.97[c]	1289.83[a]
5	1126.66[b]	1462.22[a]	911.70[b]	1382.75[a]

Mean volumetric biogas production was seen to be slightly increasing in all biogas plants over the 5-week period. On 1st week mean volumetric biogas production was maximum in PBP4 and minimum in PBP3. The volumetric biogas production in PBP1 was on par with and PBP2, whereas PBP2 was on par with that of PBP4. During subsequent weeks from 2nd to 5th, biogas production was maximum in PBP2 and was minimum in PBP3. The performance of PBP4 was on par with PBP2 towards last two weeks of the experimental period. PBP1 was on par with PBP4 during the two weeks period from 2nd to 3rd. It could be noted that PBP3 was inferior to all other plants throughout the period. On the last week of 50-day HRT, mean volumetric gas productions were 1126.66, 1462.22, 911.70 and 1382.75 $Lm^{-3}d^{-1}$in PBP1, PBP2, PBP3 and PBP4 respectively for the four biogas plants. There was no significant difference between PBP2 and PBP4 in their superiority at the end of 50-day HRT period.

Another parameter which directly gives the measure of biogas per unit volume of the feed material is biogas productivity. The mean biogas productivity over the 5 weeks of investigation at 50-day HRT is shown in Table 12.

Table 12. Mean biogas productivity during 50-day HRT

Week	Biogas productivity ($LL^{-1}d^{-1}$)			
	PBP1	PBP2	PBP3	PBP4
1	58.750^{b}	68.150^{a}	46.740^{c}	68.980^{a}
2	63.230^{c}	74.310^{a}	50.280^{d}	65.470^{b}
3	58.850^{c}	78.660^{a}	46.520^{d}	63.050^{b}
4	59.120^{c}	72.750^{a}	48.040^{d}	67.180^{b}
5	58.900^{c}	76.410^{a}	48.320^{d}	71.310^{b}

When the daily biogas productivity was analysed on weekly basis, mean biogas productivity was found highest in PBP2 during the last four weeks of 50-day HRT period whereas it was highest in PBP4 during the first week. From second week to fifth week the performance of the plants with respect to biogas productivity was consistent, PBP2 being superior to all the other plants. PBP3 showed the minimum biogas productivity throughout. Biogas productivity at the end of 50-day HRT period was observed as 58.9, 76.41, 48.32 and 71.31 $LL^{-1}d^{-1}$ respectively in PBP1, PBP2, PBP3 and PBP4. The trend of biogas productivity was in the order PBP2 > PBP4> PBP1>PBP3.

Specific biogas production is a true measure of biogas produced from a feed stock as this indicates the biogas actually recovered from unit mass of the dry matter in the feed. The mean specific biogas production of the four different biogas plants during the 50-day HRT period is depicted in Table 13.

Table 13. Mean specific gas production at 50-day HRT

Week	Specific Biogas production ($LkgTS^{-1}d^{-1}$)			
	PBP1	PBP2	PBP3	PBP4
1	592.88^{ab}	695.54^{a}	465.88^{b}	699.19^{a}
2	632.7	741.59	505.61	653.21
3	752.04^{b}	1002.41^{a}	595.9^{c}	799.87^{b}
4	627.05^{bc}	772.91^{a}	509.25^{c}	717.33^{ab}
5	763.18b^{c}	989.84^{a}	618.4^{c}	925.85^{ab}

The mean specific gas production over the entire period followed a similar trend to that of biogas productivity. In general PBP2 exhibited the maximum performance except during the first week. During the first week PBP4 had the highest specific biogas production and it was second to PBP2 for the remaining 4 weeks. PBP 3 was inferior to all the other plants during the entire 5 week period. The trend of specific biogas production for individual plants during the period showed an increase with passage of time, but with irregularities in the trend over the weeks. The maximum specific biogas production was observed in PBP 2 on the 3rd week (1002.41 $LkgTS^{-1}d^{-1}$). On the fifth week also, maximum production was achieved in PBP 2 (989.84 $LkgTS^{-1}d^{-1}$) closely followed by PBP 4 (925.85 $LkgTS^{-1}d^{-1}$).

4.3.2.2 Reduction of TS during 50-day HRT period

Reduction of the total solid content in the feed material is a direct indicator of the performance of the biogas system as the solids are converted to other products by the action of anaerobic bacteria. The performance of four biogas plants in converting the solids to biogas is illustrated in Table 14. The TS of the feed varied between 81-105 g $L^{-1}d^{-1}$.

Table 14. Reduction of TS during 50-day HRT

Week	Mean TS of feed, g $L^{-1}d^{-1}$	TS of output slurry, $gL^{-1}d^{-1}$				TS reduction (%)			
		PBP1	PBP2	PBP3	PBP4	PBP1	PBP2	PBP3	PBP4
1	102	33	32	40	26	67.74^{b}	68.72^{b}	60.90^{c}	74.58^{a}
2	105	31	30	39	24	70.50^{b}	71.46^{b}	62.89^{c}	77.16^{a}
3	79	26	25	38	21	67.13^{b}	68.39^{b}	51.96^{c}	73.45^{a}
4	96	23	25	34	19	75.99^{b}	73.90^{c}	64.51^{d}	80.17^{a}
5	81	22	23	27	18	72.74^{b}	71.50^{b}	66.54^{c}	77.70^{a}

TS of the output slurry showed a decreasing trend with respect to passage of time indicating the gradual improvement in microbial activity with time. The performance as indicated by the reduction in TS was maximum in PBP4 throughout the 5-week period followed by PBP2. Maximum TS reduction of 80.17 % was observed in the 4th week for PBP4. Minimum TS reduction in PBP4 was 73.45 % at the third week. PBP4 showed maximum TS reduction in all the weeks and its superiority was statistically established by the analysis of variance test conducted. The order of performance was PBP4> PBP2> PBP1 > PBP3 with PBP3 exhibiting lowest TS reduction throughout the experimental period.

4.3.2.3 Methane content of biogas at 50 day HRT

The methane content of biogas from all four plants over the 5-week period is illustrated in Fig. 30. The initial methane contents in all the plants were similar and it varied randomly thereafter between the range 60 to 64 percent. At the end of 5th week, PBP2 showed the minimum methane content and PBP1 and PBP4 showed the maximum methane content.

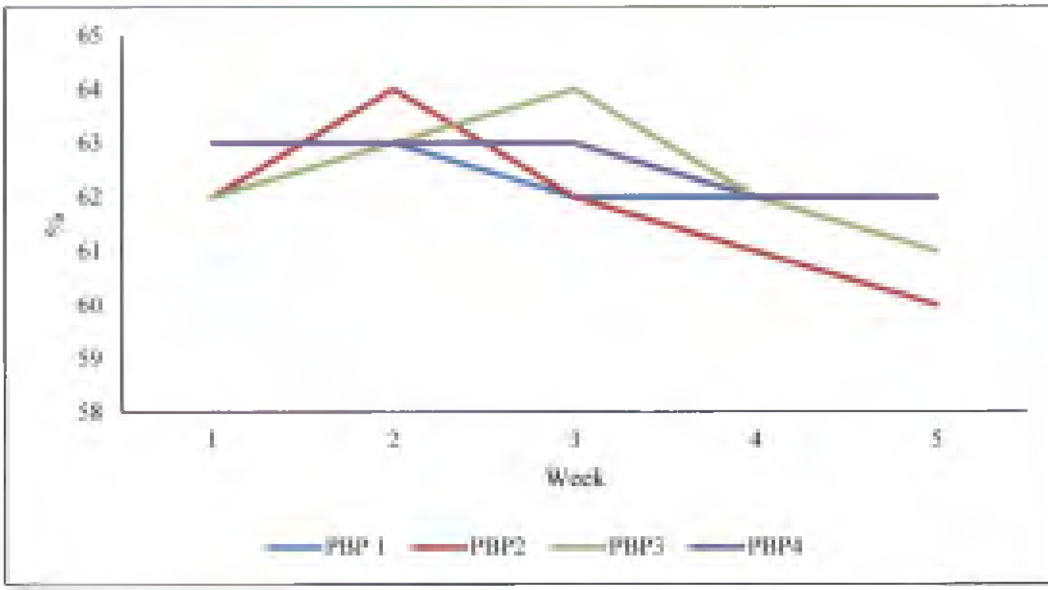


Figure 30. Weekly variation of methane content at 50-day HRT

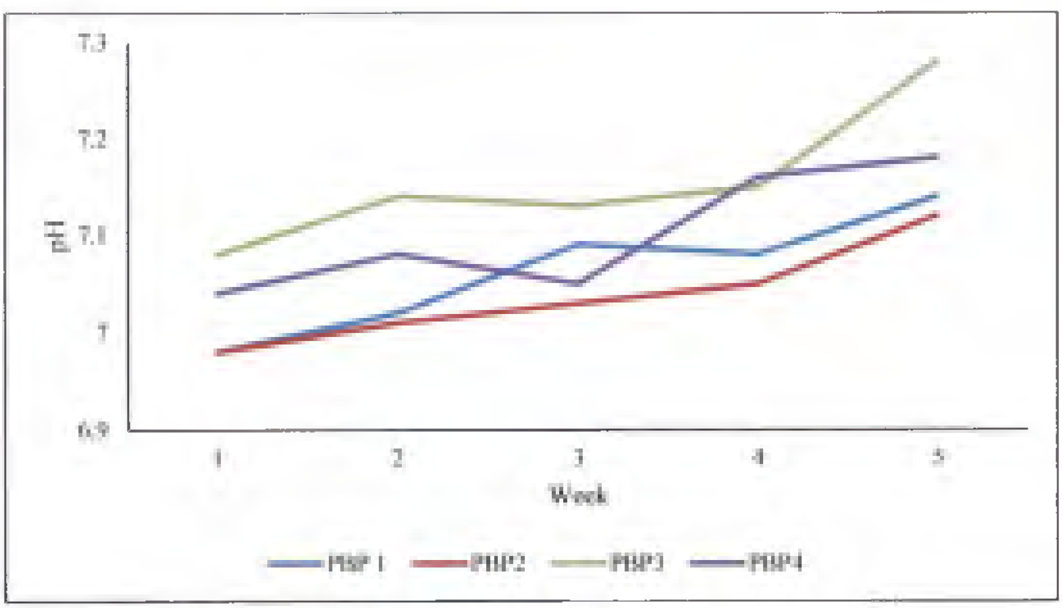


Figure 31. Weekly variation of digester pH at 50-day HRT

4.3.2.7 Digester pH at 50-day HRT

Fig. 31 shows the pH of output slurry from the digesters. pH of the out coming slurry showed an increasing trend in all PBPs over the passage of time. At the end of 5^{th} week all plants had the maximum pH values for the digester liquor. Initial pH for PBP3 and PBP4 were slightly alkaline (7.08 and 7.18) and for the other two PBPs it was slightly below neutral (6.98). But the pH was found to progressively improve to more alkaline values for all plants towards the end of the experimental period.

4.3.3 Performance of portable biogas plants at the transition period between 40 and 50-day HRT period

Overall performance of all the PBPs were found to undergo slight changes immediately when the HRT was reduced to 40 day from 50 day. Performance of PBPs during the transition period of two weeks is discussed in this section. Table 15 shows the weekly changes in the performance of PBPs at the transition period between 40 and 50-day HRT.

At the end of 50-day HRT period, volumetric biogas production in the biogas plants were in the range 1127-1462 $Lm^{-3}d^{-1}$. At the starting of 40-day HRT period a sudden increase of volumetric biogas production was observed in all PBPs. Mean volumetric biogas production at the starting week of 40-day HRT period was found to increase from 6.59 % to 27.23 %. Maximum biogas production during the 1^{st} week of transition period was observed in PBP4 and minimum biogas production was in PBP2. On the second week also the same trend was followed in all PBPs.

Specific biogas production seemed to be slightly decreasing in all biogas plants except in PBP4 during the 1^{st} week of transition period from the last week of 50-day HRT period. Specific biogas production during the first week was maximum in PBP4 and minimum in PBP3. On the first week, the specific biogas production in PBP4 was on par with and PBP2, whereas PBP2 was on par with that of PBP1 and PBP1 was on par with PBP3. During the second week of transition period, maximum biogas production was observed in PBP4 and minimum biogas production was observed in PBP3. Specific biogas production in PBP4 was on par with PBP2 although PBP2 was on par with PBP1.

Table 15. Performance of portable biogas plants at the transition period

Parameter	Week	PBPs			
		PBP1	PBP2	PBP3	PBP4
Volumetric biogas production, $Lm^{-3}d^{-1}$ of Biogas plant	1	1232.66^{c}	1627.16^{b}	975.98^{d}	1900.24^{a}
	2	1182.28^{c}	1428.57^{b}	890.39^{d}	1611.96^{a}
Specific biogas production, L $kgTS^{-1}d^{-1}$	1	649.02^{bc}	860.44^{ab}	504.13^{c}	1008.52^{a}
	2	587.85^{b}	714.46^{ab}	437.16^{c}	800.47^{a}
Biogas productivity, $LL^{-1}d^{-1}$ of daily feed	1	49.51^{c}	65.09^{b}	39.04^{d}	76.01^{a}
	2	47.49^{c}	57.14^{b}	35.62^{d}	64.48^{a}
TS reduction, %	1	81.37^{a}	72.67^{b}	68.94^{c}	81.37^{a}
	2	84.13^{a}	78.02^{b}	74.36^{c}	84.13^{a}
Average methane content of biogas, %	1	60	60	60	63
	2	58	58	62	64
Digester pH	1	7.13	7.08	7.27	7.25
	2	7.17	7.15	7.3	7.21

Biogas productivities during the last week of 50-day HRT period were in range of 76.410 $LL^{-1}d^{-1}$ (PBP2) to 48.320 $LL^{-1}d^{-1}$ (PBP3), whereas during the 1st week of transition period biogas productivity decreased by 15.94, 14.82 and 19.21 % for PBP1, PBP2 and PBP3, except in PBP4 which had an increase of 6.18%. The trends of biogas productivity during the two weeks was similar and was maximum in PBP4 and minimum in PBP3.

Higher TS reduction was found in PBP1 and PBP4 with similar TS reductions during the transition period. TS reduction was minimum in PBP3 during the transition period.

Methane content was higher in PBP4 compared to other PBPs during this period. Methane content was found to be varying in the range from 58 to 64% during the transition period. pH was above neutral in all PBPs and the maximum pH was observed in PBP3 during the transition period.

4.3.4 Performance of portable biogas plants at 40-day HRT period

Performance of portable biogas plants during 40-day HRT period is described in this section. Assessment was done on the basis of biogas production and reduction of TS. Methane content of biogas and pH of the digester were also examined periodically so as to get an indication on the working of biogas plants.

4.3.4.1 Biogas production potential of portable biogas plants at 40-day HRT

The mean volumetric biogas production from the different PBPs at quasi-steady state condition of 40-day HRT are shown in Table 16.

Table 16. Mean volumetric biogas production at 40-day HRT ($Lm^{-3}d^{-1}$)

Week	Biogas plant			
	PBP 1	PBP 2	PBP3	PBP4
1	1178.42^{b}	1412.65^{ab}	814.04^{c}	1582.37^{a}
2	1263.78^{c}	1632.85^{b}	1007.08^{d}	1823.24^{a}
3	1245.41^{b}	1297.77^{b}	866.69^{c}	1658.53^{a}
4	1297.57^{c}	1585.99^{b}	1019.70^{d}	1771.25^{a}
5	1263.19^{c}	1479.53^{b}	920.57^{d}	1804.70^{a}

Throughout the 5 week period of investigation at 40-day HRT, maximum volumetric biogas production values were found in PBP4 and the minimum values were recorded by PBP3. The gas production performance of PBP4 was on par with PBP2 during the first week while PBP2 was on par with PBP1. PBP1 was on par with PBP3 during the 3rd week. During final 2 weeks of 40-day HRT period, trend of the volumetric biogas production was in the order PBP4 > PBP2> PBP1>PBP3. PBP4 showed maximum performance throughout the 40-day HRT period.

Biogas productivity directly gives the measure of biogas per unit volume of feed material added. Biogas productivity of PBPs during the 40-day HRT period is shown in Table 17.

Table 17. Mean biogas productivity at 40-day HRT

Week	Biogas productivity ($LL^{-1}d^{-1}$)			
	PBP1	PBP2	PBP3	PBP4
1	47.33^{b}	56.51^{ab}	32.56^{c}	63.29^{a}
2	50.76^{c}	65.31^{b}	40.28^{d}	72.93^{a}
3	50.02^{c}	51.91^{b}	34.67^{d}	66.34^{a}
4	52.12^{c}	63.44^{b}	40.79^{d}	70.85^{a}
5	50.74^{c}	59.18^{b}	36.82^{d}	72.19^{a}

Mean biogas productivity was observed to be maximum in PBP4 throughout 40-day HRT period and PBP3 showed the minimum biogas productivity. On the first week biogas productivity of PBP4 was on par with PBP2 and the productivity of PBP2 was on par with PBP1. From the second week onwards the trend of biogas productivity was in the order PBP4 > PBP2> PBP1>PBP3. Mean biogas productivity during the entire 40-day HRT period was calculated as 50.20, 59.27, 37.02 and 69.12 $LL^{-1}d^{-1}$ respectively, for PBP1, PBP2, PBP3 and PBP4.

The mean specific biogas production of the four different biogas plants during the 40-day HRT period was illustrated in Table 18. Measurement of specific biogas production indicated the exact amount of biogas produced from one kilogram of dry kitchen waste.

Table 18. Mean specific gas production at 40-day HRT

Week	Specific Biogas production (L kg $TS^{-1}d^{-1}$)			
	PBP1	PBP2	PBP3	PBP4
1	660.47^{b}	754.2^{ab}	457.14^{c}	889.6^{a}
2	623.78^{b}	798.92^{a}	493.79^{c}	896.56^{a}
3	623.11^{b}	648.89^{b}	433.21^{c}	826.49^{a}
4	744.41^{b}	913.07^{a}	581.31^{c}	1017.06^{a}
5	665.86^{b}	786.26^{ab}	483.69^{c}	948.7^{a}

Similar to biogas productivity, specific biogas production was also maximum in PBP4. In consonance with the results of 50-day HRT period, PBP3 was inferior in all weeks compared to other PBPs. On the 1st week, performance of PBP2 was on par with PBP4 and PBP1 was on par with PBP2. On second week also specific biogas production of PBP4 was on par with PBP2 and in third week biogas production of PBP1 was found on par with the biogas production of PBP2. On the last two weeks of 5-week period of 40-day HRT, performance of PBP2 was found to be statistically on par with the performance of PBP4. Maximum production achieved by PBP4 was on 4th week (1017.06 L $kgTS^{-1}d^{-1}$) and that of PBP2 was 913.07 L $kgTS^{-1}d^{-1}$. During the 40-day HRT period, trend of specific biogas production followed the order: PBP4 > PBP2> PBP1>PBP3.

4.3.3.2 Reduction of TS during 40 day HRT

The performance of all PBPs on the basis of total solid reduction is shown in Table 19. TS reduction of feed material is a direct pointer to the performance of biogas systems.

Table 19. Reduction of TS during 40-day HRT

Week	Mean TS of feed, g L^{-1} d^{-1}	TS of output slurry, g $L^{-1}d^{-1}$				TS reduction (%)			
		PBP1	PBP2	PBP3	PBP4	PBP1	PBP2	PBP3	PBP4
1	75	12	18	18	13	83.33[a]	76.53[b]	76.00[b]	83.33[a]
2	83	11	16	17	12	85.51[a]	80.19[b]	80.07[b]	85.51[a]
3	81	11	14	15	12	85.34[a]	83.23[b]	81.37[b]	85.34[a]
4	71	10	12	15	12	83.85[a]	83.15[a]	79.63[b]	83.85[a]
5	78	10	11	13	10	87.23[a]	85.95[a]	83.40[b]	87.23[a]

TS reduction was exhibited an increasing trend with respect to passage of time in all PBPs. TS reduction of PBP4 was found as on par with PBP1 throughout the experimental period. Maximum TS reduction in PBP4 and PBP2 were found in the last week (87.23%). On the last two weeks, performance of PBP2 was found to be as on par with PBP1 and PBP4. PBP3 showed minimum TS reduction throughout the entire period. The TS reduction trend during the experimental period was observed to be in the order: PBP4= PBP1> PBP2> PBP3.

4.3.3.3 Methane content of biogas at 40-day HRT

Fig. 32 shows the weekly variation of methane content of biogas at 40-day HRT period. Methane content of biogas in PBPs varied between 60-64%. At the end of 40-day HRT period PBP4 showed a maximum methane content of 64% and PBP1 and PBP2 showed lower methane contents (62%).

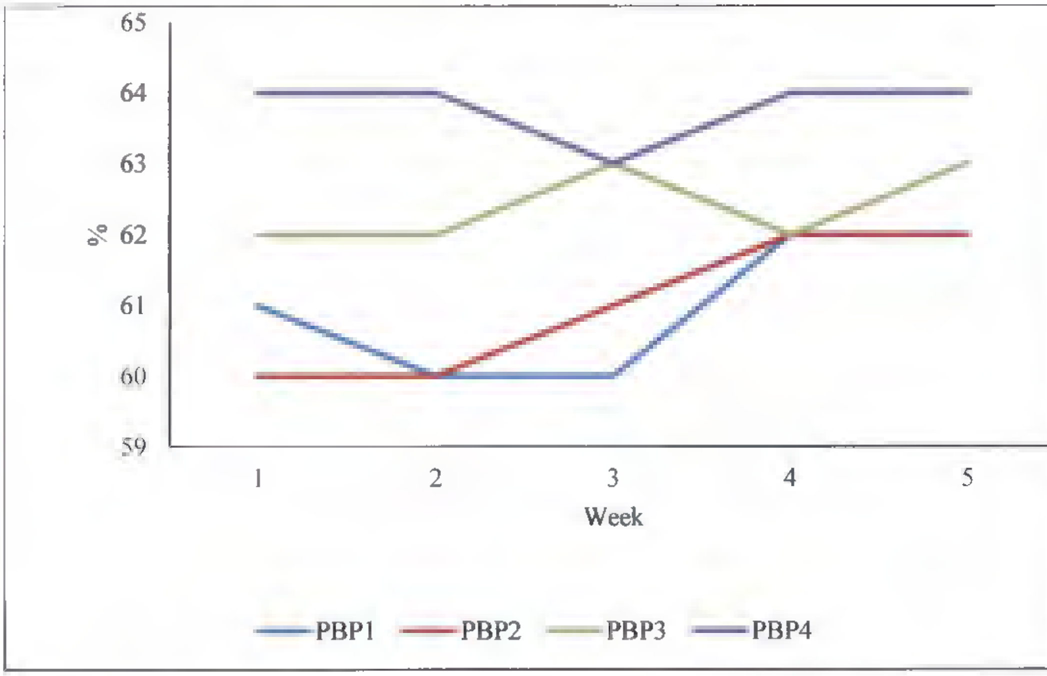


Figure 32. Weekly variation of methane content at 40-day HRT

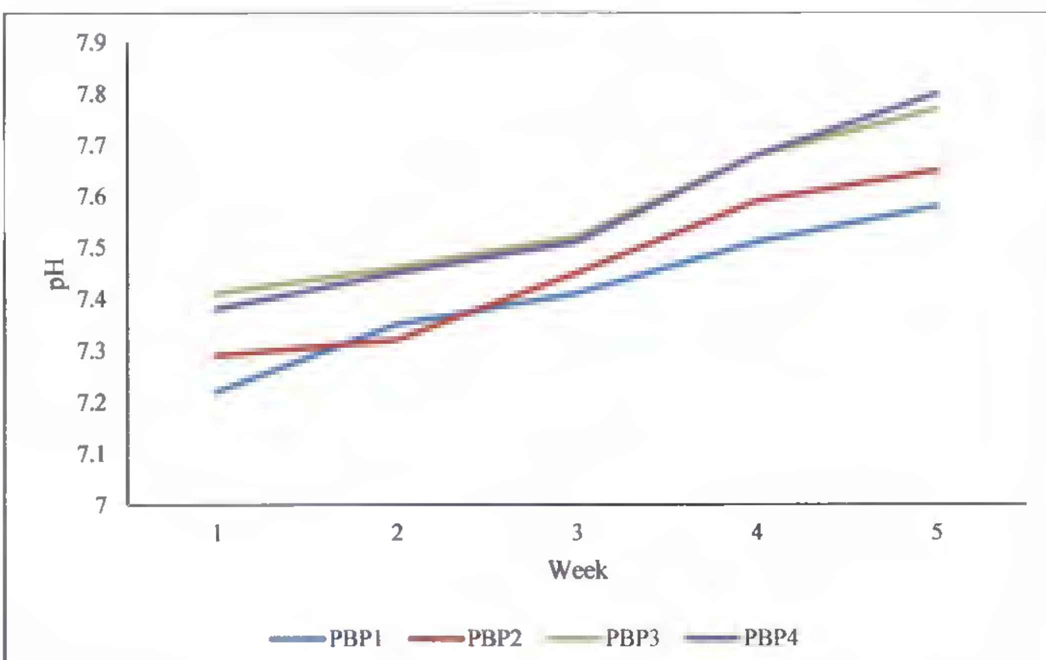


Figure 33. Weekly variation in pH of output slurry at 40-day HRT

4.3.3.4 Digester pH at 40-day HRT

The pH of digester liquor of all four plants over the 5- week period is illustrated in Fig. 33. pH of output slurry from the digester showed an increasing trend in all PBPs. Initially pH were 7.13, 7.08, 7.25 and 7.21 in PBP1, PBP2, PBP3 and PBP4 respectively and it improved to 7.58, 7.65, 7.77 and 7.8, respectively at the end of 40-day HRT.

4.3.4 Comparative performance of portable biogas plants

Fig. 34a compares the mean of the volumetric biogas production values at each HRT for the four biogas plants. At 50-day HRT, the mean volumetric biogas production was maximum in PBP2 whereas at 40-day HRT it was in PBP4. In the case of PBP1, volumetric biogas production was maximum in 40-day HRT period. In both cases, PBP3 was the poorest performer. An increase in mean volumetric biogas production was observed in all PBPs, the maximum in PBP4 (34.4 %) and the minimum increase (4.0 %) was observed in PBP3. The highest mean volumetric biogas production was seen in PBP4 at 40-day HRT. This indicated that PBP4 was more suitable for energy production from domestic kitchen waste, which could be operated at a higher gas volume availability at the shorter HRT of 40-day. According to the study conducted by Field *et al.* (1985), the average volumetric biogas production from poultry manure at 30-day HRT was 752 $Lm^{-3}d^{-1}$. In the present study, it was seen that the average biogas yield from kitchen waste in all the PBPs at 40 and 50-day HRT were 1346.27 L $m^{-3}d^{-1}$ and 1176.23 L m^{-3} d^{-1}, respectively which were much higher than that value.

The mean values of biogas productivity (Fig. 34b) was observed to decrease when HRT was shortened from 50 to 40 days, except in PBP4. The maximum value of mean biogas productivity was exhibited by PBP2 at 50-day HRT (74.06 $LL^{-1}d^{-1}$) followed by PBP4 at 40-day HRT (69.12 $LL^{-1}d^{-1}$). The minimum biogas productivity was observed in PBP3 at 40-day HRT. Even though the values were higher at 50-day HRT for all the other three PBPs, the value of PBP4 at 40-day HRT was 11% higher than the mean value for all PBPs at 50-day HRT. Average biogas productivity in all the PBPs during the 40-day HRT period was 53.9 $LL^{-1}d^{-}$

^{1} and it was 62.25 $LL^{-1}d^{-1}$ during the 50-day HRT period. It is noteworthy that PBP4 had a biogas productivity higher than these average values even at the short HRT of 40 days.

Similar to biogas productivity, specific biogas production was also observed higher at 50-day HRT period compared to 40-day HRT in all PBPs except PBP4 (Fig. 34). Maximum mean specific biogas production was observed in PBP4 (915.68 L $kgTS^{-1}d^{-1}$) during 40-day HRT, and was followed by the value of PBP2 at 50-day HRT (840.46 L $kgTS^{-1}d^{-1}$). The specific biogas production at 40-day HRT in PBP4 was 30 % and 28.5 % higher than that of the average biogas production of all the PBPs at HRTs of 50 and 40 days. According to the study conducted by Hobson *et al.*, (1981) average specific biogas production from poultry excreta in 15-day retention time was found as 362 L $kgTS^{-1}d^{-1}$ and that of 20-day HRT period was 380 L $kgTS^{-1}d^{-1}$. Study results of Field *et al.*, (1985) on poultry manure at 30-day HRT period showed that the average biogas yield as 390 L $kgTS^{-1}d^{-1}$. Here specific biogas production at 40 and 50 HRT was observed as much higher compared to the specific biogas production from the poultry manure. Study results of Bardiya *et al.*, (1996) on specific biogas production from banana peels and pineapple waste at 40-day HRT period were found as 219 and 413 L $kgTS^{-1}d^{-1}$ respectively. While comparing the specific biogas production from banana peels and pineapple waste to the specific biogas production from kitchen waste during 40-day HRT period, 69.25 and 42.02 % increase in biogas production observed in kitchen waste from the above two feed materials. Specific biogas production is a true indicator of the energy conversion efficiency of the system and hence the results give a clear testimony to the superiority of PBP4 over the other PBPs.

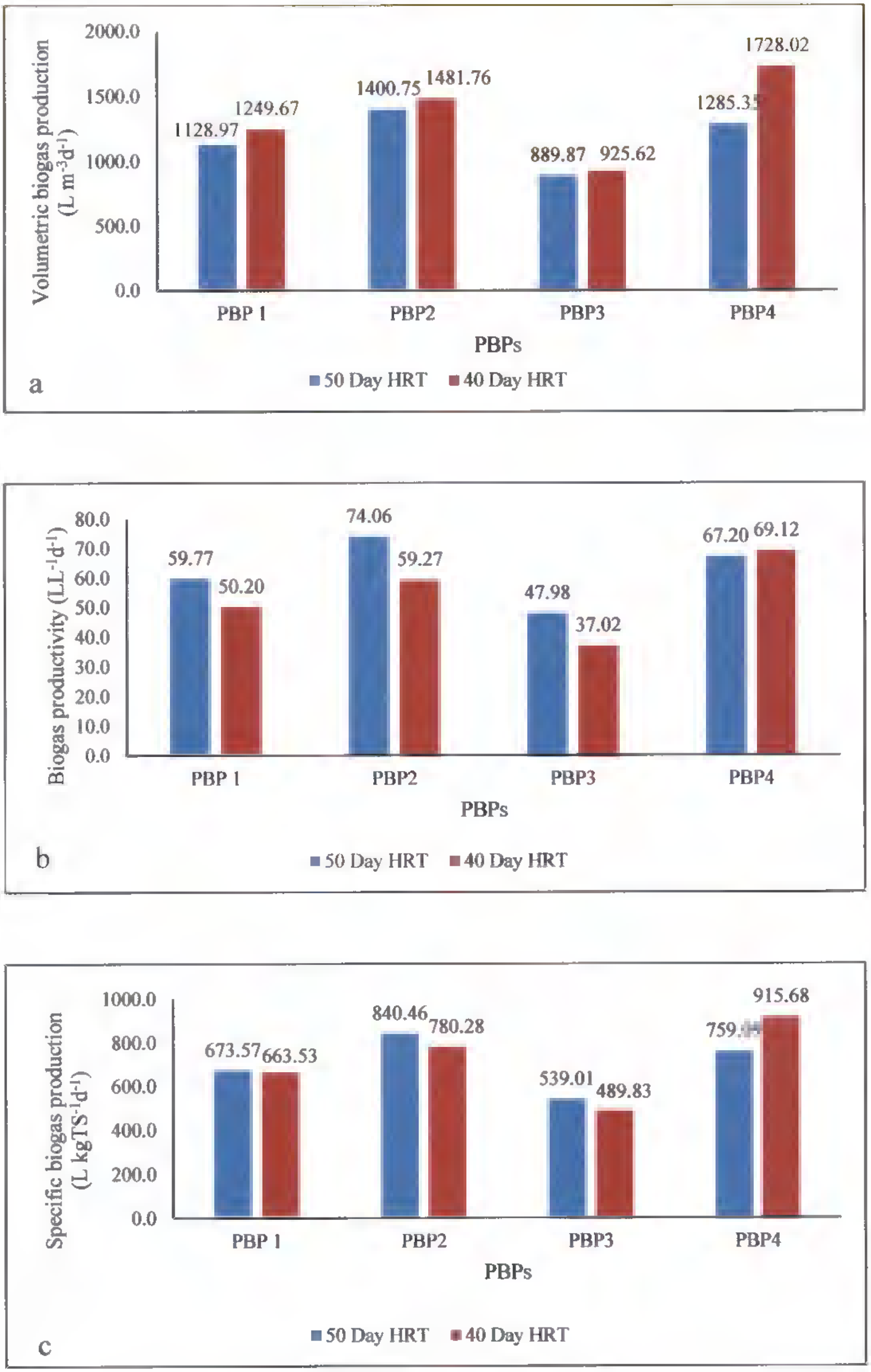


Figure 34. Comparative performance of biogas plants

4.3.5 Variation in loading rates of PBP_s during 40 and 50-day HRT periods

Figure 35 shows the variation of OLR and HLR during the 40 and 50-day HRT periods. HLR for all PBPs was same during both the HRTs and was 24.96 and 19.89 $Lm^{-3}d^{-1}$ of digester volume at 40 and 50-day HRTs, respectively. When the HRT was shortened, HLR as well as OLR increased as there was increase in daily feeding volume.

OLR during the 40-day HRT period (1.94 $kgm^{-3}d^{-1}$) was higher by 5.2 % to that at 50 day HRT period (1.84 $kgm^{-3}d^{-1}$). A similar variation was there in the case of HLR and was 25.5 % higher at 40-day HRT compared to that at 50-day HRT.

4.3.6 Variation of Specific Biogas Production with respect to change in OLR during 40 and 50-day HRT periods

Figure 36 shows the variation of specific biogas production as the OLR was changed when the HRT was shortened from 50 to 40-day. OLR was higher (1.94 $kgm^{-3}d^{-1}$) in 40-day HRT period and specific biogas production in all PBPs except PBP4 was found to decrease in the 40-day HRT period. OLR during the 40- day HRT period was higher by 5.2 % to that of 50-day HRT period. In PBP4, specific biogas production found to be higher at the increased HLR and OLR corresponding to 40-day HRT.

In the study of Singh *et al.*, (1985) the OLR during 36 and 50-day HRTs were 2.38 and 1.70 $kgm^{-3}d^{-1}$, respectively for anaerobic digestion of cattle waste. They obtained a specific biogas production of 0.610 and 0.434 $m^3kgTS^{-} d^{-1}$ in the respective HRT periods. In comparison to these values, specific biogas production in the present study was found to be higher in both the HRTs and registered an increase of 52.82 % in PBP4 at 40 day HRT and 27.38 % in PBP2 at 50 day HRT.

Contrary to the general trends of decrease in specific gas production at the higher HLR and OLR during the shorter HRT period, PBP4 exhibited an increased specific biogas production at 40 –day HRT. This is likely to be due to the better microbial environment created in the PBP4. The reasons attributable to this are the structural and constructional characteristics which were different from all the other

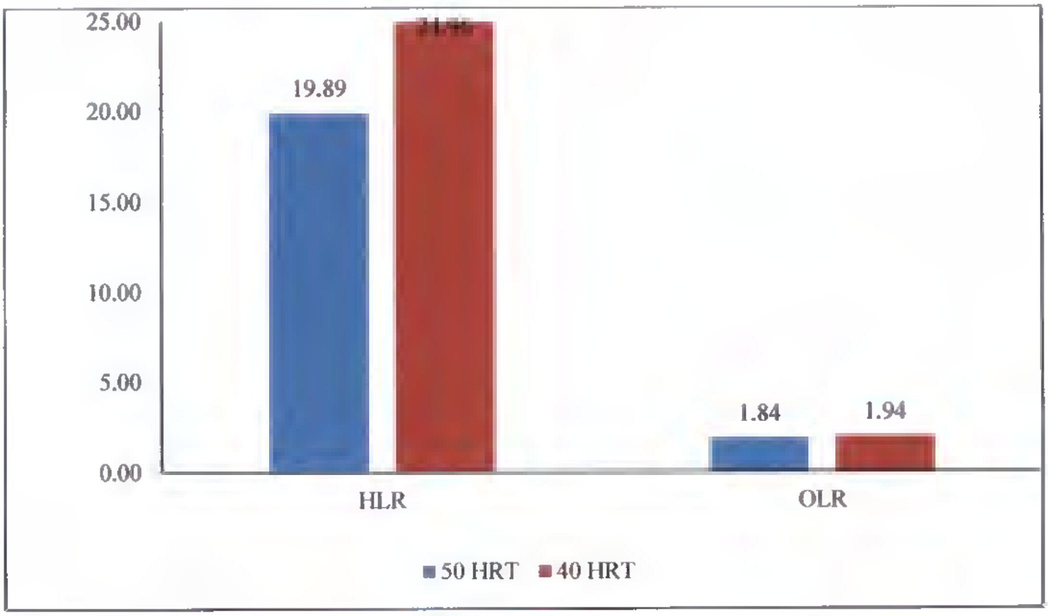


Figure 35. Variation in loading rates of PBPs

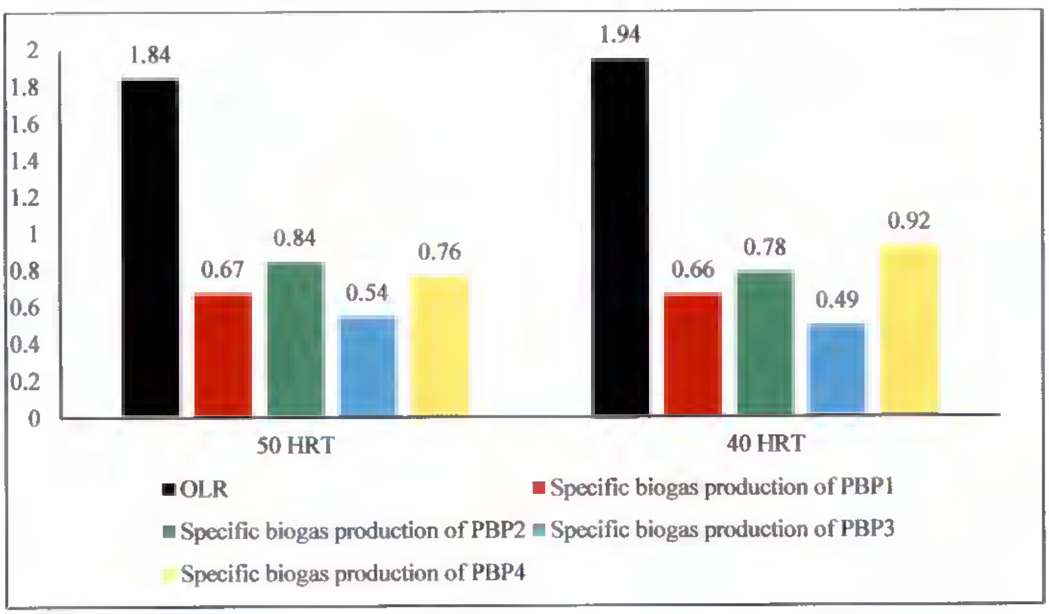


Figure 36. Variation in OLR and specific biogas production

PBPs. The inlet and the outlet of the PBP4 were diagonally opposite so as to prevent chances of short circuiting of the fresh feed. Another important aspect being the presence of a stirring arrangement, which ensured mixing of the digester liquor. It is possible that the operation of the stirrer has also aided indirectly by providing an additional surface for bacterial attachment.

4.3.7 Performance of PBPs when feeding was interrupted

The common problem associated with domestic biogas plants were observed to be interruptions in feeding due to various reasons. Table 20 depicts the salient performance parameters of the four PBPs during such an interruption.

Table 20. Daily volumetric biogas production when feeding was stopped ($Lm^{-3}d^{-1}$)

Day	PBP1	PBP2	PBP3	PBP4
1	1037.34	1114.65	866.38	1582.28
2	879.67	958.60	655.17	1299.58
3	726.14	802.55	482.76	1139.24
4	601.66	566.88	435.34	966.24
5	597.51	528.66	396.55	888.19
6	502.07	480.89	323.28	683.54
7	477.18	410.83	258.62	677.22
8	448.13	382.17	254.31	630.80
9	443.98	375.80	224.14	531.65
10	414.94	347.13	215.52	459.92
11	398.34	343.95	211.21	453.59
12	348.55	286.62	176.72	381.86

Before stopping the feeding, the weekly mean of volumetric biogas production in PBP1, PBP2, PBP3 and PBP4 were 1263.19, 1479.53, 920.57, 1804.70 $Lm^{-3}d^{-1}$ respectively. When the feeding was stopped, on the first day itself reduction in gas production was observed. The reduction in volumetric biogas production were 21.77, 32.73, 6.25, and 14.55 percent in PBP1 and in PBP2, PBP3 and PBP4, respectively. Maximum reduction in biogas production was observed in PBP2 and minimum biogas production was observed in PBP3. At the end of 12th day, percentage of reduction in volumetric biogas production were 72.40, 80.62, 80.80 and 78.84% in PBP1, PBP2, PBP3 and PBP4 respectively. Maximum reduction was observed in PBP3 followed by PBP2 and the reduction was minimum in PBP1.

Volumetric biogas production during the restart of PBPs when feeding was commenced after 12 days are shown in Table 21.

Table 21. Daily volumetric biogas production during the restart of PBPs ($Lm^{-3}d^{-1}$)

Day	PBP1	PBP2	PBP3	PBP4
1	564.32	407.64	323.28	537.97
2	663.90	767.52	556.03	791.14
3	854.77	859.87	693.97	957.81
4	950.21	1022.29	840.52	1149.79
5	1078.84	1121.02	862.07	1502.11
6	1105.81	1245.22	866.38	1740.51
7	1257.26	1423.57	883.62	1820.68
8	1286.31	1436.31	883.62	1835.44
9	1290.46	1496.82	939.66	1837.55
10	1286.31	1503.18	952.59	1845.99

After 12 day break, again the feeding was started. Volumetric biogas production before the starting of feeding were 348.55, 286.62, 176.72 and 381.86 $Lm^{-3}d^{-1}$ in PBP1, PBP2, PBP3 and PBP4 respectively. 60, 41.3, 77.7 and 42%

increase happened in PBP1, PBP2, PBP3 and PBP4 respectively in the 1st day of feeding itself. On 7th day, volumetric biogas production in PBP4 regained its production and PBP1 regained its production on 8th day. PBP2 and PBP3 took 9 days to regain their production. Here PBP4 showed fast response to regaining of biogas volume.

4.3.8 Nutrient content of output slurry

N P K content in the output slurry from PBPs fed on kitchen waste in comparison to a biogas plant fed on cow dung (BPC0) is depicted in Table 22.

Table 22. Comparison of NPK content in slurry

Parameter	BPC0	PBP1	PBP2	PBP3	PB 4
Nitrogen, N (%)	2.9[d]	4.29[a]	4.05[b]	3.54[c]	4.22[a]
Phosphorous, P (%)	1.26[a]	0.6[b]	0.48[c]	0.45[c]	0.64[b]
Potassium, K (%)	0.32[d]	1.3[b]	1.33[b]	1.26[c]	1.37[a]

Nitrogen content was maximum in PBP1 and the nitrogen content in the PBP1 was on par with PBP4. Minimum nitrogen content was observed in the biogas plant slurry working on cow dung. Phosphorous content was maximum in the biogas plant slurry working on cow dung and minimum in PBP3. Potassium content was maximum in PBP4 and minimum in BPC0. Average NPK value of biogas plant slurry working on kitchen waste was calculated as 4.025, 0.54 and 1.315 respectively. Nitrogen and potassium contents were found to be maximum in slurry from kitchen waste fed PBPs compared to the biogas plant fed on cow dung. But, the value of P was lower in the case of kitchen waste slurry. Gupta (1991) found that nitrogen, phosphorous and potassium contents of output slurry from a cow dung fed biogas plant was 1.03, 0.82 and 1.07 % respectively. In the present study NPK contents were much higher and it was found to be 2.9, 1.26 and 0.32% respectively, whereas output slurry from kitchen waste fed PBPs was 4.025, 0.54 and 1.315 % respectively.

4.3.9 Emission reduction potential of Portable Biogas Plants

Household daily kitchen waste generation was estimated as 5.28 kg. When the fraction of organic waste materials with low biodegradability was excluded from the above value, the daily kitchen waste generation was 5.2 kg. Considering this daily rate, the waste generation per annum per household was estimated to be 1898 L. Instead of disposing it openly in the landfills (usual practice), if this quantity of waste is subjected to anaerobic digestion using portable biogas plants, the multiple advantages are prevention of methane emissions from the landfills, production of cheap renewable energy for the household cooking and emission reduction due to reduction in the use of fossil fuels (LPG, Kerosene or other cooking fuels as the case may be).

If we consider that PBP4 with the biogas productivity value of 69.12 $LL^{-1}$is used in the urban households under consideration, 131190 L (131.19 m^3) of biogas can be generated per household per annum. On an average 62% of the biogas is methane and if 70% of this quantity is likely to be produced in land filling, the reduction in respect of methane emission will be 37.71 kg of CH4, which is equivalent to 943 kg of CO_2e.

The emission reduction potential of PBPs are evident from Table 23

Emission from fuel burning was found to be lower compared to the emission from landfilling. When the wastes were openly dumped, annual emissions from 1000 households were calculated as 940 tonnes of CO_2, whereas the average emission due to the fuel burning only accounts 320.53 tonnes of CO_2. It was only 25.37 % of the total emission from 1000 households. So, it's clear that, more than burning of fuels for domestic cooking, open dumping of kitchen wastes creates much more CO_2 emissions. By preventing this, huge amount of CO_2 reduction could be reduced and biogas plants offer an environmentally benign technology for decentralised fuel production and waste management

Table 23. Emission reduction potential of Portable Biogas Plants

Parameters		Single household per annum	Thousand households per annum
Waste generation, L		1898.0	1898000
Biogas production, m^3		131.2	131190
Emission reduction due to prevention of land filling, (tonnes of CO_2)		0.94	943
Equivalent quantity of fuels	Kerosene, L	81.3	81338
	LPG, kg	59.0	59036
	Electricity, kWh	615.9	615937
Emission reduction due to fossil fuel replacement (tonnes of CO_2)	Kerosene	0.22	220.98
	LPG	0.18	180.11
	Electricity	0.56	560.50
*Total emission reduction, (tonnes of CO_2)	Kerosene	1.16	1163.98
	LPG	1.12	1123.11
	Electricity	1.5	1503.5
Mean Emission reduction (tonnes of CO_2)	Due to avoidance of landfill dumping	0.94	943
	Due to fuel replacement	0.32	320.53
	Total	1.26	1263.53

*Assuming that the households use these fuels and they will be replaced by biogas produced from kitchen waste.

Hence it was inferred that by the use of Portable Biogas Plants (PBP4) total emission reductions of 1263.53 tonnes of CO_2e can be achieved per annum for 1000 households in the representative urban area of Kerala.

CHAPTER V

SUMMARY

Management of organic waste is one of the most pressing environmental issues at the present time in most urban and semi-urban areas of the developing world. Unscientific land filling of municipal solid wastes (MSW) is one among the important causes for environmental degradation. The water bodies are being polluted by their leachates, resulting in severe health hazards. Methane emission from such landfills contribute in a big way to global warming as the Global Warming Potential (GWP) of methane is 25 (IPCC, 2007) times that of CO_2.

Biogas technology for conversion of domestic organic waste into a green fuel has a huge scope under this scenario as it can help to reduce the Green House Gas (GHG) emissions with simultaneous pollution reduction. Households constitute the most basic unit in urban energy consumption and waste generation and use of biogas plants helps to reduce both. But, there are limitations for conventional biogas plants in households of densely populated urban and semi urban areas. Portable biogas plants with different designs are getting popular in Kerala. Even though many conventional biogas systems were seen to be evaluated for their performance, such studies are lacking in the case of portable biogas plants. Considering the high relevance of the portable domestic biogas plants, 4 Types of portable biogas plants viz. floating gas holder type without water seal (PBP1), Floating gas holder type with water seal (PBP2), Fixed gas holder type (PBP3) and KAU split biogas plant (PBP4) were assessed.

Preliminary investigations were carried out to assess the domestic kitchen waste generation and laboratory studies were carried out to have an insight into its biomethanation characteristics. The four different portable biogas plants were then subjected to detailed investigations at 40 and 50 days of Hydraulic Retention Times. Gas production, pH of digester liquor, methane content of biogas, and reduction of Total Solids were observed during the period of investigation.

The salient findings are summarized as follows:

- Average TS of kitchen was found as 82 gL^{-1} and the average pH was found as 3.86. Average C: N ratio of the kitchen waste was found as 53.88.
- The mean per capita waste generation in household was estimated to be 1.056 kg $person^{-1}day^{-1}$ and the average organic waste generated per household was 5.28 kg.
- Average organic waste generated in the hostel mess was 24.9 kg and the per capita waste generation was 0.622 $kg^{-1}day^{-1}person^{-1}$.
- Per capita food waste generation in households were found as 42 g and that of hostel mess was 153 g.
- Major portion of the kitchen waste generated in households as well as hostel mess was liquid waste resulting from cooking of rice.
- Biomethanation studies of kitchen waste was used to find out the biogas production potential and at higher substrate concentration, the start-up was not possible due to the low pH resulting in inhibition of methanogenic bacteria.
- Minimum possible ratio between substrate and the inoculum for the start-up of anaerobic digesters using kitchen waste was found to be 1:5.
- During the preliminary batch digestion study, the high gas production was observed in the first week showing that the readily biodegradable fraction of food wastes have already been subjected to acidification and these volatile acids were quickly subjected to methanogenesis. During subsequent period of 31-50 days, the less biodegradable fraction was possibly subjected to microbial action and the gas production was unsteady. During the last period which extended from 51- 90 days, the biogas production dropped to lower values and showed gradual decline and almost stopped at the 90th day.
- The possible biogas productivity of kitchen waste was found as 57.57 LL^{-1}. The average specific biogas production from kitchen waste was estimated as 989.05 L $kgTS^{-1}$.
- It was revealed that 80-90 % of the biogas potential of kitchen waste can be realised within 40-50 days of anaerobic digestion and hence the preferable

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HRT of biogas plants shall be 40-50 days. Average methane content in biogas produced from kitchen waste was found to be 62.18%.

- The pH of the experimental digesters of biomethanation study were found as near to neutral throughout the experimental period.
- An increase in mean volumetric biogas production was observed when the HRT was shortened from 50 to 40-day in all PBPs, the maximum increase being seen in PBP4 (34.4 %) and the minimum (4.0 %) in PBP3. The highest mean volumetric biogas production was recorded in PBP4 at 40-day HRT. This indicated that PBP4 was more suitable for energy production from domestic kitchen waste, which could be operated at a higher gas availability at the shorter HRT of 40-day.
- Maximum biogas productivity (74.06 $LL^{-1}d^{-1}$) during the 50-day HRT period was found in PBP2 and that at 40-day HRT period was found in PBP4 (69.12 $LL^{-1}d^{-1}$). Except in PBP4, all other PBPs showed maximum biogas productivity during the 50-day HRT period. The value of PBP4 at 40-day HRT was 11% higher than the mean value for all PBPs at 50-day HRT.
- Average biogas productivity in all the PBPs during the 40-day HRT period was 53.9 $LL^{-1}d^{-1}$and it was 62.25 $LL^{-1}d^{-1}$ during the 50-day HRT period. It is noteworthy that PBP4 had biogas productivity value higher than the average values even at the short HRT of 40 days.
- Maximum specific biogas production during the 50-day HRT period was found in PBP2 and that of 40-day HRT period was found in PBP4. Except in PBP4, all other PBPs showed maximum specific biogas production during the 50-day HRT period.
- The specific biogas production at 40-day HRT in PBP4 (915.68 L $kgTS^{-1}d^{-1}$) was 30 % and 28.5 % higher than that of the average specific biogas production of all the PBPs at HRTs of 50 and 40 days. Specific biogas production is a true indicator of the energy conversion efficiency of the system and hence the results give a clear testimony to the superiority of PBP4 over the other PBPs. This may be accountable to the stirrer

arrangement and the possible microbial accumulation due to the different configuration.

- Average HLR during the 40-day HRT period was 24.96 $Lm^{-3}d^{-1}$ of digester volume and that of 50-day HRT period was 19.89 $Lm^{-3}d^{-1}$.
- OLR during the 40-day HRT period (1.94 $kgm^{-3}d^{-1}$) was higher by 5.2 % to that at 50-day HRT period (1.84 $kgm^{-3}d^{-1}$). A similar variation was there in the case of HLR and was 25.5 % higher at 40-day HRT compared to that at 50-day HRT.
- When the feeding of kitchen waste was interrupted for 12 days, maximum reduction of volumetric biogas production was observed in PBP3 (80.80 %) followed by PBP2 (80.62 %) and the reduction was minimum in PBP1 (72.40%). When the feeding was restarted after interruption, PBP4 regained its volumetric biogas production faster (7th day) compared to PBP1 (8 days), PBP2 (9 days) and PBP3 (9 days).
- Average N, P and K content of biogas slurry from the biogas plant working on kitchen waste was found as 4.025, 0.54 and 1.315 % respectively, whereas slurry from cow dung fed biogas plant was 2.9, 1.26 and 0.32%, respectively. It is evident that N and K content for kitchen waste fed biogas plant slurry was higher and is ideal for meeting the nutritional requirement of kitchen gardens.
- The overall performance of the KAU Portable Split biogas plant was found to be superior in performance to all other portable biogas plants. Water seal type floating gas holder type plant had a comparable performance with respect to gas production whereas the fixed gas holder type portable biogas plant was found to be inferior.
- By the use of PBPs, a carbon emission reduction of 1263.53 tonnes of CO_2e annum can be achieved for a group of 1000 urban households. It was also evident that Portable Biogas Plants offer significant scope in emission reduction, green energy production and domestic organic waste management.

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ASSESSMENT OF PORTABLE BIOGAS PLANTS FOR THEIR ENERGY PRODUCTION AND EMISSION REDUCTION POTENTIAL

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(2011-20-107)

ABSTRACT OF THE THESIS

Submitted in partial fulfilment of the requirement for the degree

B.Sc.-M.Sc. (Integrated) Climate Change Adaptation

Faculty of Agriculture

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KERALA, INDIA

2016

ABSTRACT

Climate change is one of the serious issues faced currently by humanity. The uncontrolled emission of Green House Gases play a major role in global warming, which eventually leads to climate change. The unscientific methods of waste disposal has serious environmental impacts by continuous emission of GHGs leading to global warming. Households constitute the basic unit in urban energy consumption and waste generation. Anaerobic digestion of the organic fraction of household wastes in a decentralised manner using biogas plants offers great scope in waste management and generation of cheap renewable energy for domestic cooking.

The investigations revealed that average amount of organic waste generated per household was 5.28 kg (5 member family) and that of a hostel mess was 24.9 kg (40 inmates). Kitchen wastes in Kerala had a major fraction as liquids and per capita food waste generation in households and hostel mess were 42 g and 153 g, respectively. Average TS of kitchen waste was found as 82 gL^{-1} and the average pH was found as 3.86. Average C: N ratio of the kitchen waste was found as 53.88:1. The minimum ratio of kitchen waste and inoculum required for a successful start-up of anaerobic system was 1:5. Biogas productivity of kitchen waste was found as 57.57 $LL^{-1}$and the average specific biogas production from kitchen waste was estimated as 989.05 L $kgTS^{-1}$. 80-90 % of the potential of kitchen waste to generate biogas can be utilized if the HRT was in range of 40-50 days. Thus it is preferable to have a HRT in the range of 40-50 days for domestic biogas plants working on kitchen wastes. Average methane content in biogas produced from kitchen waste was enumerated as 62.18%. The preliminary biomethanation studies revealed the high potential of kitchen waste to generate biogas.

Portable biogas plants are easily shifted and installed, require less space and can be placed conveniently in urban conditions. The four types of portable biogas models used in the study were floating gas holder type (PBP1), floating gas holder type with water seal (PBP2), fixed gas holder type (PBP3) and KAU

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portable split biogas plant (PBP4). The four portable biogas plants (PBPs) were evaluated by operating them at 50 and 40 day HRT. An increase in mean volumetric biogas production was observed in 40-day HRT compared to 50 day HRT in all PBPs. The maximum increase in biogas production was in PBP4 (34.4 %) and the minimum increase (4.0 %) was in PBP3. This indicated that PBP4 was more suitable for energy production from domestic kitchen waste, which could be operated at a higher gas volume availability at the shorter HRT of 40-day. The maximum value of mean biogas productivity was exhibited by PBP2 at 50-day HRT followed by PBP4 at 40-day HRT. Even though the values were higher at 50-day HRT for all the other three PBPs, the value of PBP4 at 40-day HRT was 11% higher than the mean value for all PBPs at 50-day HRT. Average biogas productivity in all the PBPs during the 40-day and 50-day HRT periods were 53.9 $LL^{-1}d^{-1}$ and 62.25 $LL^{-1}d^{-1}$, respectively. It was noteworthy that PBP4 had a biogas productivity higher than these average values even at the short HRT of 40 days. The specific biogas production at 40-day HRT in PBP4 was 30 % and 28.5 % higher than that of the average biogas production of all the PBPs at HRTs of 50 and 40 days respectively. Specific biogas production is a true indicator of the energy conversion efficiency of the system and hence the results gave a clear testimony to the superiority of PBP4 over the other PBPs.

When the feeding of kitchen waste was interrupted for 12 days, maximum reduction was observed in PBP3 (80.80 %) followed by PBP2 (80.62 %) and the reduction was minimum in PBP1 (72.40%). When the feeding was restarted, PBP4 regained its biogas production faster (7th day) compared to other plants.

Average N and K content of slurry from kitchen waste fed biogas plant was found to be 4.025 and 1.315 % respectively, which was notably higher than that from cow dung fed plant. However the P content (0.54) was lower in kitchen waste fed plant.

From the study it was inferred that by the use of Portable Biogas Plants (PBP4) total emission reductions of 1263.53 tonnes of CO_2e can be achieved per annum for 1000 households in the representative urban area of Kerala.