BIOGAS PRODUCTION FOR SUSTAINABLE ENERGY GENERATION IN RURAL HIMACHAL PRADESH USING ONE-STAGE PORTABLE DIGESTER

THESIS

Submitted in fulfillment of the requirement for the Degree of

DOCTOR OF PHILOSOPHY

By

ANKUR CHOUDHARY

DEPARTMENT OF CIVIL ENGINEERING

JAYPEE UNIVERSITY OF

INFORMATION TECHNOLOGY,

WAKNAGHAT, HP, INDIA

AUGUST, 2020

Ph.D. ANKUR CHOUDHARY JUIT, WAKNAGHAT 2020

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Dedicated to almighty God, my family, and my supervisors

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DECLARATION BY THE SCHOLAR

I hereby declare that the work reported in the Ph.D. thesis entitled **“Biogas Production for Sustainable Energy Generation in Rural Himachal Pradesh using One-stage Portable Digester”** submitted at the Jaypee University of Information Technology, Waknaghat, Solan (HP), India is an authentic record of my work carried out under the supervision of **Prof. Ashish Kumar** and **Prof. Sudhir Kumar**. I have not submitted this work elsewhere for any other degree or diploma. I am fully responsible for the contents of my Ph.D. thesis.

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SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled **"Biogas Production for Sustainable Energy Generation in Rural Himachal Pradesh using One-stage Portable Digester",** submitted by **Ankur Choudhary** at the **Jaypee University of Information Technology, Waknaghat, Solan (HP), India** is a bonafide record of his original work carried out under my supervision. This work has not been submitted elsewhere for any other degree or diploma.

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Ankur Choudhary

ABSTRACT

Municipal solid waste (MSW), electronic waste, biomedical waste, and hazardous waste are different types of solid waste (SW). MSW is a major part of SW. A latest published report by central pollution control board (CPCB) reveals that urban population in India generates around 135,198 tonnes of MSW every day. Further, this is anticipated that generation of MSW is expected to escalate in future. According to a report from the CPCB, the number of cities and towns has increased from 5,161 to 7,936 from 2001 to 2011[1]. Along with the rapid economic growth, industrialization, population, living standard, and lifestyle of inhabitants of India have also improved and therefore, resulting in a gigantic amount MSW every day [2]. Proper disposal of MSW is a big challenge for almost all municipalities of the cities and towns due to a lack of awareness and funds. Dry or wet any kind of biodegradable substrate can be utilized via anaerobic digestion, it can occur either on the landfill or it can be performed in the anaerobic reactor generally known as an anaerobic reactor or biogas plant. Food Waste (FW) is a significant fraction of MSW and generally it constitutes approximately 35% of total MSW. During AD of FW apart from carbon dioxide (CO_2), emission of methane (CH_4), hydrogen sulfide (H_2S), and other gases take place. Alone CO_2 and CH_4 constitute approximately 90%. Both gases are greenhouse gases and CH_4 has 31 times more global warming potential (GWP) when compared with CO_2. FW also contributes substantially to GHG emissions if it is simply open dumped. An extensive literature reveals that, apart from sanitary landfills with landfill gas (LFG) mechanism, it can also be managed with the help of composting, combustion/incineration, and through AD in bio-reactors. Although, all the methods are capable of reducing the load on the landfills. AD in bioreactors has proven to be most efficient in terms of energy generation and curtailment of GHG emissions, capital investment (*CI*), and operation and maintenance costs (*O&MC*).

AD is a very complex biochemical process and its efficiency depends on several factors such as the substrate characterization, ambient temperature, type of reactor, the organic loading rate (OLR) during the process, *etc*. [3], [4]. Many studies are available in the literature on AD of food waste as substrate [5]–[18]. Ammonia, which is the end-product of anaerobic digestion, plays a major role in the performance and stability of the anaerobic digestion process. Optimal ammonia concentration ensures sufficient buffer capacity for the methanogenic medium, especially for nitrogen-rich organic feedstock. However, excess ammonia concentration is usually reported as the fundamental cause of digester failure when it exceeds the inhibition threshold levels.

Few of the studies related to the effect of variation of temperature on AD of FW and other substrates are available in the literature. Few studies related to the effect of variation of OLR on AD of FW and other substrates are performed by various researchers [19]–[24]. However, no study is available on optimization of organic loading rate of AD of FW and kinetics of a pilot-scale anaerobic continuous reactor at an ambient temperature range in the hilly terrain of North India. Similarly, no work has been reported so far on Techno-economic and environmental feasibility of food waste-based anaerobic digestion at psychro-tolerant and low mesophilic temperature and state-wise energy potential of MSW in India. The present study was focused on these aspects keeping in mind. Experimental work was focused on the feasibility aspect and optimization of the organic loading rate of the anaerobic digestion of food waste. Besides the optimization of OLR, techno-economic feasibility, and ecological aspects of this process in comparison to open dumping and composting were also evaluated. An attempt has also been made to estimate the energy and global warming potential of MSW of states of India.

To assess the feasibility of the AD process, experiments were performed at Jaypee University of Information Technology (JUIT), HP, India. A pilot-scale anaerobic reactor with capacity 3,000 L was used. Leftover food waste was used as a substrate and it was collected from the food mess of JUIT. The study was conducted for 324 days including winter and summer season at ambient temperature condition. The Characterization of the FW revealed that moisture content (MC) of the food waste varied from 67.5 to 86.7%, VS/TS varied 42 to 89.1% and C/N varied 8.7-14.9. The pH, partial alkalinity, total alkalinity, and VFA/alkalinity ratio of the effluent slurry of the reactor was monitored regularly to check the stability of the process. The AD process was noticed to be stable during the entire experiment. The maximum value of alkalinity of the system was found as 1,186 $CaCO_3$ mg/L however lowest value was noticed as 546.7 $CaCO_3$ mg/L, respectively and total VFA ranged 371.9-1,040 mg/L. At the end of the experiment, a total of 65,270 L biogas and 38,461L CH_4 produced. The kinetic aspect was studied with help of First order Kinetic Model (FOM), Modified Gompertz Modeld (MGM), Reaction Curve type Model (RCM) and Modified Logistic Function (MLF). For optimization of the process, experiments were conducted for 235 days and maximum OLR in summer and winter was achieved as 0.34 and 0.21 g VS/L/day respectively. As well, in the same interval CH_4, CO_2 and H_2S were reported 57.93%, 38.84%, and 608.8 ppm, respectively. Destruction of VS and BOD_5 was achieved 93.578%, and 61.88, respectively. Besides, the VFA/Total Alkalinity ratio was found 0.314 and total alkalinity was found 2,357 mg/L which indicated a stable AD. The hydrolysis rate constant '*k*', was determined from the First order Kinetic model with the help of non-linear regression.

The recalcitrance of biomass is mainly constructed by its chemical compositions. Generally, the factors affecting the accessibility of biomass can be divided into direct and indirect factors. Pre-treatment is the process to alter indirect factors and improve direct factors thus enhancing the accessibility of cellulose. It has been found that the factors affecting the enzymatic hydrolysis biomass include lignin, hemicelluloses, and acetyl group contents, cellulose crystallinity, degree of polymerization, specific surface area, pore-volume, and particle size.

On this basis of the optimized organic loading rate, the economic and ecological feasibility study of the food waste-based anaerobic digestion process was also conducted for all northern hilly states. It is estimated that capital investment in such a process will return in 5.9 years with an *IRR* of 4.6%. Besides a shorter PBT, successful implementation of the AD process for the next ten years in these hilly states will curtail 93.4% and 89% GWP from AD and composting, respectively when compared to landfill.

The data of state-wise MSW generation was taken from CPCB 2015 [25], [26] for computation of municipal solid waste energy and global warming potential of India**.** The year 2015 is assumed as the base year and computations for energy and global warming potential of India are carried out for the next 25 years. If the MSW of India is managed with a gas collection mechanism then 1,387 MW of energy can be conserved in 2040. Besides, the revenue of 877million USD can be generated via carbon credit from carbon reduction. The results of the present study will be helpful for researchers and industries who want to work in the field of AD at low mesophilic and psychrophilic temperatures conditions.

LIST OF ABBREVIATIONS

AD: Anaerobic Digestion

AnMBR: Anaerobic Submerged Membrane Bioreactor

BAU: Business-as-usual

BES: Bio-electrochemical Systems

BOD_5: Five-day Biochemical Oxygen Demand

C/N: Carbon to Nitrogen ratio

CH_4: Methane

CI: Capital Investment

CO_2: Carbon-di-Oxide

COD: Chemical Oxygen Demand

COD_t: Total Chemical Oxygen Demand

CPCB: Central Pollution Control Board

CVT: Continuously Varied Ambient Temperature

EGSB-AF: Expanded Granular Sludge Bed-Anaerobic Filter

EW: Electronic Waste

FOM: First-order kinetic model

FS: Fixed Solids

FW: Food waste

GDP: Gross Domestic Product

GHG: Greenhouse Gas

GWP: Global Warming Potential

HRT: Hydraulic Retention Time

HW: Hazardous Waste

INR: Indian National Rupees

IRR: Internal Rate of Return

KVIC: Khadi Village Industries Commission

LFG: Landfill Gas

LPG: Liquid Petroleum Gas

MC: Moisture Content

MGM: Modified Gompertz Model

MLF: Modified type of Logistic Function

MNRE: Ministry of Renewable Energy

MSL: Mean Sea Level

MSW: Municipal Solid Waste

MSWM: Municipal Solid Waste Management

MT: Million Tone

NCF: Net Cash Flow

NEERI: National Environmental Engineering Research Institute

NPV: Net Present Value

NRER: Non-Renewable Energy Resources

O &MC: Operation and Maintenance Cost

OLR: Organic Loading Rate

PBT: Payback Time

PPP: Purchasing Power Parity

RCM: Reaction Curve Type Model

RER: Renewable Energy Resources

SBR: Sequencing Batch Reactor

SCOD: Soluble Chemical Oxygen Demand

SW: Solid Waste

TKN: Total Kjeldahl Nitrogen

TPD: Tonnes per day

TPY: Tonnes per year

TS: Total Solids

TSS: Total Suspended Solid

UASB: Up Flow Anaerobic Sludge Blanket Reactor

VFA: Volatile fatty acids

VS: Volatile Solids

WtE: Waste to Energy

LIST OF SYMBOLS

P_0	Cumulative Methane production (L/g VS)
K	Hydrolysis Rate Constant (day^{-1})
P	Maximum Biogas yield (L/g VS)
R_m	Maximum specific biogas production rate (L/g VS/d)
λ	Lag phase (days)
C_t	Expected net annual cash flow (INR)
r	Discount rate (% per year)
A	CH_4 production/year (Mg/year),
y	Year of waste disposal
b	Beginning year of inventory
Q_x	Waste quantity (Mg)
L_0	CH_4 production potential (m^3/Mg)
C	CO_2 emissions (Mg/yr)
G	Fraction by volume of the CH_4 in landfill gas
SOX	Soil oxidation fraction
F_{CO2}	CO_2 emissions (Mg/yr)
$GF_{compost}$	CO_2 emission factor for composted material (Kg CO_2/kg dry solids)
n	Index for the waste material or bulk agent
N	Total number of the different waste materials added to the composting process,
$L_{compost}$	Annual mass of the material n added (wet basis)
V_n	Total solid content of the material n when added or fed to the compost (dry solids/kg wet solids)
D_{CH_4}	CH_4 emissions (Mg/ yr) for composted material
$WF_{Compost,CH_4}$	CH_4 emission factor for composted material (kg CH_4/Kg wet waste)
$P_{compost}$	Annual mass of material added or fed to the composting process (Mg/year, wet basis)
X_{N_2O}	Emissions (Mg/yr),
$LF_{compost_{N_2O}}$	emission factor for composted material (Kg/kg wet waste),
$R_{compost}$	al mass of material added or fed to the composting process (Mg/year)

MSW_t	Total waste generated in the year
MSW_f	Fraction of total waste which is disposed on the landfill
MCF	CH_4 correction factor
DOC	Degradable organic carbon
DOC_f	Fraction of DOC dissimilated
F	Fraction of CH_4 in total landfill gas
R	Recovered CH_4
OX	Oxidation factor
A_{CH_4}	Methane production per year in the year of the calculation (Mg/y
i	Increment in time (1 year)
m	(calculation year) - (initial year of waste dumping)
p	0.1 year time increment
N_i	Mass of waste accepted in the i^{th} year (Mg)
X_{ip}	Age of the j^{th} section of waste mass M_i accepted in the i^{th} year

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CHAPTER - 1

INTRODUCTION

~ The key to growth is the introduction of higher dimensions of consciousness into our awareness.

- Lao Tzu

CHAPTER-1
INTRODUCTION

1.1 Municipal Solid Waste

In ancient times, communities used to live in harmony with nature, and hence generation of solid waste (SW) was insignificant. While in the last several decades, the living patterns of people all across the globe have changed a lot. We are exploiting the natural resources for our comfort. As a result, the amount and pattern of consumption of material and goods have increased tremendously which further affected and increased the generation of SW. Besides, explosive growth in population, unrestricted, and unmonitored urbanization in the last few decades have also increased the waste generation several folds. The unattended SW has a massive adverse impact on the environment and needs to be managed. Irrespective of developed or developing countries, due to various problems the management of SW has always been a challenging task for almost every municipality across the globe.

Various anthropogenic activities at household, commercial, agricultural and industrial level results in SW and it is generally organic and inorganic. Based on the composition and source of the generation in nature, SW can also be classified into biomedical waste, municipal solid waste (MSW), hazardous waste, and electronic waste. Solid waste is a source of considerable pollution if not managed or disposed of illegitimately. Unlike developed countries, developing countries are witnessing more growth in urbanization and economy and therefore more likely to face problems associated with SW.

MSW is a major part of SW. The definition of MSW is not identical and therefore varies country wise across the globe. However, in India, it is generally called garbage or trash and generates from households, offices, hotels, restaurants, markets, commercial complexes, and institutes, *etc*. It primarily constitutes of packaging, durable and non-durable goods, garden waste, and kitchen waste which can be solid and semi-solid. Table 1.1 shows the various categories of MSW along with its description and source of generation.

Table 1.1 Classification of Municipal Solid Waste constitutes

MSW categories	Description of waste	Source
Food waste	Waste generated during the preparation or cooking of food and leftover food. Waste generated from storage, handling, and sale of vegetables and food products, crop residues, *etc*.	Households, hotels, restaurants, vegetable markets, stores, *etc*.
Rubbish	Newspaper, cardboard, leather, rubber waste, plastic material, wooden cartons, plant waste (grass leaves and yard trimmings), cloth waste, *etc*.	Household, packaging industry and plantation
Bulky waste	Waste from home appliances such as refrigerator, stoves, furniture, large wooden waste including crates, tree stump, branches, *etc*.	Households, parks, automobile industry, wood industry
Street waste	Dirt and dust from street sweepings, animal droppings, and plantation waste (leaves, *etc*.).	Streets and road
Dead Animal	Pets including cats, dogs, and horses, poultry animals (hen and chickens), buffalos, cows, calf, *etc*.	Street and house
Construction and demolition waste	Cement and concrete waste, plaster waste, roofing and	Home and building construction sites and building

	shedding scrapes, wires, pipes, insulation waste, *etc*.	demolition, repairing, and remodeling sites.
Industrial waste and sludge	Waste generated from industrial activities (manufacturing process, processing, *etc*.), scraps from metal, wood and plastic industries, waste from the sewage treatment plant	Manufacturing industries, processing units of factories, sewage treatment plants, *etc*.
Hazardous	Toxic and hazardous waste: waste from pathological assays, radioactive waste material, *etc*.	The medical institution, industries, *etc*.

Source: [27]

1.2 Management of Municipal Solid Waste

Municipal solid waste management (MSWM) system comprises of collection, transportation, recycling, suitable waste processing, and disposal to the sanitary landfills. The inefficient and unenvironment-friendly management of MSW has been a gigantic problem throughout the world. It is a huge challenge for even developed countries. Inevitably, insufficient funds and a lack of skilled manpower for efficient waste management have been a great concern for almost every developing country. In India also, due to the above-mentioned reasons, a significant amount of waste is directly being dumped openly on the free land without any treatment [28]– [33]. On the other hand, MSWM in developed countries differs in various aspects e.g., source segregation, suitable waste processing technology, and only inert and non-recyclable waste is being dumped on the landfills.

In the process of deciding a suitable waste processing technology, the waste composition is a vital factor. Therefore, needs to be investigated precisely. Various common waste processing technologies are composting, incineration, combustion, anaerobic digestion (AD), *etc*. However, all the technologies have their advantages and disadvantages in terms of economy and impact on the environment.

Inevitably, ineffective MSWM can put adverse impacts on the regional, local, and global levels and can be seen as global warming, climate change, and environmental degradation. In India, the most popular way to dispose of the MSW is in landfills. It is an integral part of any MSWM system [34], [35] because of its economic viability. Landfills can be either sanitary or unsanitary. There are only 179 sanitary landfills available in India and about 1,285 sanitary landfills are identified for construction by various urban local bodies [36]. The unsanitary landfill or open dump does not constitute a gas collection mechanism and it also does not prevent the percolation of leachate into the groundwater, thus polluting the water resource and deteriorating air quality. Therefore, unsanitary landfills are a huge threat to the environment.

1.3 Urbanization, Generation of MSW and its composition in India

India is growing as one of the fastest economies in the world. India's economy has overtaken the United Kingdom. In terms of gross domestic product (GDP) India is the sixth-biggest economy after the United States of America, China, Japan, Germany, and France [37]. Along with the India is second-most populous country. Lack of opportunities in the rural areas, education, proper sanitation, basic amenities, low profit from agriculture to the high-income possibility in the urban areas led the migration from the rural area to cities and thus rapid growth in urbanization [38]. Therefore, this can be stated that India is turning from an agricultural nation to service and industry-oriented country [1].

According to a report from the central pollution control board (CPCB), the number of cities and towns has increased from 5,161 to 7,936 from 2001 to 2011[25]. Hence, MSW is likely to increase massively in the coming time [28]. Along with the rapid economic growth and industrialization, the population, living standard, and lifestyle of inhabitants of India have also improved and therefore, resulting in a gigantic amount MSW every day [2].

The National Action Plan for MSW management 2015 stated that India produces approximately 135,197 TPD out of which 82% of the total waste is collected and only 27% is processed due to various challenges mainly due to lack of funds [25]. In India, approximately 51.5 MT of MSW was generated in 2015 while 55.4 MT of MSW was generated during 2019

[26], [39]. Table 1.2 represents the land required for the Disposal of MSW generated in the respective durations.

Table 1.2: Area of land required for unsanitary disposal of Municipal Solid Waste generation in India

Years	**Area of land occupied/required for MSW disposal (Km^2)**	**City equivalent (area wise)**
1947-2001	240	50% of Mumbai
1947-2011	380	90% of Chennai
1947-2021	590	Hyderabad
2009-2047	1,400	Hyderabad, Mumbai, and Chennai

Source: [40]

In this context, according to business-as-usual, approximately 240 Km^2 (area nearly equivalent to half of the Mumbai city) land was required in 2001 for open dumping. Besides, in 2011 this requirement reached up to 380 Km^2 (an area nearly equivalent to 90% of the Chennai city), and it is anticipated that this requirement will be 590 Km^2 (an area nearly equivalent to Hyderabad city) by the end of 2021. Also, Ministry of Finance has estimated land requirement and stated that if the current MSW handling practices do not change the land requirement would be 1,400 Km^2 by the end of 2047 which is nearly equivalent to combine area of one of the largest cities of India *i.e.*, Hyderabad, Mumbai and Chennai [40]. So, if the existing scenario does not change, the land requirement for open dumping will continue to increase in the future. There is a prompt need to manage the waste in such a manner that at least one of the fractions can be reused, recycled and another fraction must be utilized in waste to energy (WtE) facilities and rest which neither can be reused, recycled and nor can be utilized in WtE must be disposed of in a sanitary landfill. According to a report published by National Environmental Engineering Research Institute (NEERI), 40-60% of the MSW in India is biodegradable; 10-30% recyclable and 30- 50% is inert. A region-wise and temporal variation in the composition of MSW is shown in Table 1.3 and 1.4, respectively which indicates that a fraction of biodegradable waste is nearly 50% of MSW.

Table 1.3: Region wise MSW composition in India

Region/City	MSW (Mt/day)	Compostable (%)	Recyclable (%)	Inert (%)	Moisture (%)	Calorific value (Kcal/Kg)
Metros	51,402	50.89	16.28	32.82	46	1,523
Other cities	2,723	51.91	19.23	28.86	49	2,084
East India	380	50.41	21.44	28.15	46	2,341
North India	6,835	52.38	16.78	30.85	49	1,623
South India	2,343	53.41	17.02	29.57	51	1,827
West India	380	50.41	21.44	28.15	46	2,341
Overall urban India	130,000	51.30	17.48	31.21	47	1,751

Source: [41]; Metro Cities: According to Census Commission, any city having a population of more than 4 million.

Table 1.4: Temporal variation in MSW composition in India

	MSW composition (%)							
Year	**Biodegradable**	**Paper**	**Rubber**	**Metal**	**Glass**	**Rags**	**Other**	**Inert**
1996	42.21	3.63	0.60	0.49	0.60	Nil	Nil	45.13
2005	47.43	8.13	9.22	0.50	1.01	4.49	4.01	25.16
2011	52.32	13.8	7.89	1.49	0.93	1.00	-	22.57

Source: [1]

Hence a large fraction of MSW is a biodegradable waste. It generally consists of 0.64-0.80% nitrogen (N), 0.15-0.67% phosphorus (P), and 0.68-0.15% potassium (K) and has carbon to nitrogen (C/N) ratio of 26.5 [1], [30]. From the characterization of MSW, it can be seen that MSW in India has a good potential in anaerobic digestion (one of the WtE process). Across the country, there are twelve WtE plants out of which six are working and rest five plants are not functioning properly due to lack of technical expertise and high-water content of the substrate [25]. Dry as well as wet kind of substrate can be utilized via AD, it can occur either on the landfill or it can be performed in the anaerobic reactor and generally known as a biogas plant.

Based on a report, only 645 small scale anaerobic reactors are operated across India, out of which 600 are located in the state of Kerela only [36]. A report by the Ministry of Renewable Energy (MNRE) has revealed that the MSW in India has a potential of energy generation and it should be harness [42].

1.4 Food waste

From the literature survey, it is evident that FW is an enormous fraction in MSW (about 35%) and generally generated from various sources of households, restaurants, hotels, cafes, commercial complexes, institutions, and industries [43]–[50]. In Asian countries, the FW is anticipated to increase in the coming 25 years due to rapid growth in economy and population. It can increase from 278 to 416 MT from 2005 to 2025 [51]. Because the FW is an integral part of the MSW, it is incinerated, composted or openly dumped which may further lead to serious environmental problems such as contamination of groundwater, greenhouse gas (GHG) emissions, *etc* [15], [21]–[25]

The global carbon footprint of FW is estimated to be about 3.3 billion t of CO_2 every year. Generally, FW consists of comparatively higher moisture content (MC) than any other fraction of MSW and hence its incineration causes a release of dioxins [57] which further creates several problems to the environment. Apart from this, one of the main disadvantages of incineration is the loss of nutrients and hence reduces the economic value of the process. Similarly, composting has several issues. Therefore, AD is one of the appropriate technologies to manage FW [58].

Certainly, source separation of MFW is a huge issue in front of every municipality. However, in India, ‘Segregation at source’ is now increasingly practiced in households. Segregation at the source of the biodegradable (mainly kitchen and garden waste) and non-biodegradable components of household waste is recommended by Municipal Solid Waste (Management and Handling) Rules, 2000 so that the high organic content of wet waste can be used for waste to energy technologies. Therefore, the introduction of segregation of biodegradable waste from the non-biodegradable portion at the household level and storage in different containers (used plastic bins or buckets) is important.

Separation of the biodegradable components of waste will allow anaerobic digestion and other waste treatment methods and prevent this waste fraction from going to a landfill. Thus, source separation of MFW will divert organics from the waste stream, leading to cost savings associated with reduced storage, transport, and ultimate disposal requirements.

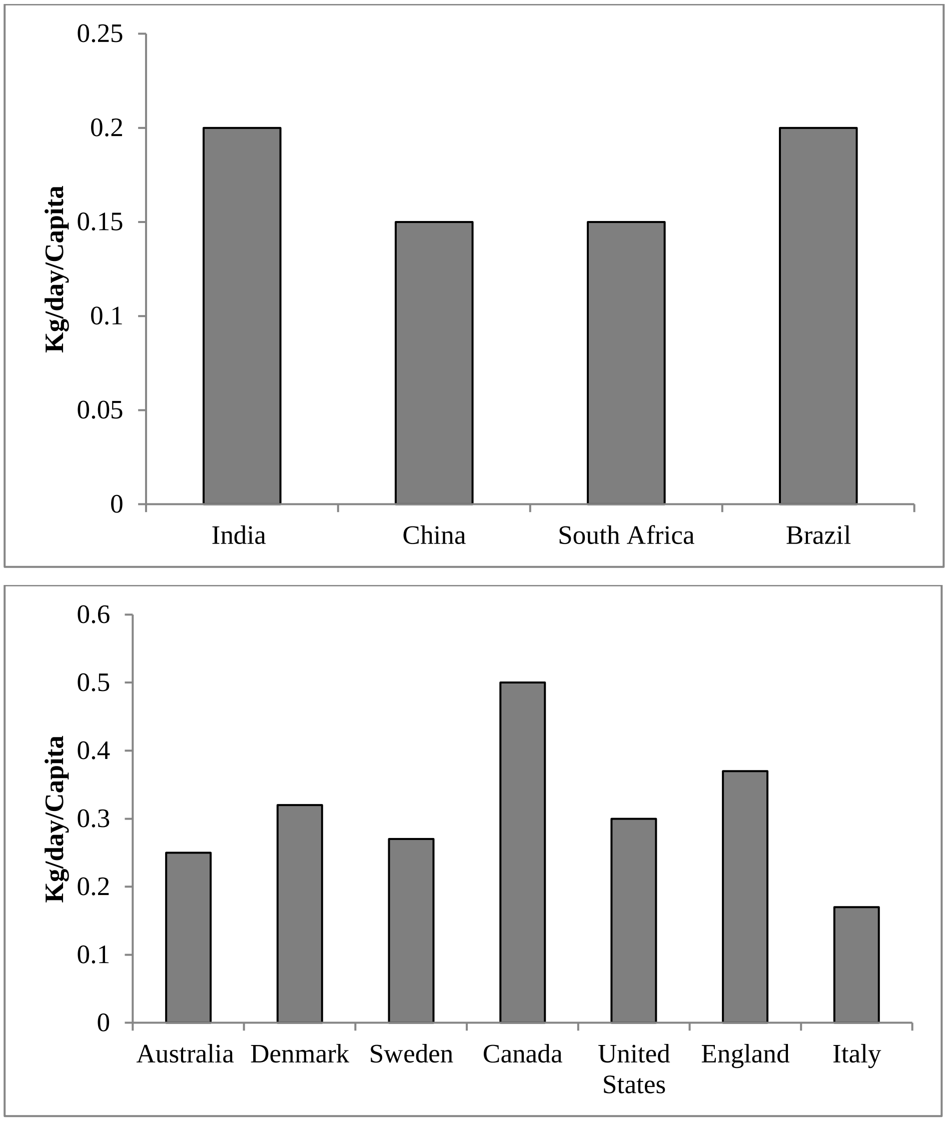


Figure 1.1: Daily food waste generation in various countries across the globe (2009-2013)

Source: [45]

AD has been an alluring option to reinforce any nation's energy quest by generating CH_4 and nutrient recycling. Various researchers have already quantified the FW [59], [60] which is shown below in Figure 1.1 and 1.2. The FW is a good substrate for AD and it has substantial energy potential. Several researchers have determined its energy potential at different temperatures which are discussed in coming section. Primarily, FW consists of proteins, carbohydrates, lipids and a significantly lesser amount of inorganic fraction. However, this composition may vary as per type of FW.

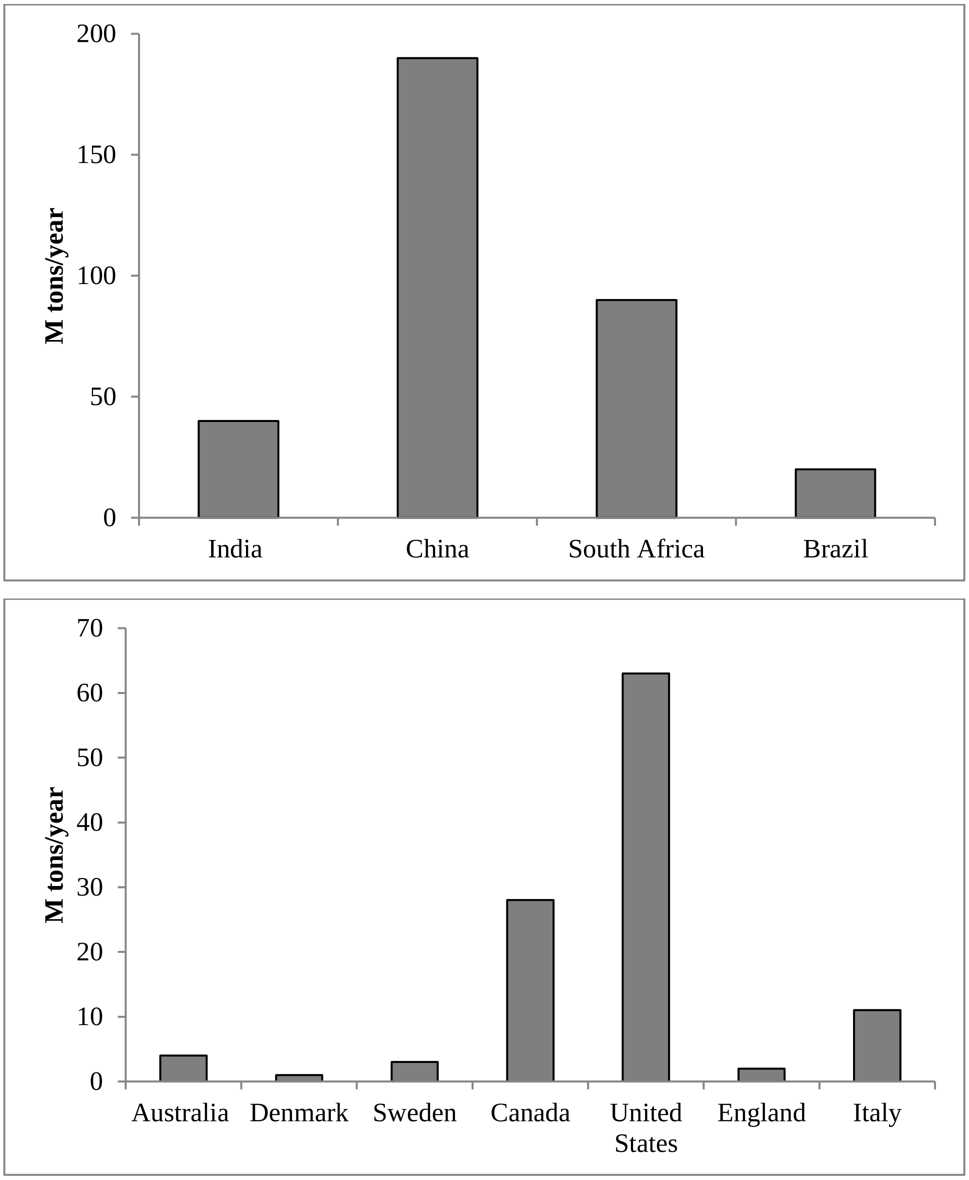


Figure 1.2: Food waste generation in various countries across the globe (2009-2013)

Source: [45]

1.5 Process of anaerobic digestion

AD consists generally of four phases, namely, hydrolysis, acid formation *i.e.*, acidogenesis, and formation of acetic acid *i.e.*, acetogenesis and methanogenesis *i.e.*, the gas production phase; Figure 1.3 illustrates the digestion process.

1.5.1 Hydrolysis

In the first phase, large molecules (polymers) that cannot be carried to the cell membranes by the microorganisms are degraded by hydrolytic bacteria. This process is known as hydrolysis.

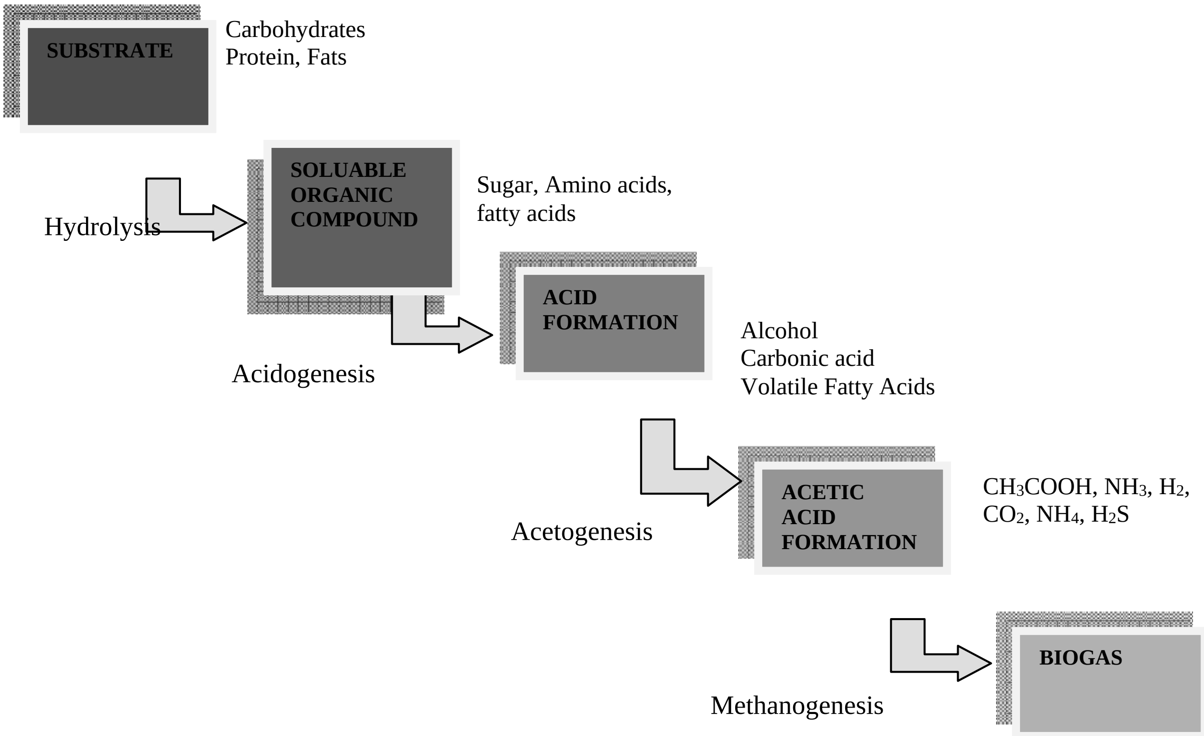


Figure 1.3: Process of Anaerobic Digestion

During the hydrolysis, polymers are degraded into the oligomer or monomeric units; polysaccharides are degraded into oligosaccharides and monosaccharides, e.g., carbohydrates are broken down into sugars, protein into amino acids and peptides and fats/lipids are converted into fatty acids and glycerol (Eq. 1.1)

$$nC_6H_{10}O_5 + nH_2O \rightarrow nC_6H_{12}O_6 \quad (1.1)$$

Hydrolysis rate is comparatively slower than that of acid formation rate during anaerobic digestion and decisively depends upon the pH, temperature, bacterial concentration, type of the substrate, and configuration of bioreactor [61].

1.5.2 Acidogenesis Phase

In this phase, the byproducts of the hydrolysis phase are converted into CO_2, hydrogen (H_2) and ammonia (NH_3). Along with these gases volatile fatty acids (VFA) such as propionate, acetate, valerate, butyrate, and isobutyrate are formed. In this phase, facultative anaerobic bacteria consume oxygen (O_2) and carbon and therefore stabilize anaerobic state for methanogenesis. The monomers produced in the first phase *i.e.* sugars, amino acids, peptides, and fatty acids and glycerol are converted into organic acids by a group of bacteria.

1.5.3 Acetogenesis

The byproducts from the acidogenesis phase are converted into acetate and H_2 by genera Syntrophomonas and Syntrophobacter [62]. Acetates produced during this phase are utilized by methanogens in the next step. Although, H_2 generated during this phase exerts the inhibitory effect on microorganisms

Therefore, in anaerobic reactors, acetogenic bacteria live in syntrophic relationship with hydrogenotrophic methanogens that remove the hydrogen by utilizing it for methane formation.

$$nC_6H_{12}O_6 \rightarrow 3nCH_3COOH \tag{1.2}$$

1.5.4 Methanogenesis

In AD, the last phase is methanogenesis which is carried out by methanogens belonging to Archaea. In this phase, the CH_4 has generally produced either due to reduction of CO_2 or by the degradation of acetic acid. Thus, byproducts of the acetogenesis and acidogenesis phases act as a precursor for the generation of CH_4. 30% of the total CH_4 produced in this phase is originating CO_2 only [63], [64].

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{1.3}$$

In fact, in the methanogenesis phase, CH_4 is generated via 2 types of methanogens*i.e.* acetoclastic methanogens and hydrogenotrophic methanogens. Acetoclastic methanogens use acetic acid while hydrogenotrophic methanogens use CO_2 in the process of CH_4 formation

$$CO_2 + 4H_2 \rightarrow CH_4 + 3H_2O \tag{1.4}$$

In a recent review, Paritosh et al. (2017) has reviewed food waste as a substrate for anaerobic digestion. They have also reviewed microbial communities involved in the anaerobic digestion of food waste.

For single-phase and two-phase anaerobic digestion of food waste, they found a predominance of Firmicutes and greater bacterial diversity in two-phase continuous stirred tank reactor that led to 23% higher methane yield in comparison to single-phase anaerobic digestion.

Methanosaeta dominated the archaeal community of both single-phase and two-phase reactors [45]. Cho et al. [47] investigated methanogenic community during dry anaerobic digestion of food waste and observed a significant reduction in methanogen diversity after acclimation to dry AD. Almost all sequences obtained from dry anaerobic digester sludge belonged to *Methanosarcina* genus reported to be more tolerant to sudden change in pH and use both acetoclastic and hydrogenotrophic pathways, which make them more suitable for surviving in comparison to *Methanosaeta*. Gou et al. [70] investigated effect of temperature and organic loading rate on microbial community of food waste anaerobic digestion and found significant effect of temperature on the richness of microbial community which was more diverse at 35℃ in comparison to 45∘ and 55℃. At 55℃ only 5 species remain abundant that explains that thermophilic bacteria are more sensitive towards temperature variation.

1.6 Factor affecting process of AD

Optimum production of CH_4 in AD depends upon stable and high metabolic activity. Methanogens are very sensitive to various primary variables such as the source of inoculums, type of substrate, organic loading rate (OLR), carbon/nitrogen (C/N) ratio, temperature *i.e.*, thermophilic, mesophilic or psychrophilic, pH, volatile fatty acid (VFA) concentration, hydraulic retention time (HRT), alkalinity and nutrient concentration [65].

1.6.1 Inoculum

Inoculum may increase the stabilization rate towards AD. Digested sewage sludge, leachate, landfill soil, and dung slurry are generally used as a source of inoculum for the AD. In literature, it is also reported that goat rumen can also be used as inoculum for optimum stabilization of the anaerobic environment and digestion process [45].

1.6.2 Temperature

Temperature plays an important role in the AD process. There are three different temperature ranges defined as psychrophilic (<20°C), mesophilic (20-45°C), and thermophilic (45-60°C) in the process of AD [66]. Methanogens perform efficiently at mesophilic (35°C) to thermophilic temperatures (55°C).

Because during the methanogenesis phase acetic acid and CO_2 are converted into CH_4 by anaerobic microbes at a certain temperature and they are very sensitive to the same. An optimum range for efficient AD process is reported 35-40°C for mesophilic and 50-65°C for thermophilic AD [67], [68].

Bouallagui *et al.* (2004) reported a relation between temperature and methane content and found 58, 65, and 62% CH_4 at 20, 35, and 55°C, respectively [69]. Similarly, Kim *et al.* (2006) reported 57 and 59% CH_4 content at 35 and 55°C, respectively and 65.6, 66.2, 67.4, and 58.9% of CH_4 at temperatures 40, 45, 50, and 55°C, respectively [8]. Gou *et al.* (2014) also studied the effect of temperature on biogas production. They found the highest biogas production at 55°C which was 1.6 and 1.3 times more than that biogas produced at 35 and 45°C, respectively [70].

1.6.3 C/N ratio

Along with inoculums, temperature, and pH, C/N is a highly important parameter. Mittal (1996) [71] reported that C/N should lie between 25-30:1 for an optimum AD. This is attributed to the fact that microbes utilize ‘C’, 25-30 times faster when compared to ‘N’. If the ratio is not maintained, consequently ‘N’ would exhaust too early and ‘C’ still would remain in the system that will lead to the death of microorganisms. On the other hand, if ‘N’ is too high and ‘C’ is too less: the lack of food for the microorganisms and ammonia formation will inhibit the digestion process. The C/N varies with different substrates. For optimum C/N, co-digestion is generally suggested. In a study co-digestion of dairy manure, chicken manure and wheat straw led to a C/N ratio of 27.2 which further increased the methane yield as well [72]. Zeshan *et al.* (2012) also reported a stable AD a C/N ratio of 27[73]. While an appropriate amount of ‘C’ has shown a positive effect on avoided excessive ammonia inhibition [45].

1.6.4 pH

The pH is a primary and vital parameter in AD. The microbial activity and optimum AD decisively depend upon the pH. During the AD, the pH should not deviate significantly from near-neutral pH. The optimum pH range for an efficient AD is reported 6.3-7.8 [72].

It is also reported that in the very initial days of the AD due to the presence of CO_2 the pH of the systems drops up to 6.2. However, thereafter it starts rising and reach up to 7 and 8. In another study, Lee *et al.* (2009) reported the optimum pH range between 6.5 to 8.2 while digesting FW leachate [74]. Inevitably, pH in the anaerobic bioreactor is governed by VFA and alkalinity. Goel *et al.* (2003) reported that a low pH in any AD can be stabilized by adding NaOH and $NaHCO_3$ during bio methanation [75].

1.6.5 Volatile Fatty Acids

Many researchers have found strong pieces of evidence that excess production and accumulation of VFA during the AD can slow down or inhibit the AD and hence less or no biogas production [76], [77]. Therefore, there VFA should be monitored at regular intervals to make sure an efficient AD process. Accumulation of VFA drops down the pH in the system which ultimately hinders or inhibits the methanogens. A high concentration of un-dissociated acids can penetrate the cell membranes and may damage macromolecules by penetrating them. Substrate like FW may result in more VFA production when compared to wastewater during the AD process. In an optimum AD process the VFA may range < 2,000-3,000 mg/L [45].

1.6.6 Organic Loading Rate

Organic loading rate can be defined rate of the amount of substrate fed per unit volume of the reactor. The decision of an appropriate OLR is very important. An underestimation of OLR may result in less biogas generation and hence less energy which corresponds to less economic viability. Whereas, overestimation of OLR may result in inhibition of the AD process due to VFA accumulation. OLR may vary with the nature of the substrates and temperature. A complex substrate and lower temperature will have lower OLR and a rapidly digestible substrate with higher temperatures will have a higher OLR.

Therefore, based on the nature of the substrate and temperature during the AD process, the optimization of OLR has great importance. Agyeman and Tao (2014) co- digested FW with dairy manure at an OLR of 1 to 2 g VS/L/d and reported an increase of 101-116% in specific CH_4 yield.

However, when the OLR is increased to 2 to 3g VS/L/d the specific methane yield is increased to25-38% only [5]. The maximum specific CH_4 yield was reported at an OLR of 2 g VS/L/d. In this study, FW was also co-digested with activated sewage sludge at thermophilic and mesophilic temperatures. The thermophilic temperature has supported the maximum OLR (7 g VS/L/d), however, systems at mesophilic temperatures have shown the best process stabilities at relatively lower OLRs [78]–[80].

1.6.7 Anaerobic Reactors

The process of biomethanation is performed in a reactor generally known as a bioreactor or anaerobic reactor. Generally, researchers have used two types of anaerobic reactors *i.e.*, single-stage and two-stage reactors. Further, these can be classified into a solid-state, wet, semi-solid state, up-flow solid-state, and hybrid reactors. When all the processes names as hydrolysis, acidogenesis, acetogenesis, and methanogenesis perform simultaneously in a single reactor generally known as Single-stage anaerobic reactor [81]. While on the other hand when hydrolysis and acidogenesis perform is one vessel and acetogenesis and methanogenesis perform in another vessel it is known as two-stage anaerobic reactors [82]. Both types of reactors their advantages and disadvantages in terms of process efficiency and economic process feasibility [82].

The different types of anaerobic digester used to generate bio-methane are as follows: Fixed Dome Biogas Plants, Floating Drum Plants, Low-Cost Polyethylene Tube Digester, Balloon Plants, Horizontal Plants, Earth-pit Plants and Ferro-cement Plants.

1.7 Present State of Knowledge

Several investigations are available in the literature on the utilization of various types of substrates such as FW, wheat straw, rice Husk, animal manure, sewage waste, *etc*. in AD for the production of biogas.

The process of AD depends upon various factors such as pH, alkalinity, organic loading rate (OLR), carbon/nitrogen (C/N) ratio, temperature *i.e.* thermophilic, mesophilic or psychrophilic, pH, volatile fatty acid (VFA) concentration, hydraulic retention time (HRT), *etc*. [5], [8], [45], [66]–[80].

As a result, a large number of experimental studies have been conducted on these factors affecting anaerobic digestion using different substrates [83]–[88]. A few studies are also available on energy and global warming potential and ecological aspects of MSW [89]–[94]. The present study however focuses on the utilization of FW as substrate. A brief review of anaerobic digestion of FW as a substrate at varying conditions is presented here. The detailed review however is presented in chapter 2.

1.7.1 Food Waste as a substrate in Anaerobic Digestion

There are clear shreds of evidence available in the literature that FW can be utilized in the AD process for energy generation and nutrient recovery. FW can be managed via AD and CH_4 is a valuable byproduct of this biochemical process. In comparison to the other treatment methods, it needs less capital investment and has lesser residual waste production [95], [96]. Several studies are available in the literature on AD of food waste as substrate [5]–[18]. Viturtia *et al.* (1989) investigated a two-stage AD of FW and achieved a CH_4 yield of 530 mL/g VS with a volatile solids (VS) reduction of 95.1% [12]. Similarly, in a study conducted by Lee *et al.* (1999), FW was subjected to continuous anaerobic digestion and resulted in a CH_4 yield of 440 mL/g VS and a VS reduction of 70% [97]. Gunaseelan (2004) has investigated around 54 types of FW and reported their CH_4 yield and it varied in the range of 180-732 mL/g VS [6]. Cho *et al.* (1995) examined the CH_4 potential of Korean FW and it was found approximately 472 mL/g VS [47]. Yong *et al.* (2015) utilized canteen waste with straw in a ratio of 5:1 and reported a CH_4 yield of 392 mL/g VS [15]. Therefore, FW as a substrate has a huge potential to generate CH_4 when compared to other conventional substrates such as animal dung, whey, corn silage, and so on [98].

Few of the studies related to the effect of variation of temperature on AD of FW and other substrates are performed by Angelidaki and Ahring (1994); Bouallagui *et al.* (2004); El-Mashad *et al.* (2004); Kim *et al.* (2017); Lianhua *et al.* (2010); Puhakka *et al.* (1988); Sánchez *et al.* (2000); Sun *et al.* (2016); Wilson *et al.* (2008); Zhang *et al.* (2015). [66], [69], [99]–[106]. Angelidaki and Ahring (1994) have studied the effect of temperature (40-64°C) on AD of cattle dung.

They observed poor performance of the process during various combinations of temperatures. Zhang *et al.* (2015) examined the effect of temperature on the removal efficiency of antibiotic removal gene by anaerobic digestion of activated sewage sludge at mesophilic and thermophilic temperatures. Kim *et al.* (2017) have studied the effect of ambient temperature over the AD of FW. They have concluded that temperature is one of the most crucial parameters during AD process. In their study, they have compared the performance of AD at mesophilic and thermophilic temperatures. They concluded that the system had successfully run at an OLR of 6.7 g COD/L/d however it failed while running at OLR of 5.0g COD/L/d at thermophilic temperature. Few studies related to the effect of variation of OLR on AD of FW and other substrates are performed by Dhar *et al.* (2016); Ganidi *et al.* (2011); González-Fernández *et al.* (2013); Liu *et al.* (2012); Menardo *et al.* (2011); Sánchez *et al.* (2005) [19]–[24]. González-Fernández *et al.* (2013) have investigated the effect of OLR on the AD of one of the microalgae. They have reported that CH_4 yield has increased significantly when OLR has been increased from 1 to 2.5 g COD/L/d. Liu *et al.* (2012) studied the effect of OLR on AD of MSW and waste activated sludge in a pilot-scale reactor. They have reported that the reactor has successfully run at 1.2-8.0 Kg VS/L/d however when OLR was increased further 8.0 Kg VS/L/d the reactor has gone in acidic phase. Menardo *et al.* (2011) studied the effect of OLR on AD of the digestate of a pilot-scale plant. They have also reported that OLR has a significant role during the AD process. In developing countries like India, the most common way to manage the FW is open dumping. In a few places, it is also experienced that composting is also being practiced. In the case of open dumping, the FW undergoes the natural AD. Consequently, emissions of GHG take place which further leads to global warming and climate change. On the other hand, though composting has several advantages nevertheless one of the main disadvantages is GHG emissions during the process. Therefore, this study proposes that the management of FW should be done with the help of AD in a reactor.

However, apart from the economic feasibility of any waste management method the decision of most suitable waste management methods should be made keeping the view in mind that by which method not only WtE conversion can be achieved but also curtailment of GHG emissions is performed. Therefore, the economic and ecological feasibility of the proposed process is also performed in this study.

1.8 Objectives of the Study

The present study was taken up to fulfill the above-mentioned gaps in knowledge on the AD process of FW at psychrophilic and mesophilic temperature range using one stage biogas reactor at variable temperatures. The broad objective of the investigation was to conduct a carefully controlled set of experiments for deriving a better understanding of the AD process under variable temperature conditions in a pilot-scale anaerobic continuous reactor.

The following main objectives are stipulated for the present study:

1. Feasibility of a pilot-scale anaerobic continuous reactor (food waste-based) at psychrotolerant and low mesophilic temperature.
2. Optimization of organic loading rate, hydraulic retention time, and kinetics of a pilot- scale anaerobic continuous reactor (food waste-based) at an ambient temperature range in hilly terrain.
3. Techno-economic and environmental feasibility of food waste-based anaerobic digestion at psychro-tolerant and low mesophilic temperature.
4. To determine the state-wise energy potential of MSW in India.

1.9 Limitation of the Study

a. Experimental study is based on MSW specially kitchen waste (cooked food waste).

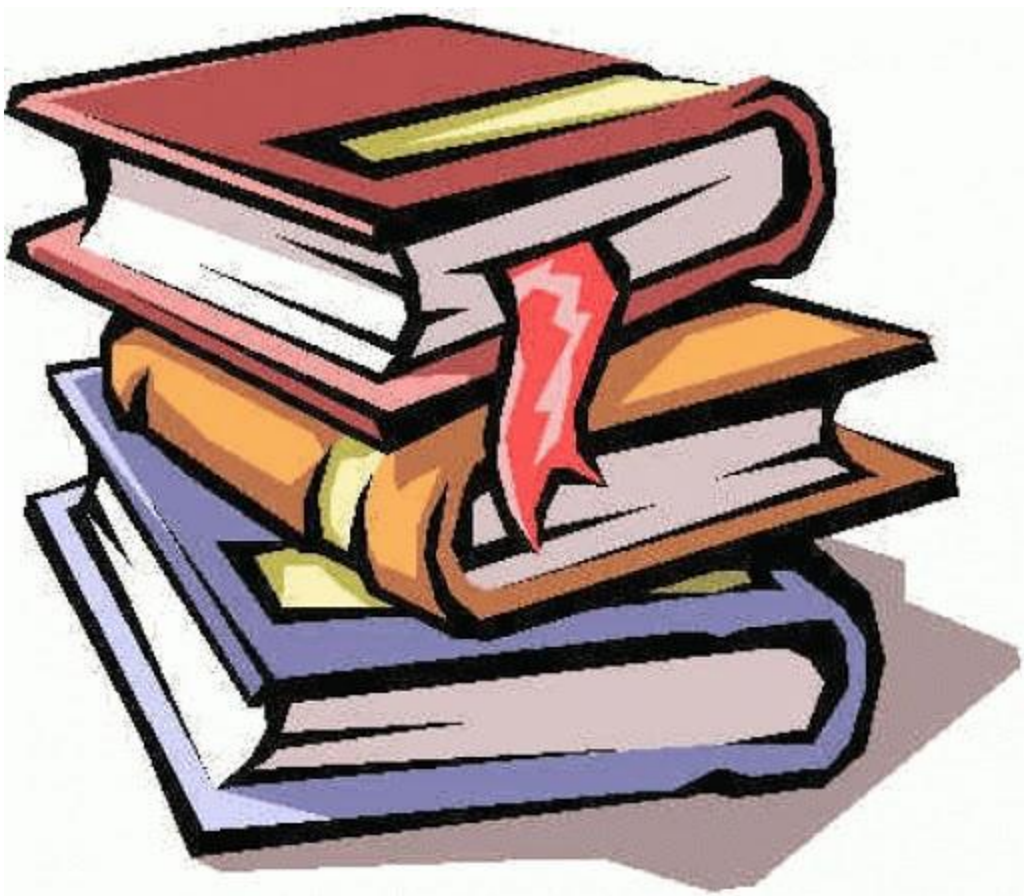
b. Experimental study has been conducted with the volatile solid ranging from 11.84 to 21.17%.

c. One stage anaerobic reactor has been used in the present study, due to the simplicity in design, cost effectiveness and easy applicability. Routine monitoring of pH, and VFA/Alkalinity ratio is required.

d. Experimental study has been conducted at variable ambient temperature conditions and it affects the biogas production as indicated in the present work.

CHAPTER - 2

Literature Review



~ Great literature is simply language charged with meaning to the utmost possible degree.

- Ezra Pound

CHAPTER 2
LITERATURE REVIEW

2.1 General

As of now, in the previous chapter, we have discussed that MSW is a huge concern in front of every developed and developing country [107]–[110]. Inevitably, a significant fraction of the MSW is FW [111]–[114] which should be managed in an engineered manner by the municipal authorities [115]–[117]. If municipalities fail to manage the FW scientifically it may impose a potential threat to the environment in the form of ground, surface water contamination, and air pollution [118]–[121]. The FW can be managed via various scientific methods such as landfilling, combustion, paralysis, composting, and AD [122]–[131]. Landfilling, combustion, pyrolysis, and composting have severed/moderate negatives impacts on the environment when compared to AD [132], [133]. However, AD is one of the most suitable technology to manage FW [14] environment friendly manner. Besides, AD opens opportunities for generating revenue, therefore, it is an eye-catching technology for investors and decision makers [134]–[136]. AD is a very complex biochemical process and its efficiency depends on several factors such as the substrate characterization, temperature, type of reactor, the organic loading rate during the process, *etc.* [4], [137]. This chapter primarily discusses the literature of characterization of FW, AD of FW, temperature, reactors, organic loading in various reactors and temperatures. Besides, the kinetic and ecological aspects of AD have also been discussed in this chapter.

2.2 Review of Literature

2.2.1 Characteristics of FW

The process stability and efficiency are decisively dependent upon the physical and chemical composition of the FW selected for the CH_4 generation [138]. The moisture content (MC), C/N ratio, and VS/TS ratio are one of the basic physical and chemical composition and should be considered during designing and operating of any AD process [139].

The composition of FW may vary concerning the place. Characterization of food waste in various countries across the globe is shown in Table 2.1. For example, Han and Shin (2014);

Kwon and Lee (2004); Shin *et al.* (2004); Kim *et al.* (2004) determined the composition of FW in Korea. They reported that Korean FW has a MC in the range of 90-93%, the VS/TS ratio lies in the range of 94-96% and C/N ratio lies in the range of 14.7-18.3 [139]–[142]. Nordberg, A., Edstrom, M (1997) studied the composition of the German FW from mixed municipal sources, the MC was approximately 90%, the VS/TS ratio was 80% [143]. Steffen *et al.* (1998) studied the Australian FW from mixed municipal sources, the FW consisted of 74% MC and the VS/TS was reported 90-97% [144]. Rao and Singh (2004) studied Indian FW, it comprised 85% of MC, the VS/TS was reported 89% and the C/N was reported 36.4 [145]. A detailed characterization of various types of FW leftovers is also discussed in a book written by Miller and Clesceri (2003) [146]. In the reported literature it can be noticed that the MC in FW varies from 74-90%, VS/TS vary in the range of 90-97% and C/N ratio varies in the range of 14.7-36.6. Because of the reason, it consists of high moisture content, bioconversion technologies (such as AD) are more suitable when compared to thermo-chemical conversion technologies (such as combustion and paralysis) to manage the FW [139].

Table 2.1: Characterization of food waste in various countries across the globe

Source	**Characteristics**			
	MC (%)	**VS/TS (%)**	**C/N**	**Country**
A dining hall	80-93	94-96	14.7-18.3	Korea
Mixed municipal source	90	80	-	Germany
Mixed municipal source	74	90-97	-	Australia
Fruit and vegetable market, household and juices centers	85	89	36.4	India

Source: [139]–[143], [145], [147]

Table2.2: Volatile and total solid fraction in Food Waste

Parameter			
TS (wt %)	20.5	30.9±0.1	18.1±0.6
MC (wt %)	79.5	69.1	81.9
VS (wt %)	19.5	26.4±0.1	17.1±0.6
VS/TS ratio	0.95	0.85	0.94±0.01
References	[147]	[139]	[17]

2.2.2 Food waste as a substrate and its Anaerobic mono-digestion

Based on the literature reported in the earlier section of this chapter it can be concluded that FW has great volatile potential. Along with it has substantial volatile potential, the MC and C/N ratio makes it a more suitable feed to utilize in the anaerobic bioreactor. Earlier the AD of FW is extensively studied and reported by various researchers across the globe. Findings of the few studies are reported below:

Banks *et al.* (2011) utilized FW as a substrate in AD. This study reported the composition of the FW and stated that FW is a substrate with high VS and TS, hence high biodegradability. They have also reported that FW has low pH, N, and substantial C/N. In their study, they concluded that mono-digestion of FW has several process limitations and therefore the process had either long HRT or low OLR. Besides, the OLR should be kept below 2.5 g VS/L/d to make sure a long-term stable and efficient biogas production [148]. Zhang *et al.* (2014) reviewed various types of food wastes and found that the composition of FW varies geographically and seasonally. Besides, they reported the bio-methane potential of FW in the range of 0.440-0.480 m^3/Kg VS [16]. Agyeman and Tao (2014) reported that in comparison to other substrates FW has higher bio-methane potential [5]. Wang *et al.* (2014) reported that FW has high biodegradability and high volatile solid destruction during AD and hence high bio-methane potential. They also reported that FW has various other advantages which primarily include nominal collection and transportation cost, therefore, lower operational cost [149]. Dhar *et al.* (2016) concluded that though FW has good bio-methane potential. During their study, the maximum bio-methane potential was reported 168 mL/g VS. [19]. Tampio *et al.* (2014) segregated FW from the bio- waste digestion plant in the United Kingdom and utilized it in AD.

They have reported TS and VS 247.5 g/Kg and 229.9 g/Kg, respectively, the VS/TS ratio was reported 92.8%, the pH of FW was reported 4.96. The bio-methane potential was reported at 0.501 m^3/Kg VS [150]. Bankas *et al.* (2012) utilized source segregated kitchen waste in the UK. The TS and VS were reported 27.7 and 24.4%, respectively, the VS/TS was reported 88.09%. They reported a bio- methane potential of 0.642 m^3/Kg VS and CH_4 content was reported 62% [151]. Brown and Murphy (2013) utilized university canteen FW in Ireland, the biomethane potential was reported
0.529 m^3/Kg VS [112]. Garcia-Peña *et al.* (2011) collected FW from the central food distribution market in Mexico. The TS and VS were reported 98.9% and 96.4 g/Kg, respectively with pH equivalent to 4.02. The bio-methane potential was reported at 0.529 m^3/Kg VS [152]. Jabeen *et al.* (2015) collected FW from a university canteen in Pakistan and utilized it in AD. The bio-methane potential was reported at 0.446 m^3/Kg VS [153]. Yan *et al.* (2016) utilized kitchen waste in China and reported TS and VS as 40.0 and 39.2%, respectively. The VS/TS ratio was reported 98.5% while the bio-methane potential was reported 0.270 m^3/Kg VS [154]. Yong *et al.* (2015) collected FW from a University canteen and reported TS and VS as 20.05 and 19.86%, respectively. The C/N was reported 28.4, while the pH of the FW was reported in the range of 7.0 to 7.3 Li and Jin (2015) [155], Zhai *et al.* (2015**)** [156], Chen *et al.* (2014) [157], Wang *et al*. (2014) [149], Sun *et al.* (2014) [158], Sheng *et al.* (2014) [159], Zhang *et al.* (2013) [160], Wu *et al.* (2016) [161], Kawai *et al.* (2014) [162], Ventura *et al.* (2014) [163] reported biomethane potential of 0.606, 0.859, 0.326, 0.7, 0.267, 0.314, 0.347, 0.60, 0.435, 0.44 m^3/Kg VS, respectively.

2.2.3 Temperature and Anaerobic Digestion of Food Waste

Amongst the enormous number of factors temperature is one of the very important factors which can preside over the whole AD process [66], [101], [164]–[168]. It is reported that mostly the biogas plants are operated at mesophilic temperatures (30–40 °C) [100], [169]–[171] however relatively lesser studies are reported at thermophilic temperatures (50–60 °C) [172]–
[174] and very fewer are reported at hyper-thermophilic temperatures (65–75 °C) [175]–[177]. However, in comparison to the mesophilic and thermophilic significantly fewer biogas plants are installed at low mesophilic or psychrophilic temperatures. [178]–[181]. The process at all the above-mentioned temperatures has its advantages and disadvantages. For example, at higher

temperatures, rapid hydrolysis, reduced odor, and destructions of pathogens occur. Fermentation processes at mesophilic temperatures require less energy and less vulnerable to shock loss when compared to higher temperatures. Furthermore, generally, under mesophilic conditions, there is a very diverse microbial population is expected which can degrade various types of substrates [100]. Further an extensive literature review of AD of FW at various temperatures is discussed below:

Banks *et al.* (2011) utilized FW at an OLR of 2.5 Kg VS/m^3/d in a continuous anaerobic reactor at constant 42°C temperatures. They reported a stable digestion process and CH_4 yield of 0.642 m^3/ Kg VS with a CH_4 content of 62% [148]. Browne and Murphy (2013) utilized FW in batch BMP assays at 37°C, reported CH_4 yield of 0.467, 0.433 and 0.429 m^3/ Kg VS under various experimental conditions [112], Sheng *et al.* (2013) utilized canteen FW in batch reactors at 35°C, reported a CH_4 yield of 0.315 m^3/ Kg VS [159]. Ventura *et al.* (2014) collected FW from a waste recycling facility operated at 36±1°C and 55±1°C at an OLR of 4.5 g COD/L/d. In this study, the AD was performed in a two-stage anaerobic reactor. They concluded that methanogens performed better than that of acidogens under thermophilic environment. Besides, an increase in the pH was also reported when the temperature was elevated. This study reported a CH_4 yield of 0.44 m^3/ Kg VS under both temperatures' conditions [163]. Tampio *et al.* (2014) performed AD of FW in a semi-continuous reactor under mesophilic conditions (37°C). The digestion was performed at an OLR of 3 Kg VS/m^3/d. The FW was autoclaved at 160 °C before the AD however it resulted in a reduction of 12.4% in the biogas yield. They reported a CH_4 yield of 0.483 m^3/ Kg VS however CH_4 content was reported 58% [150]. Kawai *et al.* (2014) treated FW in a batch reactor at an OLR of 0.33 g VS substrate/ g VS inoculums under mesophilic temperature conditions (37°C). They reported a CH_4 yield of 0.435 m^3/ Kg VS with a CH_4 content of 40% [162]. Li and Jin (2015) used canteen FW in the AD process under mesophilic conditions and reported a biogas yield of 1.2 m^3 biogas/Kg VS (with a CH_4 content of 74.92%) after a pre-treatment at 120°C for 50 min (35°C) [155]. Yong *et al.* (2015) [15]. Grimberg *et al.* (2015) treated canteen FW from a university using a single and two-stage anaerobic reactor under mesophilic conditions (37.4°C). A two-stage anaerobic reactor reported a better CH_4 yield when compared to the single-stage anaerobic reactor *i.e.*, 0.380 and 0.446 m^3/ Kg VS, respectively. However, both types of reactors reported approximately the same CH_4 potential in the biogas *i.e.*, 58.6 and 59 m^3/ Kg VS for the single and two-stage reactors, respectively.

Surprisingly, both types of reactors produced similar effluent in terms of COD and VS [182]. Wu *et al.* (2016) collected dining hall FW from an institute and co-digested with de- oiled grease trap waste treated in single-stage and two-stage continuous stirred tank reactor (CSTR) under mesophilic (35°C) and thermophilic conditions (55°C). Co-digestion has increased the methane yield by up to 19%. A two-stage co-digestion with recycling yielded a CH_4 potential of 1.2 m^3/ Kg VS [161]. Rajagopal *et al.* 2017 reported that in cold climate regions (Canada and United states in their case) mesophilic and thermophilic anaerobic reactors have a huge limitation that they require a significant amount of energy to maintain temperature during the digestion process [183]. Therefore, the process feasibility of various substrates in cold climate regions is needed to be studied. However, Rajagopal *et al.* (2013a) [184] and Massé *et al.* (2014) [185] reported a successful sequencing batch reactor feasibility of animal manure and excess ammonia containing substrates in the psychrophilic environment. Rajagopal *et al.* 2017 also reported that there is very confined literature are available on AD of various substrates below 35°C [183]. Table 2.3 shows a few of the literature available related to the AD of various substrates below 35°C *i.e.*, below mesophilic and at psychrophilic temperatures.

Table 2.3: Various operation parameters of Anaerobic Digestion process at low mesophilic or psychrophilic temperatures

Reference	Substrate	Reactor type	T (°C)	OLR Or VLR	VS, COD or BOD (%)	CH_4 (%)	Study period
[186]	Municipal Waste Water	AnMBR UASB Pilot Scale	18 ± 2ºC	2–2.5 kg COD_t/m^3d	87 ± 1% (COD_t)	80-83%	3 year
[187]	Municipal wastewater treatment	Pilot-scale AnMBR (350 L)	35°C 20°C	0.6 to 1.1 g COD/L d At 35 ºC 0.5 to 0.9 g COD/L d at 20 ºC	90%(COD) for both the temperature	88%	100 days
[188]	Swine manure	Batch (41 L)	17°C	4 g COD/L	71.4±1.9% (TS) 79.9	69.2 ± 4.2%	28 days

					±1.5%(SCOD) 77.3±1.3% (VS)		
[189]	Guinea pig manure	Tubular digester (10 m^3)	CVT (14 to 23°C)	(0.6 kg VS /m^3/ d)	22.08 % (VS/TS)	Approximately 65%	7 months
[190]	Dairy manure fibre	Batch (6 L)	22°C	0.4-2.0 g VS/L/d	NR	73.6%	120 days
[191]	Domestic waste water	AnMBR (10L)	35°C 15°C	NR	94 ± 2%, at 35°C ≥80% at 15°C 94-90 % (COD_t)	NR	209
[192]	Cow feces and wheat straw	Batch digestion (40 L)	20°C	350.5 g VS	87.77% (TS)	71.69%	113 days
[193]	brewery effluent	EGSB-AF (3.381 L)	15°C 37°C	NR	85-93% COD	57.8-74.4%	194 days
[194]	Animal manure and highland barley straw	Batch (0.52 L)	35°C and 15°C	NR	28.65% at 35°C 31.77% at 15°C	76% (±3%) at 15˚C and 66% (±2%) at 35˚C,	90 days for psychrophilic 29 days for mesophilic
[195]	Food waste and cow manure	SBR	20°C	0.8-4.2 kg VS/m^3/d	—	64-69%	228 days
[196]	Domestic waste water	AnMBR (7L)	15°C	440 and 660 mg COD/(L d)	92±5% COD removal	NR	350 days
[197]	Food waste	SBR (1.1 L)	19.8 ± 2.9°C	Up to 2-6.0 kg COD/m^3/d	76-83% COD	NR	80 days
[198]	Swine carcasses and swine manure	SBR (42 L)	20°C and 25°C	3.2 g COD/L/d	70-82.6% COD 64.2-73.2% VS	72-75%	14 weeks
[199]	Dairy manure	Batch (250 mL)	14 and 24°C	NR	23-32% VS	51-63.7%	216 days

[200]	Wheat straw and cow feces	sequential batch reactors (SBR) (40 L)	20°C	6.0 g TCOD/kg inoculums /day	42.4 ± 4.3% VS	NR	147 days
[201]	Paunch	Leach bed reactor (1.34 L)	22°C 40°C	0.7-2.7 g VS /L/d	32.9–55.5% VS reduction for 40°C 24.8-38.6% reduction for 22°C	NR	135 days (40°C) 300days (22°C)
[202]	Cow Feces (feces) and Wheat Straw (WS)	Batch (40 L)	20°C	0.60-2.44 g VS/L/d	NR	NR	63 days
[203]	Municipal sewage	UASB (11 L)	23°C 19°C 17°C	NR	74.2 - 75.8 % (TSS)	80 % (±1)	430 days
[204]	Highland barley straw (BS) with Tibet pig manure (TPM)	Batch (0.52 L)	15°C	25 g	0.21-11% TSS 4-63% VS	NR	80 days
[205]	Dairy cow feces	Batch (40 L)	20°C	3.0, 4.0, and 5.0 g COD_t/kg inoculums /d	30-40% TSS	NR	252 days
[206]	Dairy manure and wheat straw	SBR (40 L)	(20°C)	4.0, 5.0 and 6.0 g COD_t /kg inoculum /d	NR	NR	315 days experiment
[207]	Low-organic strength wastewater	BES (200 mL)	20, 12, and 8 °C	330 mg-COD/L	65-85% COD	NR	NA

[208]	Cattle dung	Plug flow (3 m$^{3)}$	CVT (24-10.5°C)	10.4-10.6 Kg VS/day	16-32% VS	55-60%	79 days
[209]	Cattle dung	Continuously fed floating-drum type (3m^3)	3-32°C CVT	60kg cattle dung/day	NR	NR	12 months
[210]	Manure	3m^3 and 2m^{3}Continuously fed	CVT 24-14°C	20 Kg manure/m^3	16-33.5%VS	55-60%	12 months
[210]	Dung	1 m^3	CVT 11.3-23.4°C	20kg dung per day	NR	56-58.5%	8 months
[211]	Llama, sheep and cow manure	Bench (15 L)	11 to 32°C	2-2.1 kg VSm^3/d	13-29.4% VS	49-61%	60 days
[212]	Pig manure and urine mixture	Batch (225 L)	22.6(experiment-1) 32.5(experiment-2)	24.8 (g/L) (experiment-1 23.8 (g/L) (experiment-2)	NR	22.2 ± 0.9%(experiment-1) 48.7 ± 0.9%(experiment-2)	80days (experiment-1) 80 days (experiment-2)
[189]	Guinea pig manure	Low-cost unheated tubular PVC digesters pilot plant 10 m^3	CVT 9-13°C	0.6 kg VS/m^3 /d	NR	NR	7 months
[213]	Cattle dung	Fixed dome type biogas plants (Capacity 2 m^3)	CVT 11-33°C	NR	NR	60%	Approximately 25 month
[214]	Swine manure and cooking grease	250 L each plug-flow digester	CVT Average 25°C	20.1, 26.6, 80.7, 563 g/L VS	90.5-98.0%, VS	66.9%	Nine months

Where, AnMBR: Anaerobic submerged membrane bioreactor; UASB: Up-flow anaerobic sludge blanket reactor; SCOD: Soluble Chemical Oxygen Demand; COD: Chemical Oxygen Demand; EGSB-AF: Expanded granular sludge bed-anaerobic filter; SBR: Sequencing batch reactor; TSS:

Total suspended solid; BES: Bio-electrochemical systems; CVT: Continuously varied ambient temperature.

Connaughton *et al.* (2006b); Dolejs *et al.* (2017); Gouveia *et al.* (2015); Ma *et al.* (2013); Martinez-Sosa *et al.* (2011); Massé *et al.* (2008); Park *et al.* (2018); Rajagopal *et al.* (2017b); Smith *et al.* (2013); Wei and Guo (2018); Witarsa and Lansing (2015) have conducted their studies using various substrates. Nevertheless, all the studies are performed at constant temperature [186], [187], [190], [190], [191], [194]–[199], [215]. Although, there are studies which have carried out at continuously varying ambient temperatures, such as Garfí *et al.* (2011); Kalia (1988b); Kalia and Kanwar (1989); Kalia and Kanwar (1996); Kalia and Singh (1998); Khoiyangbam *et al.* (2004); Lansing *et al.* (2010) and utilized various substrates such as cattle dung, pig manure, and other various dung [189], [189], [209], [210], [213], [214], [216], [217]. Nevertheless, to the best of our knowledge literature related to the AD of FW below mesophilic temperature lacks. Though, few studies of AD of FW at controlled temperature (below mesophilic) are performed by Rajgopal *et al.* (2017) in the context of North America [195].

2.2.4 Optimization of Organic Loading Rate

The OLR can decisively govern the productivity and equilibrium of AD and therefore it has been a vital performance criterion [218]. The high OLR has several advantages and disadvantages. One of the main advantages of high OLR is that it augments many numbers of microbial species and curtails energy demand by increasing internal heat [11]. On the other hand, high OLR may result in inhibition of the process due to quite a lot of reasons such as accumulation of VFA and ethanol, non-homogenous transfer of heat in the reactor, irregular distribution of feed, *etc* [70]. As of now, the determination of optimum OLR has been performed for FW using several types of operating conditions, temperatures, mono, and co-digestions. Agyeman *et al.* (2014) co-digested FW with animal manure at various OLR (0.067-3 g VS/L/d) [5]. However, during the investigation, they found maximum CH_4 yield at an OLR of 2 g VS/L/day. Marañ on *et al.*´(2012) utilized animal dung, FW and sewage sludge with a proportion of 70, 20 and 10%, respectively [219]. The digestion was performed in a continuous stirred anaerobic reactor under mesophilic conditions (36°C). During the experiment the OLR varied in the range of 1.2 to 1.5 g VS/L/d. This study reported the optimum digestion at an OLR of 1.2 gVS/L/d.

Tanimu *et al.* (2014) determined the optimum OLR of FW at thermophilic temperature (55 °C) [220]. During the experiment, the OLR was varied in the range of 1.0 to 6.1 g VS/L/d. However, the optimum OLR was reported was 2.1 g VS/L/day. Certainly, different optimized OLR was reported due to various co-digestion and characteristics of the substrates. Generally, at and above mesophilic temperatures the optimum OLR was reported in the range of 1 to 4 g VS/L/ [139].

2.2.5 Kinematics of Anaerobic Digestion process

The performance of any anaerobic reactor can be predicted with the help of kinetic studies. Besides, generally to design an appropriate anaerobic process the kinetic studies are carried out. Apart from that, there are various other advantages of conducting kinetic studies such as knowing the hydrolysis rate or understand inhibitory mechanisms of the anaerobic digestion process. There are various models available by which these predictions can be made. However, the first-order kinetic model is one of the ancient and simplest models available in the literature. This model allows comparing various processes based on the substrate, pretreatment, *etc.* under various experimental conditions. There various studies in which this model have been used, few of the studies are Bala *et al.* (2019); Bampalioutas *et al.* (2019); Browne and Murphy (2013); Feng *et al.* (2017); Villamil *et al.* (2019); Yin *et al.* (2018); Zhang *et al.* (2016) [112], [221]–[223], [223], [224], [224]–[226]. This model has been used in various studies to determine the hydrolysis rate constant (k) of various substrates at various temperatures. Browne and Murphy (2013) conducted a study in which FW is utilized as a substrate at a temperature of 37°C and reported the value of k in the range of 0.056-0.364 d^{-1}. Bala *et al.* (2019) managed the organic fraction of MSW with the help of AD (at 20-40°C) and reported the value of k in the range of 0.143-0.182 d^{-1}. Villamil *et al.* (2019) utilized flocculent sludge in the AD process at 35°C and reported the value of k 0.100-0.168 d^{-1}. Therefore, we can see that k varies with respect to the experimental variable.

2.2.6 Ecological aspects of Organic fraction of Municipal Solid Waste

Generally, in India, once the MSW is generated from various sources, it undergoes different stages such as collection, transportation, segregation, recycling, treatment (such as composting, incineration, or any other WtE technology) and disposal on landfills (Figure 2.1). The biodegradable fraction of MSW undergoes aerobic and anaerobic digestion (during waste treatment and at a landfill) where along with several gases primarily generation of CO_2 and CH_4 takes place and generally known as Biogas or Landfill gas (LFG) (in context to landfills) [227]. Though local factors, during the aerobic or anaerobic digestion at landfill or waste treatment facility; are temperature, moisture content, and waste characterization which play a decisive role. Usually, CH_4 and CO_2 collectively constitute approximately 90% by volume (≅50% CH_4 and 40% CO_2) [228]–[230] and are amongst the main GHG. Besides, the sun's radiation is absorbed by GHG and it further increases the earth's temperature, therefore, leads to global warming and climate change [231]–[233].

Generally, there are two types of landfills across the globe. First, "managed landfill" and the other one is unmanaged and generally known as "Open dump". Both types of landfills generate GHG and contribute to global warming therefore they are a serious threat to local biodiversity and creates an extremely unhygienic environment. There are massive disadvantages of an open dump but causing fire incidents is one of the most serious ones because of the CH_4 present in the LFG. In addition to this, amongst LFG, CH_4 is the most detrimental GHG and contributes a noteworthy amount to yearly global CH_4 emissions, which further results in climate change. Today, every country is fighting against the anthropogenic factor which contributes to global GHG emissions [234].

Various studies reported that landfills have a great contribution to global warming potential across the globe. Therefore, there is a prompt need in the direction of quantifying CH_4 emissions and taking suitable measures against curtail the emissions and provide social and environmental benefits. Henceforth, it opens a scope for researchers to work in this direction and provide appropriate measures. Further, these measures can be analyzed by policy and decision makes for the sustainable development of any nation [235].

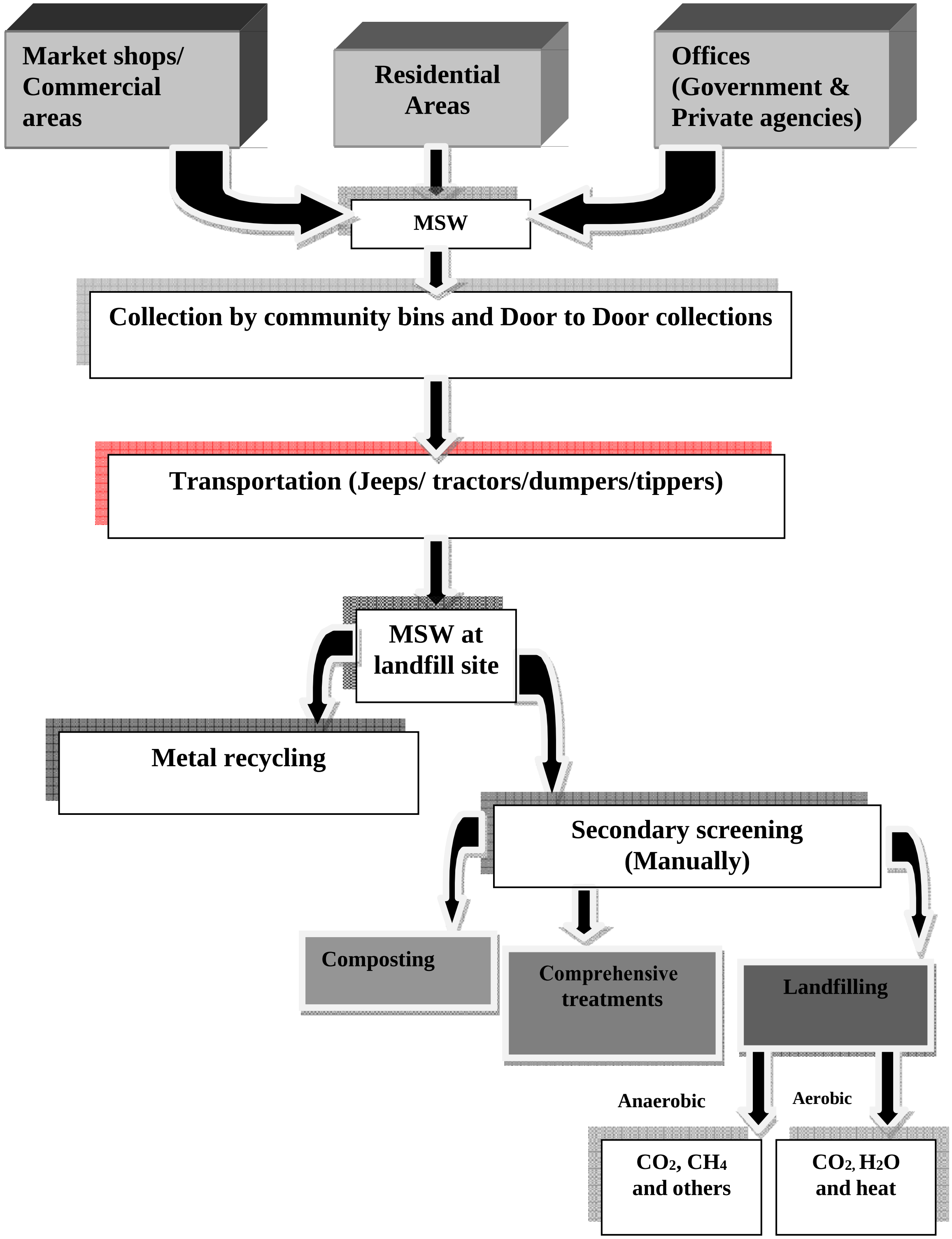


Figure 2.1: Greenhouse Gas emissions from MSW on the Landfills

2.2.7 Factors Affecting the Greenhouse Gas Emissions from Solid Waste Dumping Sites

Emissions from the MSW decisively depend upon various variables such as waste disposal practices, waste composition, and physical compositions of the solid waste disposal site. Various studies reported that GHG emissions directly depend upon waste disposal practices *i.e.*, managed landfills and open dumps. Generally, open dumps tend to emit significantly higher GHG emissions when compared to the managed landfills. It is attributed to the fact that at managed landfills anaerobic microbial activities are ensured and LFG produced during the digestion process is captured. However, it is not possible to capture 100% of the LFG but still, 50-60% efficiency is attained. Secondly, the waste composition has also a huge influence on GHG emissions. Any waste stream generally constitutes biodegradable organic matter that under anaerobic conditions results in GHG emissions. The composition of degradable organic matter decisively influences the quantity and quality of CH_4 produced and it may change at a local and regional level. Therefore, the quantity and quality of CH_4 are region-specific and may change. Physical factors such as moisture content of the waste stream, pH, environmental temperature, and nutrient availability during the anaerobic activity can significantly influence GHG emissions. For microbial growth, metabolism, and transport of nutrients for microorganisms' moisture content, within the solid waste disposal facility is a vital parameter. Hence, it can influence the LFG production. Nutrient availability, temperature, and pH affect the microbial growth and hence the LFG production. Generally, once the anaerobic conditions are stabilized within a solid waste disposal facility the landfill temperature is reported in the range of 25-40°C regardless of the ambient temperature of the facility. However, if the ambient temperature of the facility is reduced that can reduce the potential CH_4 production. The optimum pH within the facility is suggested around equals to 7.0. The vital nutrients for microbial growth are reported sulfur, phosphorus, sodium, and calcium.

2.2.8 Greenhouse Gas Emissions and Climate Change

The surface of the planet earth is surrounded by several gases, commonly known as atmosphere. In the atmosphere nitrogen, oxygen and argon have main constitutes *i.e*. 78.09, 20.95 and 0.93%, respectively, whereas other trace gases are CO_2, CH_4, carbon mono-oxide (CO), nitrous oxide (N_2O), nitric oxide (NO), chlorofluorocarbons (CFCs), water vapor (H_2O) and ozone (O_3).

Water vapor, CO_2, CH_4, and nitrous oxide are some of the major greenhouse gases and tend to absorb infrared radiation that further raises the earth's temperature. Across the globe in various human activities such as agricultural, deforestation, industrial, transportation, and waste disposal and more importantly burning of fossil fuels generates greenhouse gases and causes global warming, this phenomenon is known as Greenhouse effect [236]. The consequences of these activities in the last decades changed the composition of these gases in the atmosphere. More specifically, the concentration of GHG increased and therefore, and global warming and climate change. Though waste disposal has a smaller contribution to the increase in GHG emissions in the coming time this is going to increase significantly and hence its contribution cannot be neglected.

In 2010, the United States has emitted maximum CH_4 (125.4 MT CO_2 eq) across the globe [237], and 148.0 MT CO_2 eq during 2014 [238]. In 2010, China was the second-largest GHG emitter in the world with 47.5 MT CO_2 eq. On the other hand, Mexico, Russia, Canada, Saudi Arabia, and Brazil have emitted 35.5, 33.2, 27.7, 22.1, and 17.5 MT CO_2 eq in 2010. Besides, Europe landfilled approximately 80 MT of MSW in 2013[239]. China generates approximately 1800 Gg of CH_4 from the MSW every year [240]. Malaysia has produced 310,220 t CH_4 every year [237]. Though, in the context of India, there is no such literature is available which reveals national global warming potential every year. Nevertheless, CH_4 and global warming potential of various cities and landfill sites of India have been investigated and therefore it is not a new practice in India. A literature survey discloses that various researchers have used different methods. The zero-order method by IPCC which is also known as the IPCC Default method, First-order decay method by IPCC, LandGEM developed by USEPA are analytical methods whereas modified triangular method, In-situ flux method are *in-situ* methods [241]–[244]. Table 2.4 describes greenhouse gas emissions from MSW in various cities and landfills in India. Along with this, the methodology adopted by researchers is also tabulated.

Table 2.4: Greenhouse gas emissions from Municipal Solid Waste in various cities and landfills in India

Sr. no	References	Method used	Important outcomes
1.	Kumar *et al.* (2004) [242]	Triangular method and default method by IPCC	In this study assessment of CH_4 emission from MSW landfills in 17 [Class I & Class II] cities have been done. In this study, one of the main hypotheses was that about 70% of total MSW is disposed of in landfills without treatment. For the estimation default method by IPCC and the triangular method was used and compared. More realistic results were obtained by using the Triangular method.
2.	Mor *et al.* (2006) [244]	First-order decay method by IPCC and triangular method	In this study CH_4 potential of Ghazipur Landfill, Delhi has been determined. To study the waste characteristics 9 m deep vertical hole is made on the waste dumping facility. An estimate of CH_4 potential is done by using the first-order method decay method by IPCC and triangular method. This study found both the method suitable for the estimation of methane potential.
3.	Akolkar *et al.* (2008) [245]	Chamber Method and Stoichiometric Method and	In this study estimation of CH_4 emission from various landfill sites in Maharashtra has been done. The sites were Bhandewadi, Nagpur, and Amravati. The study concluded that GHG emissions from the landfill depend upon various factors such as the depth and age of the landfill. Besides, the chemical composition of the waste also affects emissions. This study also concluded that it is a very tedious task to identify the active zone within the landfill facility in which the anaerobic digestion is going on.
4.	Jha *et al.* (2008)	First-order decay method	This study estimated the GHG emissions from two landfills (*i.e*. Kodungaiyer and Perungudi) in Chennai

	[241]	by IPCC and Chamber method	city. This study found a difference between the estimation made by the First-order decay method by IPCC and Chamber method. They reported that this difference is mainly due to the lack of region-specific model input parameters. The study also concluded that the amount of waste dumped on the landfill site, its composition is vital parameters. In the absence of these parameters, there can be uncertainties in the estimations. Besides, the generation of MSW is over-riding the population growth rate in Chennai.
5.	US EPA (2009) [246]	LandGEM, Version 3.02 by USEPA	In this study assessment of LFG potential from Okhla Landfill, Delhi has been done. Along with this assessment, a feasibility study for the use of LFG for flaring was also conducted. The study suggested that LFG from Okhla Landfill may be a feasible option for domestic fuel or flaring.
6.	Siddiqui and Khan (2011) [247]	Ecuador LFG Model	In this study assessment of LFG from various landfill sites across India has been done. Landfill sites included in this study were Okhla (Delhi), Deonar and Gorai (Mumbai), Pirana of (Ahmedabad), Uruli Devachi (Pune), and Autonagar. In the study, it was found that the landfill site in Mumbai has the maximum LFG potential while landfill in the Hyderabad has the least LFG potential. Besides, the study also reported that assessment with the least uncertainties is very difficult because of the lack of input data for the models.
7.	Chakraborty *et al.* (2011) [243]	Default, first-order decay method by IPCC and	In this study potential of CH_4 from Ghazipur, Okhla, and Bhalswa Landfills of Delhi with the help of Direct, first-order decay method by IPCC and modified triangular method and Chamber Method has been done.

		modified triangular method and Chamber Method	Estimation of CH_4 emission from Ghazipur, Okhla, and Bhalswa Landfills of Delhi. In this study, a methane emission factor was also developed which reduced the uncertainties in the emissions. The study found that the first-order decay method by IPCC can give good results when compared to the *in-situ* chamber if the correct composition of the waste is known.
8.	Kumar and Sharma (2013) [248]	LandGEM, Version 3.02 by USEPA	In this study potential of CH_4 and energy recovery potential from Ghazipur, Okhla, and Bhalswa Landfills of Delhi with the help of LandGEM, Version 3.02 has been done. The results of this study were compared with earlier studies that used direct, first-order decay method by IPCC and modified triangular method, Chamber Method, and modified triangular methods. In comparison, it was found that this model is applicable and predicted the results very close to in-situ methods of the other studies. Besides, the results of this model are also utilized for the computation of green electricity production from these landfill sites.
9.	Kumar and Sharma (2014) [249]	LandGEM, Version 3.02 By USEPA	In this study GHG emission from landfills of 23 metro cities across India has been estimated. For the estimation, LandGEM Version 3.02 has been used. The study found that Mumbai is the largest GHG emitter while the Visakhapatnam is the least.
10.	Ghosh *et al.* (2019) [250]	Default, first-order decay method by IPCC and LandGEM, Version 3.02	This is the most recent study conducted by researchers in India. In this study, GHG emissions from Ghazipur, Okhla, Bhalswa landfills have been estimated between 1984 and 2015 using Default, first-order decay method by IPCC and LandGEM, Version 3.02 by USEPA with Inventory values. The study found that all the landfill

	By USEPA with Inventory values	sites have great methane potential therefore if the methane can be captured it may result in electricity supply to the vicinity areas. Along with this, this study has also highlighted the uncertainties in methane emissions if the input variable changes.

2.3 Summary of the Literature Survey and Research Gaps

During the literature review, we have discussed the SW and its classification based on the source of generation. We found that MSW constitutes a huge part of SW. Further, we have discussed problems caused by MSW to the environment and possible ways by which these problems can be minimized. We have also discussed various methods by which MSW can be managed and their comparison. In that comparison we have found that anaerobic digestion in an anaerobic reactor is one of the suitable ways to manage waste when compared to the landfill, composting, and incineration.

It was also found that FW constitutes a huge fraction of MSW and it is also causing various problems to the environment therefore it should also be managed with the help of anaerobic digestion. Now, to know whether FW can be used as a substrate in anaerobic digestion or not, characteristics of food waste from various studies in terms of moisture content, total solids, volatile solids, carbon to nitrogen ratio has been reviewed. It was found that food waste has a substantial amount of volatile fraction therefore it can be used as a substrate in anaerobic digestion.

Further, the process of anaerobic digestion of food waste has also been reviewed. During that, it was found that the anaerobic digestion process can be influenced by various input factors. One of the parameters is the process is mono or co-digestion of food waste. In this regard, it was found that during mono-digestion of food waste there are more chances of accumulation of volatile fatty acids during digestion when compared to co-digestion. Due to this reason only, a high organic loading rate cannot be achieved in the mono-digestion of food waste.

Also, temperature plays a huge role in the anaerobic digestion process. It can significantly influence the quantity and quality of the by-product.

During the anaerobic digestion process, three types of temperature can be there *i.e.* mesophilic, thermophilic, and psychrophilic. During the literature survey, it was observed that there are ample numbers of studies which are performed at constant and variable mesophilic temperature. However, fewer studies are available in which food waste is managed with the help of anaerobic digestion at thermophilic temperature when compare to mesophilic. This is attributed to the fact that maintaining thermophilic temperature during the digestion at pilot itself requires huge energy demand. On the other hand, there are very few studies have been reported in which food waste is utilized at constant psychrophilic temperature. In fact, to the best of our knowledge, we have not found any study which has been performed at continuously varied low mesophilic and psychrophilic temperature.

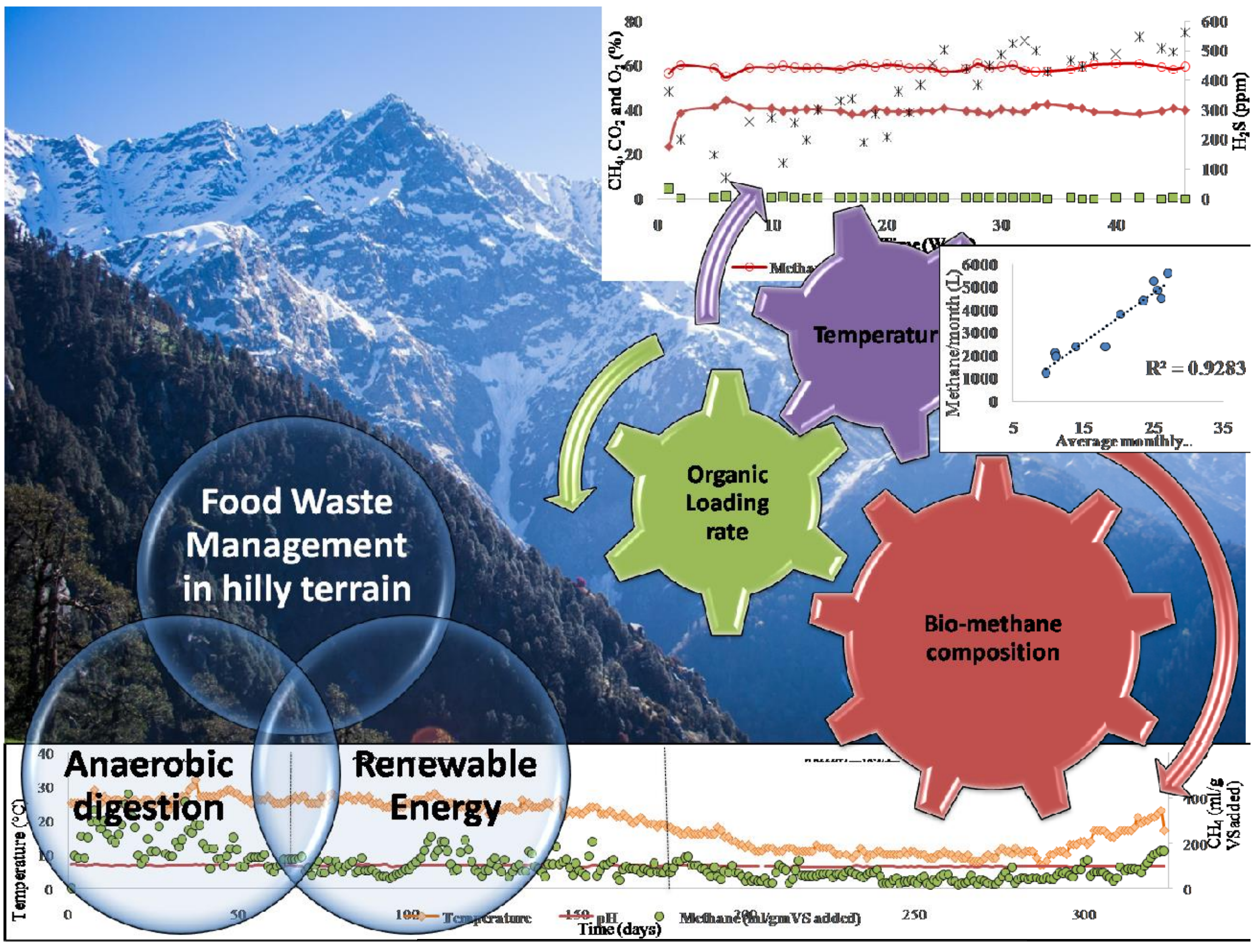
Optimization of organic loading rate and its importance has also been reviewed in which it was found that that literature lacks in terms of optimized organic loading rate of food waste-based anaerobic digestion process at continuously varied low mesophilic and psychrophilic temperature.

Further, the kinetics of various substrates at various temperatures has also been reviewed. During that, it was found that kinetics of food waste at low mesophilic and psychrophilic temperatures has not been reported.

Besides, in this chapter, literature related to the MSW greenhouse gas emissions and its energy potential in India has been reviewed. In which it was found that there are city and town specific studies are available in which energy potential, greenhouse gas emissions from MSW has been computed. Nevertheless, the literature lacks in terms of state-level or national-level study which reveals MSW greenhouse gas emission and energy potential of MSW in India.

CHAPTER - 3

Feasibility of a Pilot-Scale Semi-Continuous Anaerobic Reactor (Food waste-based) at Psychro tolerant and Low Mesophilic Temperature



~ Strive not to be a success, but rather to be of value.

- Albert Einstein

CHAPTER-3
FEASIBILITY OF A PILOT SCALE SEMI-CONTINUOUS ANAEROBIC REACTOR (FOOD WASTE BASED) AT PSYCHRO TOLERANT AND LOW MESOPHILIC TEMPERATURE

3.1 Introduction

Across the globe, almost every developing and developed country is facing problems due to the huge generation of MSW [251]. In India, approximately 51.5 MT of MSW was generated in 2015 while 55.4 MT of MSW was generated during 2019 [26], [39]. It is further expected to increase at a very high rate in the coming decades [252]. From the literature survey, it is evident that FW has a large volatile fraction. It constitutes an enormous fraction in MSW [43]–[50]. Odor, surface and groundwater contamination, emission of GHG, vermin attraction is some of the major problems associated with open dumping of FW. On the other hand, it has significant organic potential which can be readily utilized through the process of AD [253].

The mechanism of AD is highly complicated wherein organic wastes such as cow dung, horse dung, swine manure, fruit, vegetable, food waste, and various lignocellulosic biomasses can be utilized as input and CH_4 is one of the main byproducts of this process [253]–[256]. A stable AD has a wide range of advantages over the other used technologies for the generation of energy that could be utilized for cooking and lighting purposes. This will also aid in the generation of electricity, reduction in the use of firewood, production of nutrient-rich fertilizer and other advantages like reduction in contamination of soil, air, and water [257], [258]. AD process decisively depends upon temperature; generally, it is practiced at steady and control temperatures [259]–[261]. There are three main temperature ranges; psychrophilic (<20°C), mesophilic (20–40°C) and thermophilic (>40°C) [262]. A large number of studies have been carried out at low altitudes where the climate is warmer and the temperature is in mesophilic or just near to this and these areas are more favorable for the AD process [263]–[266]. Nonetheless, there are a large number of places with relatively moderate or higher altitudes (*i.e.*, ≥1,000 m above mean sea level (MSL)) where the AD process is performed in an extremely unfavorable environment, and such process face difficulty or drawbacks in terms of performance of the anaerobic reactor. Such anaerobic reactors in these environmental conditions generally lead to instability of the reactor if suitable OLR is not decided [211], [257], [267].

AD at mesophilic or higher mesophilic and thermophilic temperature is comparatively well understood and reported in the literature in comparison to a relatively lower mesophilic and at psychrophilic temperature ranges [262]–[264], [268], [269] and for this reason, comparatively fewer studies are available at such temperatures. Few of the studies are conducted by Kalia (1988); Kalia and Kanwar (1996); Kalia and Kanwar (1989); Kalia and Singh (1998); Kanwar and Guleri (1994); Safley and Westerman (1990); Singh *et al.* (1995), *etc*. Kanwar and Guleria reported in their study that the temperature significantly varied in winter and summer which in turn affected the CH_4 generation rate critically during the anaerobic digestion of cattle dung *i.e.*, 0.03m^3/kg feed in summer and 0.007m^3/kg feed in the winter [270]. Previous studies have also reported a linear decrement in CH_4 production as temperature declined over the range between 10–23°C. However, the CH_4 production in winters (0.07 m^3/kg VS) was reported significantly less when compared to summer (0.33m^3/kg VS) with swine manure as a substrate in a covered lagoon reactor [261], [271].

Generally, areas having elevation ≥1,000 m above from MSL are having more unfavorable conditions for the AD process due to undulated land, stony soil, rocky strata, heavy rainfall, snowfall, and low temperature during night time in summer and winters. In the past, various reactors have been proposed and used for such climatic and geological locations. Janta, Khadi Village Industries Commission (KVIC), and Deenbandhu plants were among the most successful and widely accepted plants at a local, national, and global level [272]. These plants were not only propagated substantially in India but also in neighboring countries of India and globally. Nevertheless, the practice of these reactors could not succeed significantly due to problems such as leakage, the requirement of skilled labor, high construction cost, complicated design, rocky strata, undulated topography, and lower temperature range in hilly regions. Between 1980 and 2000, several studies have been conducted at altitude ≥1,000 to check the bio- CH_4 potential of various organic substrates like cattle dung, wastewater, sludge, and night soil [209], [210], [273]. To the best of our knowledge, no study has been performed and reported in the literature as of now in a pilot-scale semi-continuous anaerobic reactor at low mesophilic and psychrophilic variable temperature ranges in which FW is utilized as a substrate in the northern hilly states of India. Rao *et al*. (2000) concluded that AD of FW is not as same as conventional AD of wastewater and cattle dung [253].

Therefore, the performance of FW as a substrate in the AD process at a low-temperature range needs to be studied. So, because of that, one of the main objectives of the present study is to access the feasibility of AD of FW at low mesophilic and psychrophilic temperatures. Apart from that anaerobic digestibility and hydrolysis rate of this process have been investigated with the help of some kinetic and mathematical models.

3.2 Material and Methods

3.2.1 Study Location

The location of the study area is shown in Figure 3.1. All experiments were performed at Jaypee University of Information Technology (JUIT) which is located in Himachal Pradesh, India.

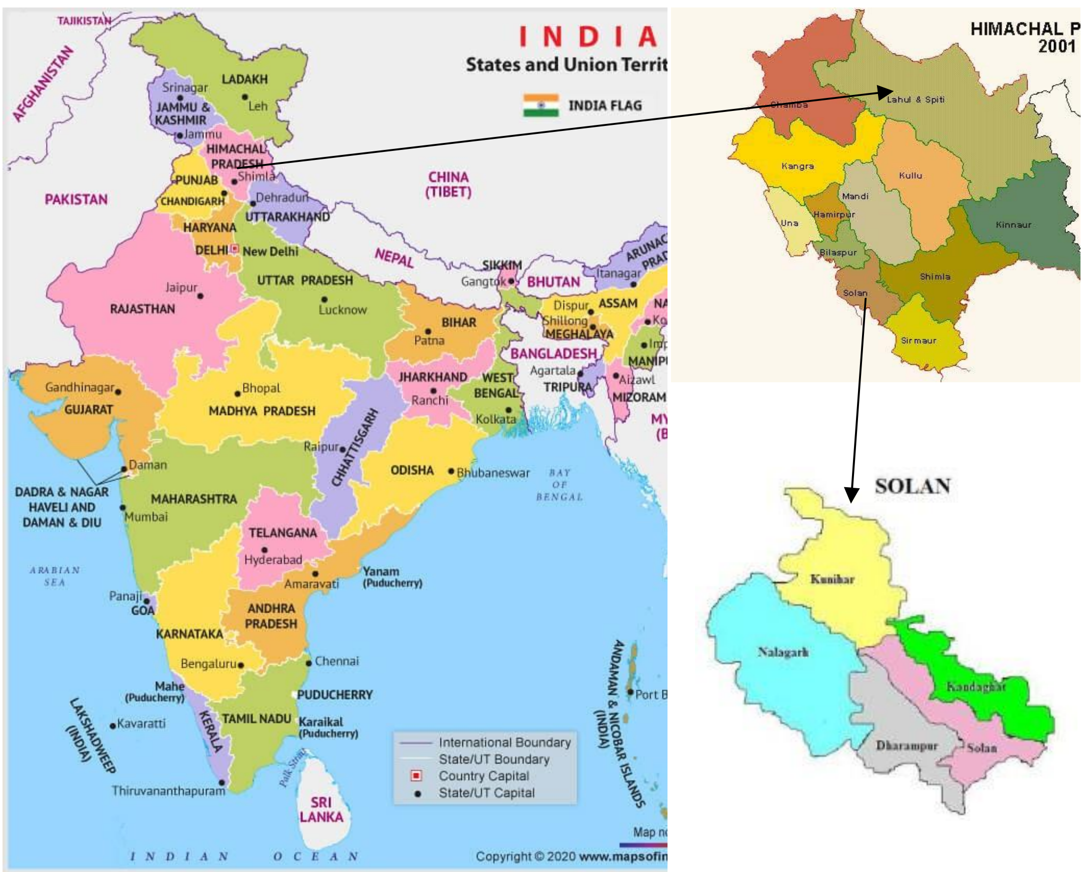


Figure 3.1: Location of the Study Area

Himachal Pradesh is one of the northern hilly states of India and its elevation varies in the range of 450 m to 6,826 m above from MSL. Specifically, JUIT is located in Waknaghat which is one of the small towns of district Solan. Waknaghat is located at an elevation of 1,544 m above mean sea level with latitude and longitude of 31.0079° N, 77.0881° E.

3.2.2 Details of Experimental Setup

The anaerobic reactor used in this study was the floating drum type. The two main components of the reactor were the reactor and the gasholder. The volume of the reactor was 3,000 L and the volume of gasholder was 2,000 L. Both of them were cylindrical and made of Poly Vinyl Chloride (PVC). The arrangement of the gasholder was inverted in the reactor and can also be seen in Figures 3.2 and 3.3. The experimental setup was allowed to perform at variable atmospheric temperature.

Figure 3.2: Photo view of an outdoor 3,000L Anaerobic continuous reactor at the Jaypee University of Information Technology in Himachal Pradesh

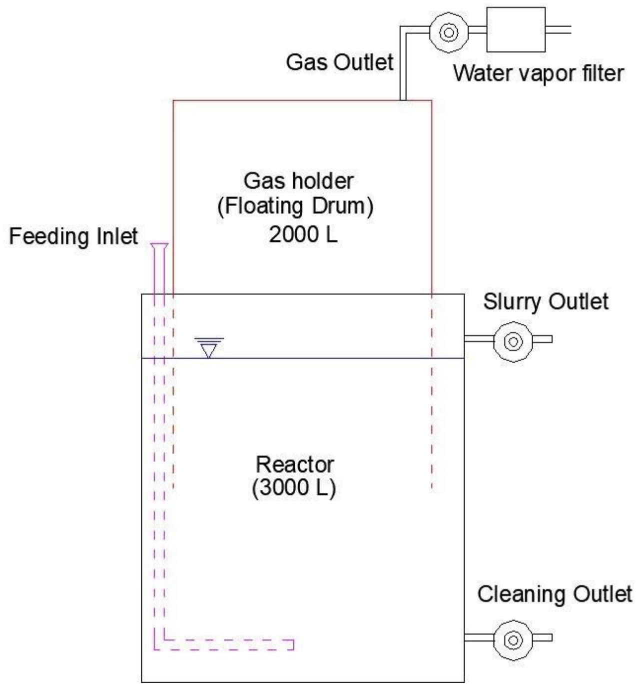


Figure 3.3: Schematic diagram of an outdoor 3,000-L Anaerobic semi-continuous reactor at the Jaypee University of Information Technology in Himachal Pradesh.

3.2.3 Details of Substrate, its Characterization, and Inoculum

In this study, FW was used as a substrate. In the beginning, to decide suitable OLR characterization of substrate needed to be performed. In this direction, daily 3 Kg of FW sample was taken from the cafeteria of JUIT for 30 days. Characterization of FW was done based on analytical parameters such as MC, TS, VS, C, and N. Cow dung was utilized as an Inoculum and collected from the villages located in the vicinity of the JUIT.

3.2.4 Measurement of Biogas

The biogas was measured volumetrically. The daily rise in the gasholder was measured accurately from four opposite directions around the periphery of the holder and the average of the same was taken as the rise of gas holder. The volume of the gas was thus computed. The composition of Biogas (O_2, CO_2, H_2S, *etc.*) was measured by Biogas sensor 5000 Geotech gas analyzer (QED Environmental System, Coventry, UK).

3.2.5 Analytical Method

Before starting the experiments, the first and foremost step was to know the composition of the substrate in terms of checking its biodegradable fraction with the help of some analytical parameters. Apart from this, the characterization of influent and effluent slurry was determined with the help of several analytical parameters. These parameters are as follows: MC, TS, VS FS, TKN, TOC, pH, temperature, total alkalinity, VFA, BOD_5. Amongst these parameters, determination of pH, TS, VS, VS, MC, TOC, TKN, alkalinity, and VFA were determined with the help of standard instruments and methods as suggested by APHA (2005) [274].

The daily ambient temperature was determined with the help of a digital/electronic thermometer.

3.2.6 Kinetic and Mathematical Modeling

In this study one kinetic and three mathematical models have been used to study the overall performance of the AD process. With the help of these models, various kinetic parameters such as hydrolysis rate constant, maximum biogas yield, and cumulative methane production have been determined. These parameters have significant importance while designing any anaerobic bio-reactor, determination of leachate generation on the landfills in such climatic conditions. Apart from that, these parameters can further be used for the determination of GHG emissions and GWP of various organic wastes on landfills and open dumping sites. In this direction, the first model used is the First-order kinetic model (FOM). It is a kinetic model and generally used in various studies to determine hydrolysis rate constant (k in day^{-1}), maximum biogas yield (P in L/g VS), and cumulative methane production (P_0 in L/g VS). This model is given as Eq. (3.1). During curve fitting, 'k' is one of the main parameters obtained. Generally, during AD of various organic wastes such as activated sludge, dung, *etc*. 'k' decisively governs the whole process. Generally, from the literature, it is observed that complex organic wastes such as any lignocellulosic waste have less 'k' when compared to other organic wastes such as animal dung, sludge, and FW [275].

$$P_0 = P(1 - \exp(-k.t)) \quad (3.1)$$

Where t is the time of biogas accumulation (days).

Apart from the FOM, the modified Gompertz model (MGM) is a widely accepted and used model. This model has been used in various disciplines of sciences and engineering. Modified Gompertz model has also been used to study methane generation from various substrates [3], [276]. Apart from this, MGM is significantly used to study hydrogen production in various studies [277], [278]. It is used in the determination of various parameters such as maximum specific biogas production rate *(R_m)*, lag phase (λ in days), P, and P_0 during the AD process [275]. The equation is given as: (Eq. (3.2)).

$$P_0 = P\left(-exp\left(\frac{R_m.e}{P}(\lambda - t) + 1\right)\right) \tag{3.2}$$

Similarly, the Reaction curve type model (RCM) also known as transfer function is also used in a few studies associated with the anaerobic fermentation [279]. This function is used primarily for control purposes. This function considers that any practice can be analyzed as a system which receives various inputs and produces outputs. This model also is used in the anaerobic digestion process in a few cases [275] [280], [281]. The equation is given as: (Eq. (3.3)).

$$P_0 = P\left(1 - exp\left(\frac{-R_m.(t-\lambda)}{P}\right)\right) \tag{3.3}$$

Similarly, the logistic function is also used in various studies to fit in the global shape of biogas generation kinetics *i.e.,* initial exponential and further followed by stabilization at peak production. This model has been used widely for the determination of methane yield in various anaerobic digestion processes occurring in the landfill and bio-reactor [282], [283]. In this study, a modified type of logistic function (MLF) is used for curve fitting of experimental data into the model as suggested by [284]. The equation is given as: (Eq. (3.4)).

$$P_0 = \frac{P}{1+exp\left(\frac{4.R_m(\lambda-t)}{P}+2\right)} \tag{3.4}$$

The curve fitting of predicted methane generation from these models with observed methane generation is carried out using non-linear regression. To perform non-linear regression IBM® SPSS® Statistics Version 20 data editor and MS excel has been used.

3.3 Experimental Procedure

One of the objectives of the present study was to access the feasibility of pilot-scale semi-continuous anaerobic reactor at psychrotolerant and low mesophilic temperature using food waste as a substrate. The present section represents the working strategy of the experiments conducted.

3.3.1 Organic Loading Rate and Cycles

The decision on OLR for first feeding was made with the help of following Safley and Westerman (1990) [261][28]. They proposed an equation and concluded that the decision of OLR is a temperature-dependent process. During utilizing swine dung with the help of AD, they suggested that if the reactor is going to function at a temperature near around 10°C then the OLR should lie in the range of 0.08-0.24 g VS/L/d.

In this study the substrate to be utilized in the AD process is FW, therefore it was decided to start the reactor with an OLR in the range of 0.041-0.083 g VS/L/d based on the ambient temperature. Besides temperature, it is attributed to the reason reported in the literature that high accumulation of VFA is generally observed during mono-digestion of FW which can further lead to inefficient digestion, instability of inhibition of the entire process. The whole experiment was divided into 3 cycles *i.e.*, C1, C2, and C3. The OLR maintained during C1, C2 and C3 were 0.041, 0.083, and 0.06 g VS/L/day, respectively.

3.3.2 Feeding, and Working Details of the Reactor

Feeding of the anaerobic reactor was not started until the complete acclimation of anaerobic microorganisms achieved. Once the acclimation of the anaerobic environment has been established within the reactor the first feeding was done.

The feeding was done at an interval of 5 or 7 days. During every feeding, it was also made sure that the peeling of raw fruits and vegetables not included in the feed. Before every feed, the FW was completely crushed manually and converted into a particle size of approximately 1-2 mm and later mixed with water to make homogenous slurry. On the day of each feeding, samples of influent slurry were taken and characterization based on such as VS, TS, BOD_5 was performed.

From the day of feeding to the day of next feeding daily temperature (ambient and inside the reactor), pH and, amount of biogas generated was recorded. During the feasibility assessment, OLR was varied from 0.041- 0.083g VS/L/d in three cycles C1-C3.

Quantification of biogas generated (in L) was done volumetrically. The composition of biogas was determined by analyzing the sample for CO_2, CH_4, H_2S, and O_2 with the help of a biogas sensor. On the day of next feeding, samples from new influent slurry and the effluent slurry were also taken. With the help of effluent slurry determination of alkalinity, VFA, pH, VS, and BOD_5 were determined. Besides, the influent slurry was characterized as mentioned earlier. The overall workflow to investigate the feasibility of the reactor in a long-term period is shown in Figure 3.4 below.

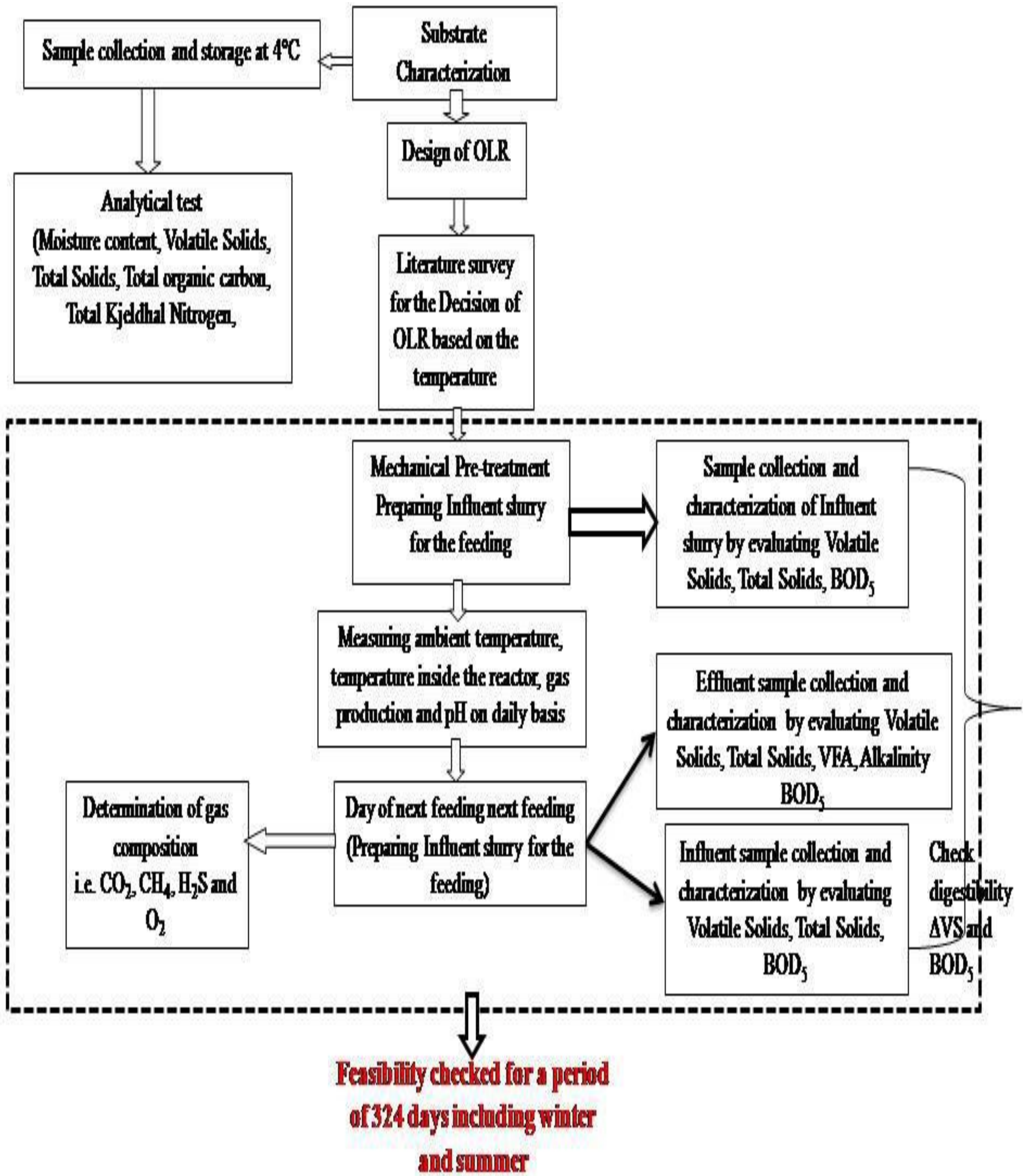


Figure 3.4: Workflow diagram for the study

3.4 Results and Discussion

3.4.1 Characteristics of Inoculum and Substrate

The amount of moisture content present in the waste sample plays an important role in deciding the treatment processes to be followed. Wastes with high moisture content cannot be treated by methods like incineration, combustion or pyrolysis, *etc*., but out of all these, AD is one of the most suitable methods by which waste can be treated readily. Characterization of the Inoculum and substrate used in the present study are shown in Table 3.1 and Table 3.2, respectively. The moisture content of leftover FW was observed 76.98±6.75% indicating that the waste can be utilized through wet AD.

Table 3.1: Characterization of Inoculum

MC%	TS %	VS%	FS%	VS/TS%	C%	N%	C/N
79.49	20.51	16.3	4.21	79.47	43.22	2.03	21.29

Table 3.2: Characterization of Substrate

Day	MC	TS%	VS%	VS/TS	C%	N%	C/N
Monday	80.41	19.59	12.32	62.88	41.98	3.27	12.83
Tuesday	86.71	13.29	11.84	89.08	44.2	3.80	11.63
Wednesday	76.78	23.22	16.79	72.30	46.22	5.30	8.72
Thursday	71.66	28.34	11.9	41.99	43.49	2.92	14.89
Friday	67.49	32.51	21.17	65.11	49.71	4.39	11.32
Saturday	78.88	21.12	15.73	74.47	44.83	4.22	10.62

The ratio of VS to the TS is a decisive parameter to identify the organic fraction in the substrate. The VS/TS for cow dung was 79.47% whereas for FW it was 67.64±15.59%. Researchers such as Yong *et al*. (2015) and Zhang *et al*. (2014) conducted studies on FW and reported VS/TS in the range of 85-96% which is more than the results obtained in the present study [285], [286]. The lesser values of VS/TS in this study are attributed to the fact that the Indian food is cooked at a very high temperature and pressure, therefore, resulting in the significant destruction of the organic fraction.

Although, in the present study, it was found that Indian food has enough potential to be utilized for AD. Other researchers such as Awasthi *et al*. (2018) and Dhamodharan *et al*. (2015) also reported VS/TS ratio in a similar range and concluded that the waste used in their study has good potential for the utilization in AD process [264], [287]. There is a great need for carbon and nitrogen during the digestion because both have their importance. Carbon is utilized as food or feed by the micro-organisms while on the other hand nitrogen plays a role as a nutrient for micro-organisms during the AD process. Therefore, the C/N ratio is a highly important parameter for experimental design and optimum process. In this study, the C/N for FW is found lower when compared to various other studies. Nevertheless, several studies such as El-Mashad *et al*. (2004); Sánchez *et al*. (2001); Zhang *et al.* (2007) suggested that digester can also perform well at low C/N ratio [262], [288], [289]. Although, Lehtomäki *et al.* (2007) suggested the optimum C/N ratio for the AD process varies in the range of 25-32 for FW and 11-14 for local manure [290].

3.4.2 Gas Production its Composition and Temperature

Figure 3.5 depicts the time variation of cumulative biogas and CH_4 gas generated in the anaerobic reactor during the experiment. At the end of the experiment, a total of 65,270 L biogas and 38,461L CH_4 produced. The CH_4 generated per day varied from 330 to 16.25 L/day. The gas composition is shown in Figure 3.6.

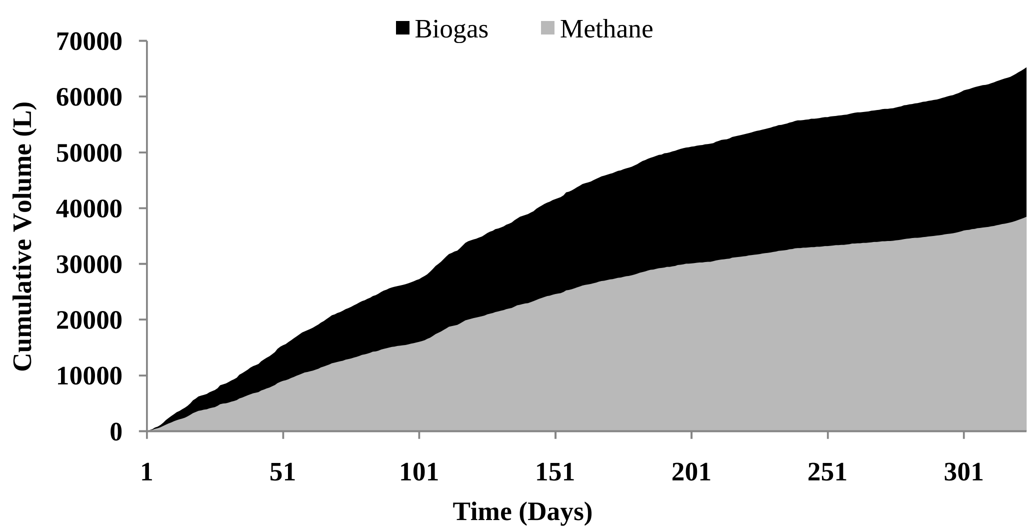


Figure 3.5: Temporal Variation of cumulative Biogas and Methane

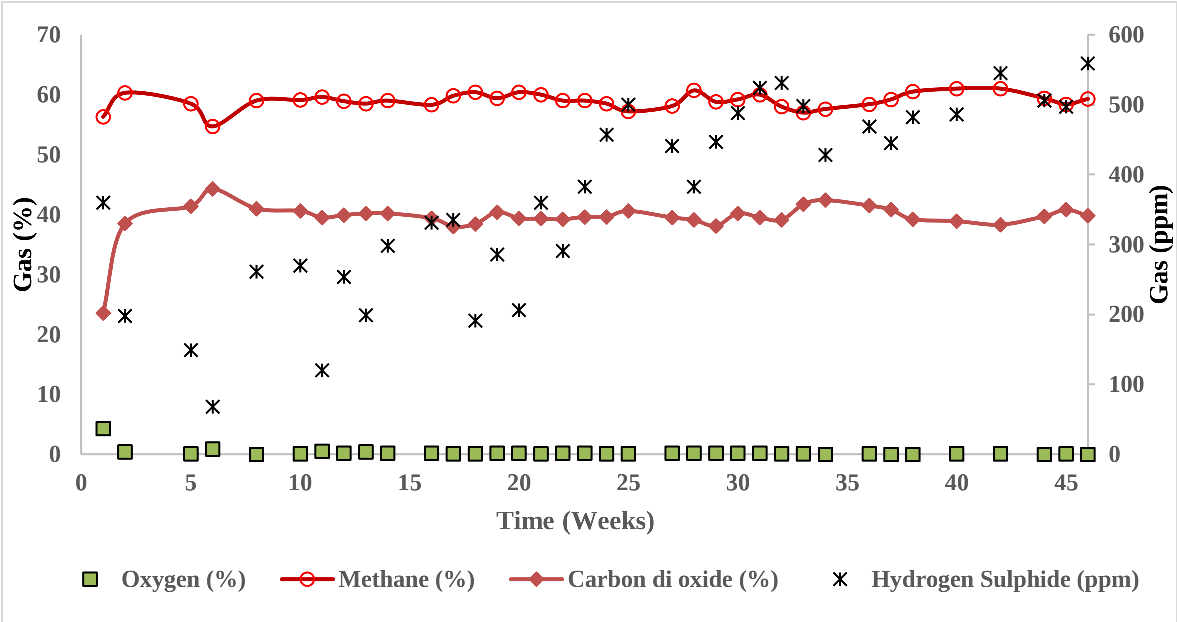


Figure 3.6: Composition of biogas

Various factors are responsible for this large variation in biogas generation however temperature has been one of the most important parameters. During the experiment, the maximum ambient temperature was reported in June 2017 as 29°C whereas the minimum temperature in day and night was reported in January and February was 8°C and -2.6°C, respectively.

Variation of CH_4 with temperature and time is shown in Figure 3.7. In summer (1st May 2017-15th October 2017), the production rate of CH_4 varied in the range of 56.39-330.46 L/day. Maximum CH_4 was generated in June *i.e.*, 5,581 L while minimum CH_4 was generated in September *i.e.*, 4,303 L. However, in winter season (15th October 2017-24th March 2018) CH_4 production rate fallen drastically and it varied between 16.25-191 L/day. Variation of Biogas and Methane in different months is shown in Table 3.3. Maximum production of methane was observed in March 2018 *i.e.* 2,404 L whereas minimum production was noticed in January *i.e.* 1,206 L. An average reduction of 54.82% in CH_4 production is observed in winter when compared to summer. A study made by Kanwar and Galleria (1994) reported a drastic change (77%) in CH_4 yield during the summer and winter [270].

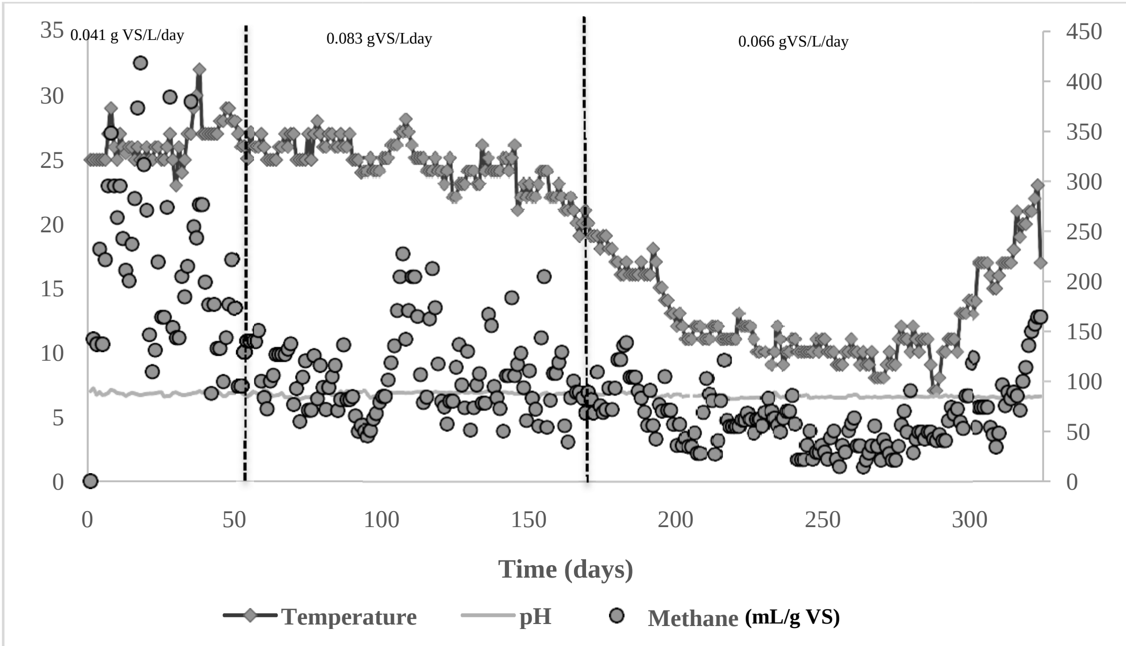


Figure 3.7: Variation of methane with pH and ambient Temperature

Table 3.3: Variation of Biogas and Methane in different months

Month	OLR g VS /L	Total Biogas (L)	Total CH_4 (L)	Average day temperature (°C)	Maximum day temperature (°C)	Minimum day temperature (°C)	Minimum night temperature (°C)
May 2017	0.041	8,405	4,867	25.5±1.0	27	19	18.4
June,2017	0.041	9,547	5,581	27.03±1.7	29	23	20.1
July	0.083	7,652	4,500	26.1±0.8	28	23	21.6
August 2017	0.083	8,794	5,271	24.8±1.1	28	23	16.0
September 2017	0.083	7,249	4,303	23.5±1.2	26	21	15.9
October*, 2017	0.083	6,510	3,812	19.9±2.3	24	16	11.6
November 2017	0.066	4,076	2,398	13.3±2.2	18	11	6.2
December	0.06	3,583	2,091	10.6±0.9	13	9	-1.2

2017	6						
January 2018	0.066	2,051	1,206	9.5±0.87	11	8	-2.1
February 2018	0.066	3,378	1,936	11.9±1.7	15	10	-2.6
March 2018	0.066	4,021	2,404	16.4±2.5	16.4	10	5.7

*0.066 g VS /L was started from the third week of October

The data of average monthly temperature (°C) and CH_4 generation per month has been plotted in Figure 3.8. It is clear from the figure that there is a linear relationship between these two factors with $R^2 = 0.9283$.

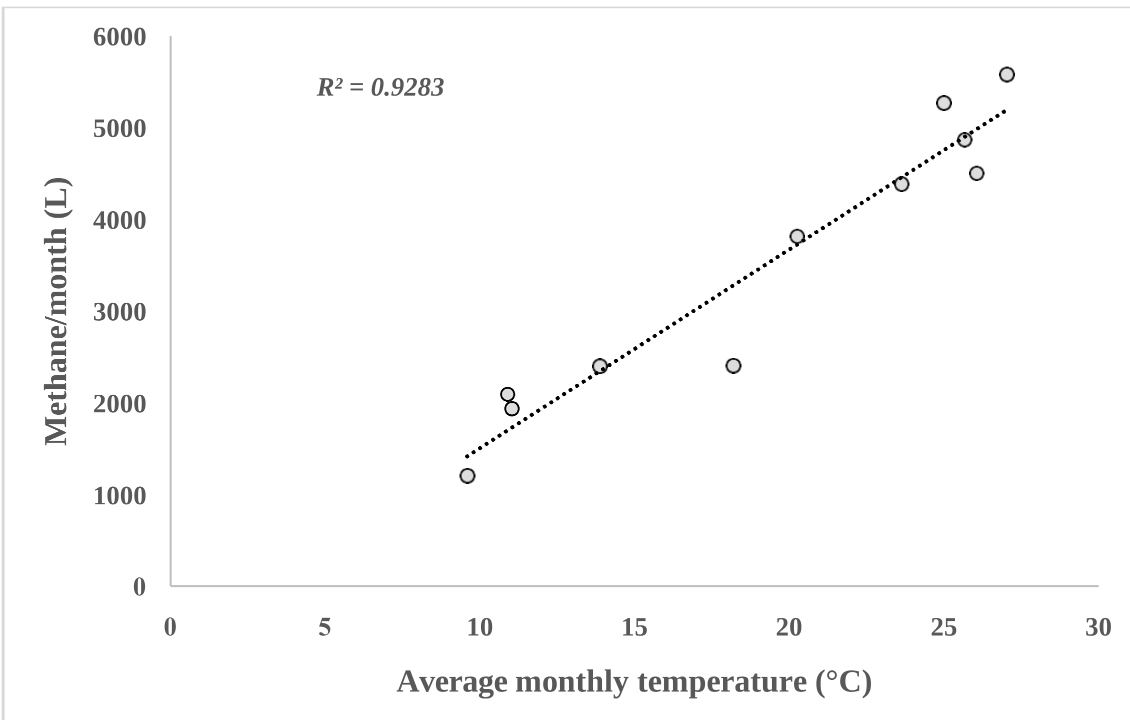


Figure 3.8: Correlation between average monthly Temperature and Methane production per month

3.4.3 Stability Analysis

Various authors like Alvarez *et al.* (2006); Hill *et al.* (2001); Kalia and Kanwar (1998); Kanwar and Guleri (1994); Marín *et al.* (2018); Nozhevnikova *et al.* (1999b); Safley and Westerman (1994a) reported that temperature during the AD process has a significant influence [257], [261], [270], [291]–[294]. These researchers have conducted the studies at low mesophilic or psychrophilic temperatures and found that temperature may even influence the stability of the reactor. If the ambient temperature around the reactor is low and the reactor is subjected to inappropriate OLR (generally more than the optimized OLR) the digestion in the reactor may inhibit due to the accumulation of significant VFA. This is attributed to the fact that significant accumulation of VFA in the reactor lowers down the overall pH and therefore makes the methanogenesis micro-organisms inefficient or inactive. Apart from that quantity and quality of bio-slurry in terms of nutrients such as N, P and K may get affect by the temperature which is due to the reason that temperature governs the activity of enzyme and co-enzymes [286].

During this study, the reactor was operated at a low mesophilic temperature from May 2017-September, 2018. In this phase, the average monthly temperature was recorded as 22.65°C. While, from October 2017 to March 2018; the reactor was operated at a psychrophilic temperature range. In this period the average monthly temperature was recorded 12°C. Various parameters can indicate the stability of any AD process. However, in this study, monitoring of the pH, partial alkalinity, total alkalinity, and VFA/alkalinity ratio of the effluent slurry of the reactor was monitored regularly to check the stability of the process. Figure 3.9 shows partial alkalinity, total alkalinity, and VFA/alkalinity ratio during the experiment.

In winters, as the temperature has fallen, alkalinity, pH, and methane yield of digester were also affected immensely. The maximum value of alkalinity of the system was achieved as 2,987 in May and June 2017 however lowest value was noticed as 960 $CaCO_3$ mg/L in February 2018 respectively. It is also evident from Figure 3.7 that ambient temperature dropped drastically during December 2017 and in the same month the lowest drop in alkalinity was also observed. However, after February 2018, a rise in temperature was noticed, and hence a small improvement in alkalinity, pH, and CH_4 production was also recorded. Nevertheless, it is found that during the experiment, digester inhibited occasionally due to instability because the reactor did not have enough buffering capacity. Therefore, for those instances, external alkalinity has been provided.

Other than those instances, always, there was the availability of appropriate alkalinity in the reactor because of which desirable pH was maintained.

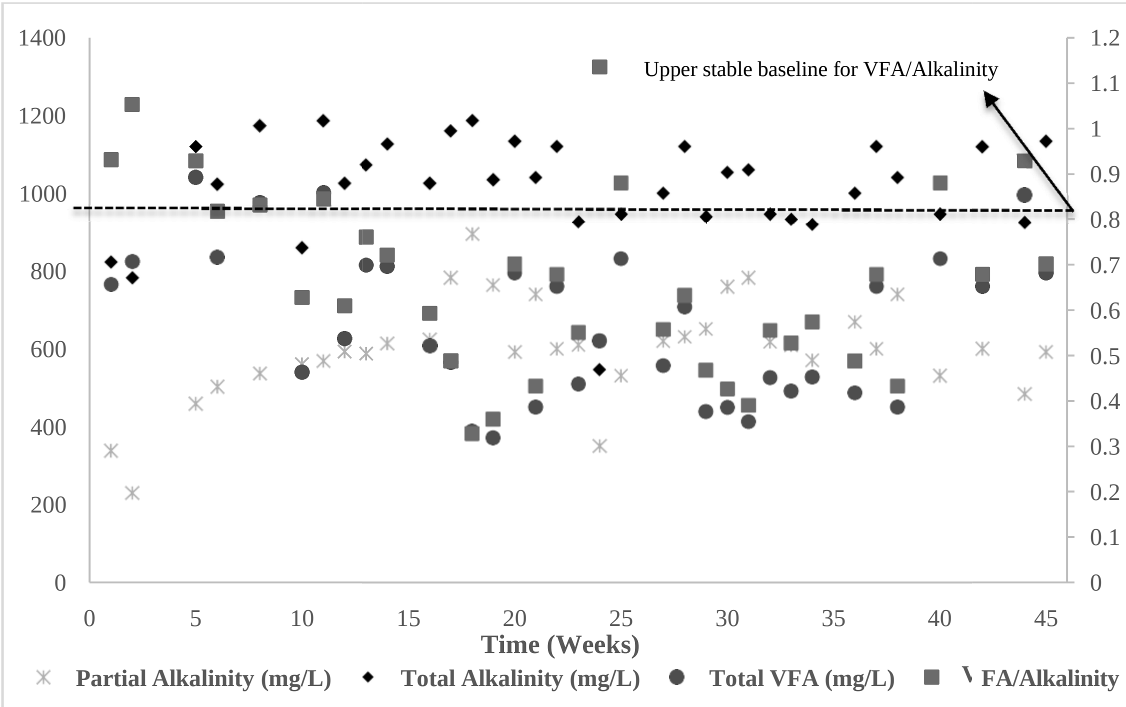


Figure 3.9: Variation of Stability parameters of the reactor with time

3.4.4 Synergy between various parameters

The temperature is found to be the most crucial parameter in this study and further, it affected other parameters decisively. The decision of OLR is also found to be temperature-dependent. As the temperature increases the digester can be made run at higher OLRs while on the contrary at lower temperatures the OLR is reduced accordingly for optimum biogas production.

Similarly, OLR and methane production is also found to be dependable on each other. During the feasibility study, the digester was run on various OLRs. As the OLR increases the methane production is also increasing. Apart from the methane production, the stability parameters such as pH, Alkalinity, VFA, VFA/Alkalinity ratio, CO_2, H_2S is also found to be dependent upon OLR.

It is very important to maintain the optimum pH in the digester. The optimum pH in the digester can only be maintained if and only if the digester is running at optimum or near optimum OLR. OLR can affect the VFA. If the digester is running above optimum OLR the accumulation of

VFA occurs which may inhibit the overall process if sufficient alkalinity is not present in the digester. Therefore, the ratio of VFA/alkalinity ratio is also very important for optimum performance of the digester. Apart from that if the digester is not running at suitable OLR it also affects the composition of biogas. An anaerobic digestion process is said to be running at optimum if the percentage of CH_4 is maximum while the percentage of CO_2 and H_2S are minimum.

3.5 Mathematical and Kinetic modeling

The FOM, MGM, RCM, MLF were selected to decide the most accurate fitting model for AD of FW in such ambient conditions. Figure 3.10 summarizes the curve fitting accuracy of every model and comparison with each other and summary and comparison of coefficients and fitting accuracy of models Table 3.4. Amongst several parameters, Latency (λ) is one of them. Latency is generally defined as the time taken to begin the methanogenesis process and it is generally also known as Lag phase. In the present study, λ is reported about 1(day). The RCM predicted λ as 2.3 days, on the other hand, MLF and MGM have predicted $\lambda<0$ which practically has no meaning. Donoso-Brabo *et al.* (2010) also reported $\lambda<0$ while treating primary and secondary sludge. They further concluded that these models should not be used for the prediction of λ when work is in the context of CH_4 generation. Rather, these models should be used where higher λ is observed relatively higher side like during Hydrogen production. Therefore, based on the results obtained from this study as well we can state that RCM should be used to predict λ during the production of CH_4 during the AD process [275].

Table 3.4: Summary and Comparison of coefficients and fitting accuracy of models

Model parameters	FOM	MGM	RCM	MLF
P^* (LCH4/g VS)	34.125	32.951	33.861	32.051
R_m (mL CH_4/g VS/day)	NA	134.51	-248.301	121.777
k (d^{-1})	0.0073	NA	NA	NA
λ (days)	NA	0	2.32	0
R^2	0.991	0.990	0.990	0.979
$(P_0)^*$ (LCH_4/g VS)	29.970	31.031	30.052	31.625

*indicates cumulative

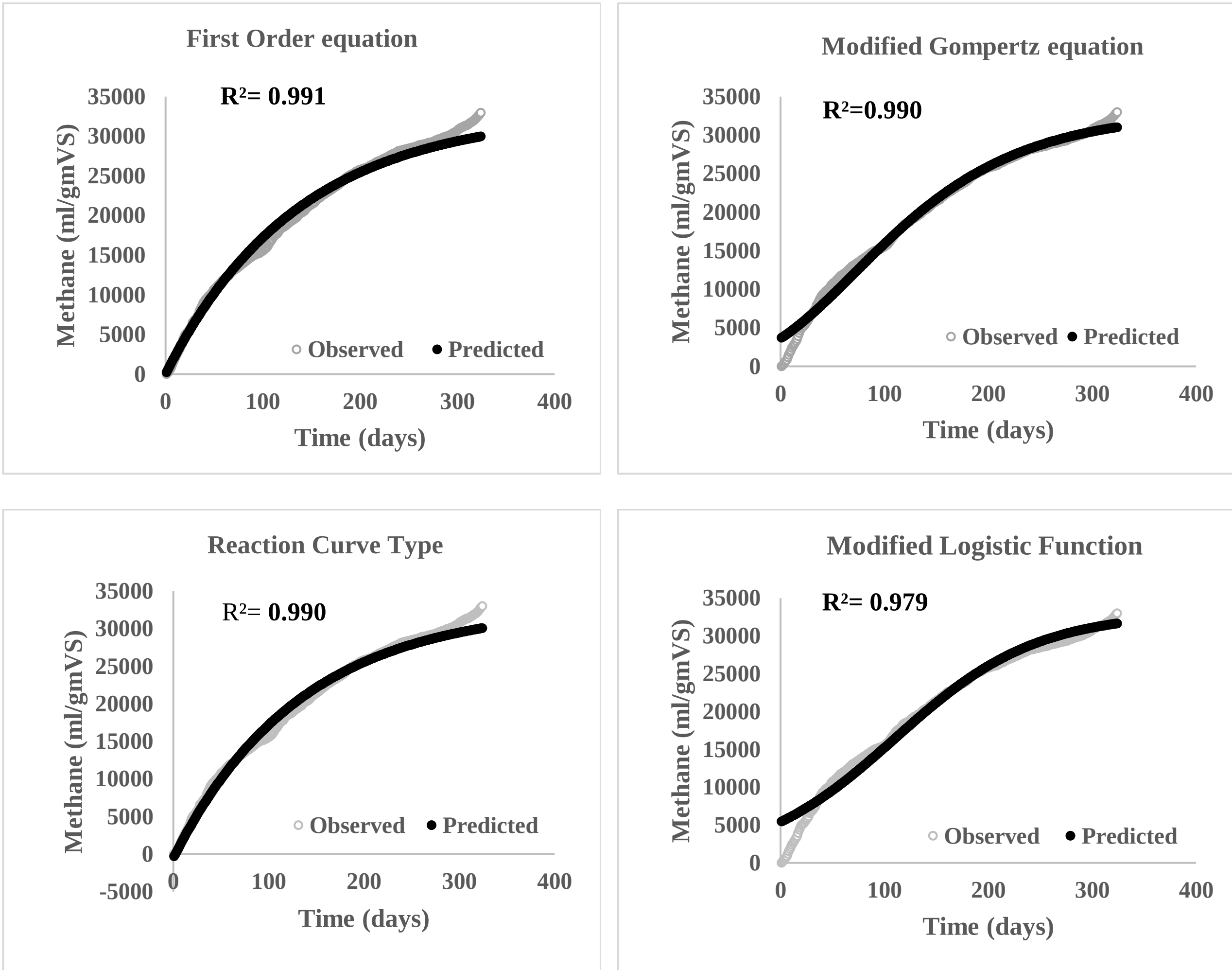


Figure 3.10: Comparison of mathematical and kinetic models

So, overall FOM was the most accurate model with *k* =0.007 day^{-1} and with R^2=0.990, *P*= 32.951 L CH_4/g VS, and *R*=134.51 L CH_4/g VS/day MGM was the best mathematical model. For other parameters like R_m, *P*, and P_0, no significant difference was noticed. Moreover; MLF has predicted the P_0 with the least deviation of 4.107%, and all models have shown an average deviation of 7% only.

3.6 Concluding Remark

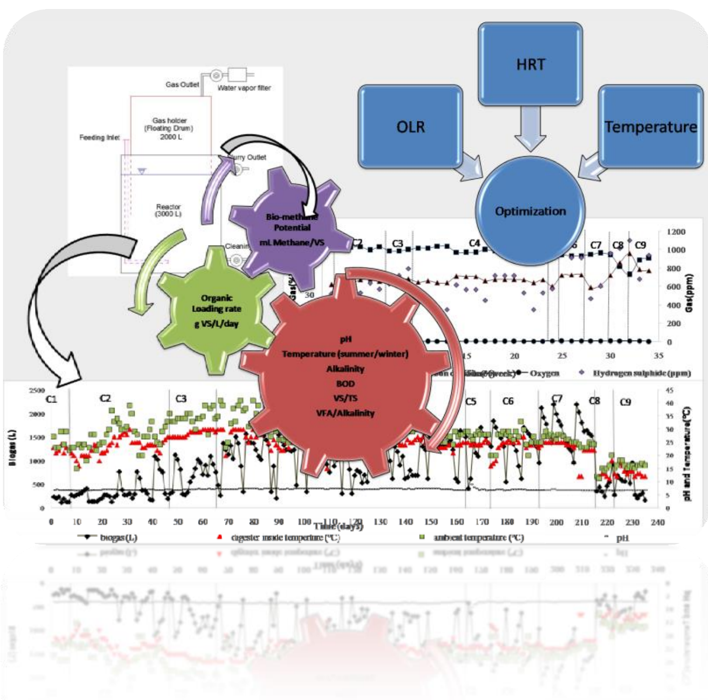
The experiments on the pilot-scale (3,000L) were conducted for 324 days at ambient temperature conditions with the varying atmospheric condition. The basic objective of the present study was to check the feasibility of working of the digester at low mesophilic and psychrophilic temperatures conditions using food waste as substrate. The major findings from the investigation are as follows:

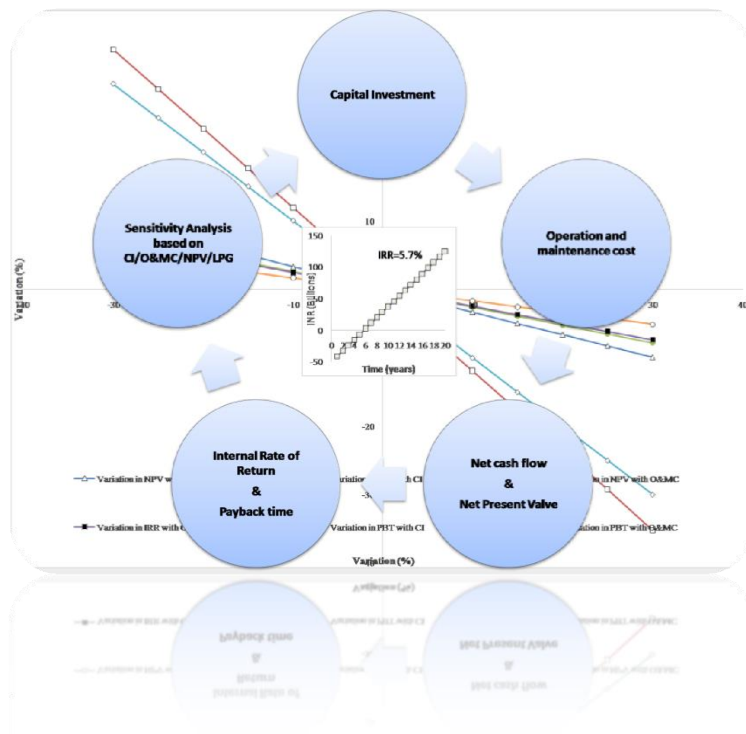
1. AD of FW at continuously varied psychrophilic and low mesophilic temperatures (at an altitude 1,544 m above MSL) is not as similar as at mesophilic and thermophilic temperatures (at an altitude ≤ 1,000 m above MSL).
2. The maximum and minimum biogas was reported in June 2017 and January 2018, respectively. In the winter season, the production of biogas has decreased drastically (approximately 55%). Although, after February 2018, a significant improvement in the stability of digester and biogas production was attained. Also, the production of methane per month has a linear dependency ($R^2 = 0.9283$) on the average monthly temperature.
3. Despite such adverse environmental conditions (at such low temperature *i.e.* -2.6°C) the AD process was not inhibited. As far as AD in Himachal Pradesh is concerned, more substantial studies are required for the special environmental conditions in HP due to very large temperature fluctuations in day and night.
4. Furthermore, in the future, based on our study maximum OLR can be made to be achieved in summer and winter season at a similar altitude. There should be some modification in the current reactor so that improved biogas production can also be achieved in winters. With optimized OLR and suitable modifications to the design of the reactor; it can also be made to utilize FW from households, hotels, canteens, *etc*. in the state.
5. Among all the mathematical methods used in the present study, FOM was the most accurate model with k =0.007 day^{-1} and with R^2=0.990, P= 32.951 L CH_4/g VS, and R=134.51 L CH_4/g VS/day MGM was the best mathematical model.

The results of the present study will be helpful for researchers and industries who want to work in the field of AD at low mesophilic and psychrophilic temperatures conditions. The effect of daily temperature variation on the continuous AD, performance of the digester is analyzed for daily biogas production rate, methane yield, and reduction in the volatile solid fraction. Moreover, it will help in the safe disposal of household, hotel, restaurant, and institutional leftover food waste and will provide a rich source of energy in the kitchen and generation of nutrient-rich bio-slurry which can be utilized in field for optimum growth of crops.

CHAPTER - 4

Techno-Economic Analysis, Kinetics, Global Warming Potential Comparison and Optimization of a Pilot-Scale Unheated Semicontinuous Anaerobic Reactor in a Hilly Area





~ Continuous improvement is better than delayed perfection.

-Mark Twain

CHAPTER-4

TECHNO-ECONOMIC ANALYSIS, KINETICS, GLOBAL WARMING POTENTIAL COMPARISON AND OPTIMIZATION OF A PILOT-SCALE UNHEATED SEMICONTINOUS ANAEROBIC REACTOR IN A HILLY AREA

4.1 Introduction

The development of any nation relies upon several pillars and energy is one of them. Besides, the economic growth of any nation to a large extent depends upon the energy. Therefore, approximately all developed and developing countries are continuously working in the direction of increasing energy growth to grow the economy. India is also capitalizing in the energy sector significantly and witnessed growth in the energy sector but despite this growth, India is still suffering from energy crises. In India, a significant fraction of urban and more specifically rural areas at the domestic level utilize non-renewable energy sources (NRES). In general, the main NRES used in India is petroleum, diesel, coal, firewood, and lignite. In this context, the Ministry of Statistics in its one of the reports confirmed that India still majorly relies on these NRES [295]. Now it is very essential to notice that these NRES are diminishing with time. Therefore, in future energy supply or available NRES cannot uphold energy demands. Overall infrastructure development and a huge rise in the population are some of the key factors for this exhaustion of NRER. According to a study conducted between 2011-2017, the compound annual energy growth has increased by 3.54% [296]. Therefore, available NRER are not able to deal with India's considerably escalating energy demand [297]. A recent report revealed that demand for natural gas, crude oil has increased significantly during 2007-2017. Consequently, the import of natural gas and crude oil has also increased by 15.42 and 5.46%, respectively [296], [297]. Due to this reason, India is one of the leading importers of crude oil across the world [295].

It is also a fact that in the process of utilizing these NRER emits GHG that further cause huge problems for the environment. In this regard, various suitable policies are made by the various governments at regular intervals. In India, the Intended Nationally Determined Contributions has aimed for curtailing GHG emissions concentration per unit Gross Domestic Product (GDP) by 33-35% below 2005 levels by 2030 through various measures [298].

Therefore, across the globe, the researchers and industries should come up together and investigate alternative renewable energy resources (RER). Uses of this RER will reduce the dependence on NRER. One of the important advantages of practicing RER is the curtailment of long term GHG which further will reduce global warming. Today for any developing nation, RER is playing an influential part for augmentation of abating utilization of NRES and thus promoting the low carbon production pathways. There is various RER such as hydro, wind, solar, and bio-energy. Bio-energy is one of the fundamental and ancient ones and it is satisfying 10% of the world's total energy demand [295]. In one of its reports by Word energy Council, it was stated that if energy policies are effectively implemented then approximately 60% of the total world's energy demand can be satisfied by bio-energy till 2025. This will reduce reliance on NRER by approximately 30% [299].

In this direction, a cumulative project of 63 GW has been set up by the Government of India, in which bio-energy has a contribution of 14.29% [298]. Nevertheless, renewable energy harnessed from biowastes such as FW, sewage sludge, dungs, *etc*. is only 0.26% [296].

The biogas is one of the types of bioenergy which is generated through the utilization of biomasses generated from various sources such as industries, households, commercial, and institutions through the process of AD. Biomass converts into biogas through the process of anaerobic digestion. The very well-known components of biogas are CH_4, CO_2, and there is an insignificant fraction of H_2S and oxygen (O_2). AD is gaining popularity globally because it is feasible to move from smaller to a larger scale in transforming biodegradable waste to energy [300], [301]. AD has a sustainable potential to help in meeting the energy demand for a nation and has several advantages over NRES such as curtailment in GHG emissions, reduces the load on landfills, *etc*.

In India, the basic sources of generation of biomasses are municipal solid waste (MSW), animal dung, residues from agro-industries, *etc*. which are highly susceptible to pollute the environment if not managed or treated scientifically. In India, 80-90% of MSW collected is open-dumped [302]. A study reveals that 90% of the collected waste is directly dumped to the landfill site without any further scientific treatment [303], [304].

MSW generation is increasing every year and country like India is struggling to manage the MSW in a scientific and eco- friendly manner [305].

Even the northern hilly states of India remain untouched from this problem. Here also a similar kind of scenario is taking place. In fact, in some of the states, even quantification of MSW has also not been done before 2014. Here also, the municipalities are struggling with improper handling and treatment of MSW. It is primarily due to a lack of funds and skilled labor in these areas. Besides, comparatively higher rainfalls and some geological constraints are also one of the prime reasons. Although to manage MSW, the practice of biogas reactor, refuse- derived fuel, composting, and sanitary landfills are highly recommended by one of the reports [302], [306]. From the literature survey, it is evident that FW has an enormous fraction in MSW (about 35%) and due to its volatile nature, it is a suitable substrate for AD for the production of CH_4[43]–[50]. Keeping in mind the potential hazards of direct emissions of CH_4 and CO_2, in the atmosphere through direct dumping of FW, this chapter focuses on the optimized utilization of FW through the process of AD for all hilly states of Northern India. Based on optimized OLR, techno-economic aspects and ecological aspects of the anaerobic digestion of food waste in all northern hilly states of India have been addressed.

4.2 Material and Methods

To optimized OLR, a pilot-scale study on AD of FW has been conducted in Himachal Pradesh. Based on the results obtained from the study a TEA, GHG emissions, global warming potential (GWP) and energy potential are also analyzed for 11 hilly states (Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Arunachal Pradesh, Assam, Meghalaya, Mizoram, Sikkim, Tripura, Nagaland, and Manipur) in Himalayan ranges due to similar topography, climate and living habits across northern India. These states cover a geographical area equivalent to 2,87,623 Km^2 (75.3 million inhabitants) with an MSW generation of 12,549.6 tons per day (TPD). Even though the core focus of the article is on the northern hilly states of India but it would be relevant to other developing countries looking for safe disposal of FW through anaerobic mono-digestion specifically in hilly regions.

4.2.1 Optimization Study

To assess the maximum OLR for the process in summer and winter seasons in natural environmental conditions (without heating), the optimization study was carried out for 235 days including both seasons.

In this study, the decision of OLR to start the reactor has been decided with the help of results obtained from the feasibility study of AR (Refer to Chapter-3). During the experiment, the OLR was increased systematically throughout the experiment. The whole experiment was divided into 10 different cycles: Cycle-1 (C1) to Cycle-10 (C10).

The details regarding the study location, description experimental setup, substrate, characterization of the substrate, inoculums, and feeding, analytical methods have already been discussed in the Material and methods section of Chapter-3. To study the kinematics of the process First order Kinetic model has been used. The formulation and other details of the model are already given in Chapter-3. The workflow for the optimization study is shown in Figure 4.1.

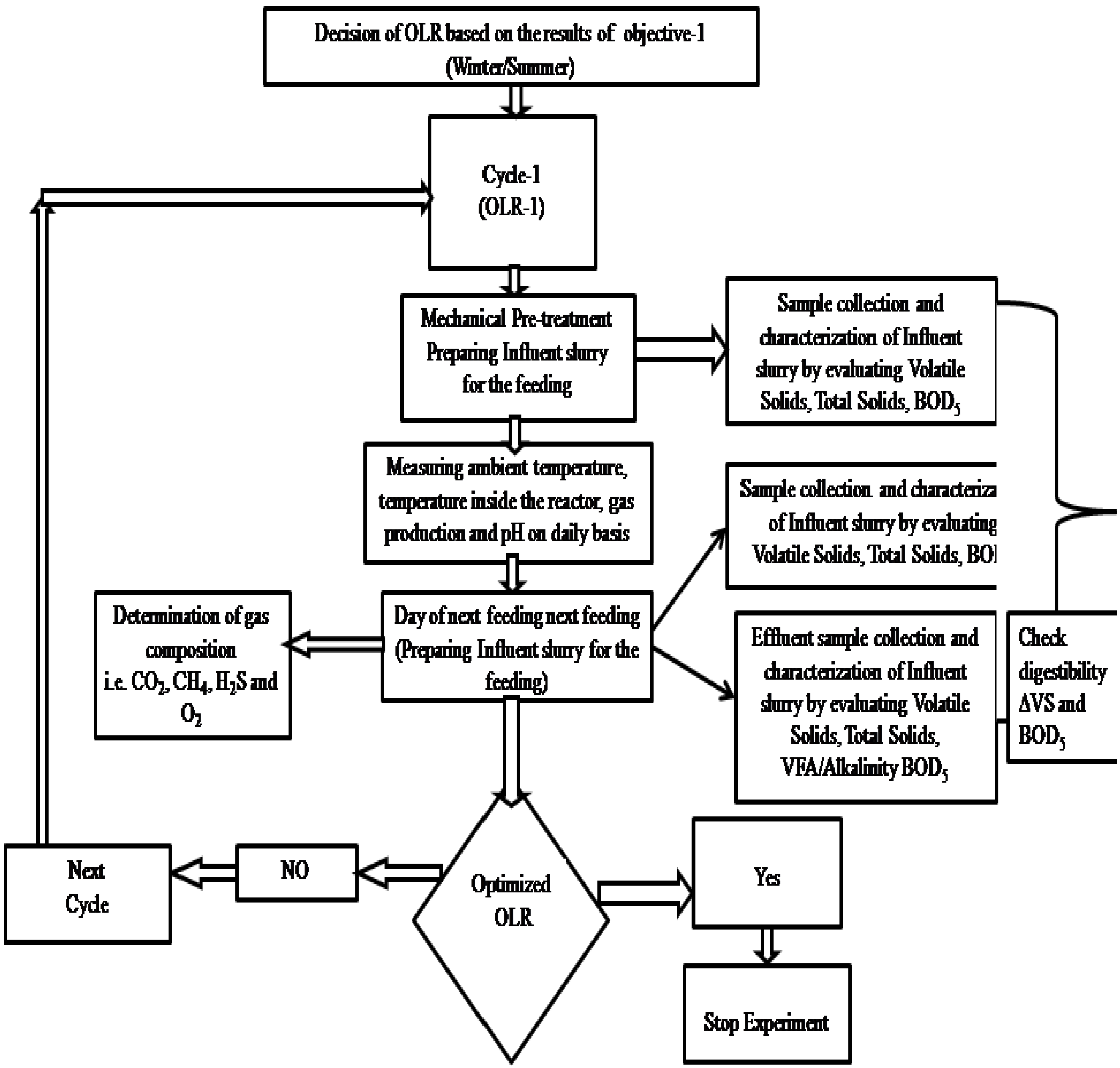


Figure 4.1: Workflow diagram for Optimization study for OLR

4.2.2 Techno-economic aspects of AD of FW

Generally, before the final decision for the conversion of any lab-scale model to pilot scale, economic feasibility studies are carried out. These studies are conducted with the help of TEA. In the present study, TEA has been carried out to investigate the economic feasibility of this process on a large scale. The results obtained (the optimized OLR and methane potential) during the optimization process has been used to calculate input parameters for this analysis. Primarily, before setting up any pilot-scale anaerobic process Capital Investment (*CI*) and Operation and Maintenance (*O&MC*) Costs need to be determined. In this study, the determination of *CI* and *O&MC* has been done with the help of the method suggested by Shah *et al*. (2016) [307]. In this study, FW generated from 11 northern hilly states of India has been utilized for the AD process to generate CH_4. It will partially replace the LPG requirement in these states. The current price of LPG in these states is approximately 1,500 INR per commercial cylinder. So, in this regard determination of payback time (*PBT*), net present value (*NPV*) and, Internal rate of return (*IRR*) has been carried out. Apart from that in the future, there is a possibility that the *CI*, *O&MC* may also change so considering these facts a detailed sensitivity analysis has also been performed. A change of ±5, ±10, ±15, ±20, ±25 and ±30 % was made in CI and O&MC and the respective change on NPV, IRR and PBT reported. A workflow chart for the TEA is illustrated below in Figure 4.2.

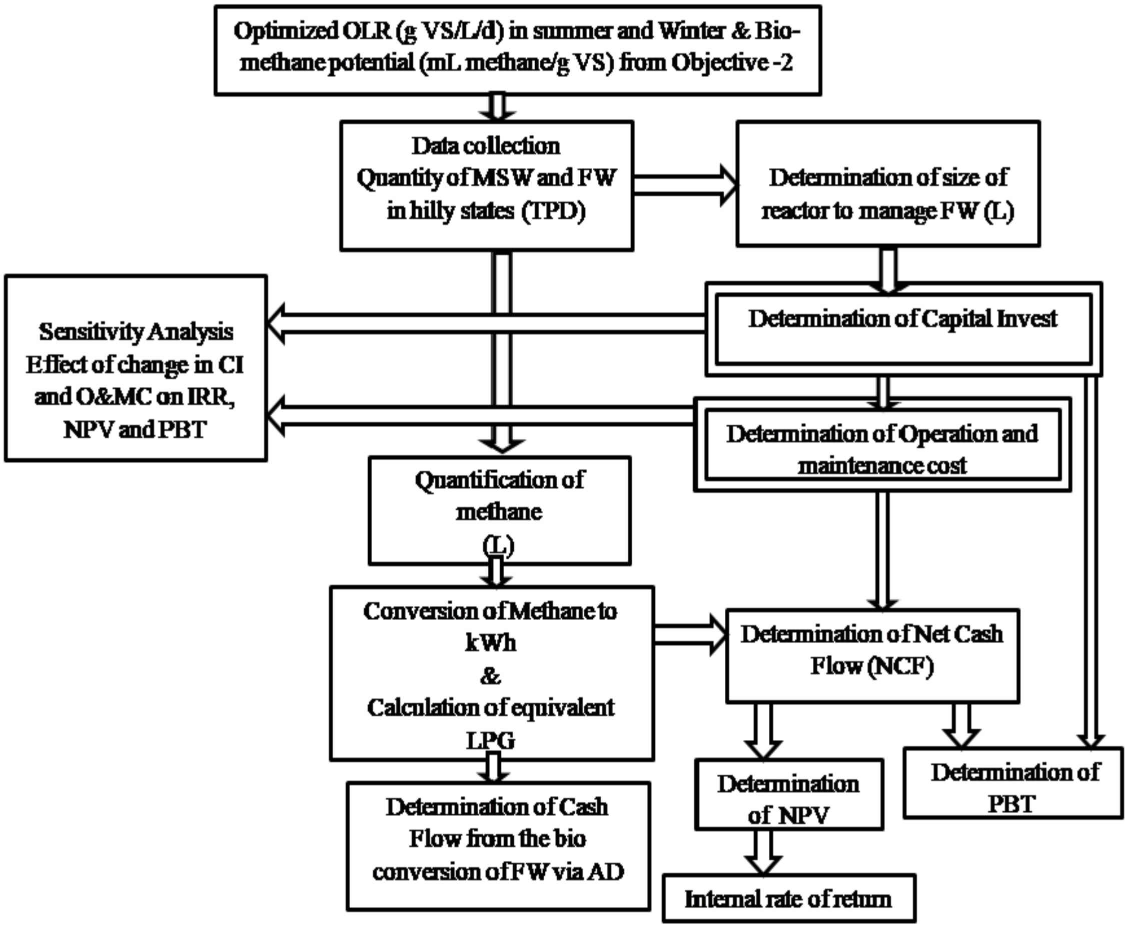


Figure 4.2: Workflow for Techno-economic Analysis

NPV is an effective cash flow based on the time value of money consideration. To conclude the cost-effectiveness of the proposed process, NPV is analyzed using Eq. (4.1) [308]

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{CI}{(1+r)^t} \quad (4.1)$$

Here, C_t is expected net annual cash flow at any time t (years), r is the discount rate (% per year) and T is the total operation time of the reactor.

To evaluate the profitability of any project apart from the *NPV*, *IRR (%)* is an important evaluation criterion for decision making and can be calculated using Eq. (4.2) [308]

$$0 = NPV = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t} - \sum_{t=0}^{T} \frac{CI}{(1+IRR)^t} \quad (4.2)$$

To assess the application perspective of the planned anaerobic reactor, the *PBT* is used as other assessment criteria. Payback time is a modest way to determine the duration in which expected cumulative cash flow matches the initial *CI*. It was calculated with the help of Eq. (4.3) [309]:

$$CI = \sum_{t=1}^{PBT} C_t \tag{4.3}$$

4.2.3 Ecological characteristics of AD of FW

Generally, in these hilly states either the FW is being dumped on the landfill or it is utilized in compost facilities. One of the aims of this study was to treat FW with the AD process. To assess the GHG emissions due to FW on landfill, compost, and also from the AD process, a methodology suggested by the IPCC guidelines 2006 was adopted [310]. Formulations used during the determination of the emissions are given below:

(a) CH_4 emissions from open dumping

$$A = \sum_{y-b}^{T-1} \{ Q_x L_0 \left(e^{-k(T-y-1)} - e^{-k(T-y)} \right) \} \tag{4.4}$$

Where *A* is CH_4 production/year (Mg/year), *y* is the year of waste disposal, *b* is the beginning year of inventory, *T* is the year for which the emission is to be determined, L_0 is the waste quantity (Mg), M_x is CH_4 production potential and *k* is decay rate constant (y^{-1}).

(b) CO_2 emissions from open dumping

$$C = A . \left(\frac{1-G}{G} + SOX \right) . \frac{44}{16} \tag{4.5}$$

Where *C* is CO_2 emissions (Mg/yr), *A* is CH_4 generation from Eq. (4.4), *G* is the fraction by volume of the CH_4 in landfill gas *SOX* is soil oxidation fraction typically of 0.1 (fraction)

(c) CO_2 emissions from Composting

$$F_{CO_2} = GF_{Compost} . \sum_{n=1}^{N} (L_{Compost} . Vn) \tag{4.6}$$

Where F_{CO2} is CO_2 emissions (Mg/yr), $GF_{compost}$ is CO_2 emission factor for composted material (Kg CO_2/kg dry solids), *n* is Index for the waste material or bulk agent, *N* is the total number of the different waste materials added to the composting process, $L_{compost}$ is the annual mass of the material *n* added (wet basis), V_n is total solid content of the material *n* when added or fed to the

the compost (dry solids/kg wet solids).

(d) CH_4 emissions from Composting

$$D_{CH_4} = WF_{Compost,CH_4} . P_{Compost} \tag{4.7}$$

Where D_{CH_4} is CH_4 emissions (Mg/ yr), $WF_{Compost,CH_4}$ is CH_4 emission factor for composted material (kg CH_4/Kg wet waste), $P_{compost}$ is an annual mass of material added or fed to the composting process (Mg/year, wet basis)

(e) N_2O emissions from Composting

$$X_{N_2O} = LF_{compost_{N_2O}} . R_{compost} \tag{4.8}$$

Where X_{N_20} are emissions (Mg/yr), $LF_{compost_{N_2o}}$ is N_2O emission factor for composted material (Kg/kg wet waste), $R_{compost}$ is an annual mass of material added or fed to the composting process (Mg/year, wet basis)

4.3 Results and Discussions

4.3.1 Decision of suitable OLR with Temperature

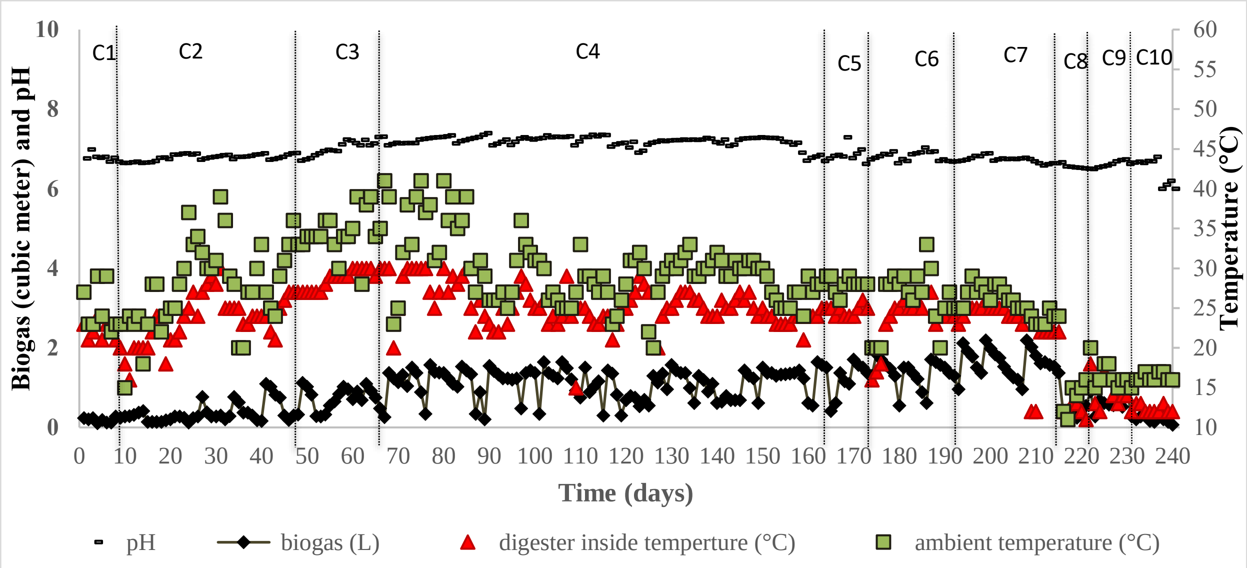
A decision of correct OLR is very important while running any anaerobic reactor. Certainly, its decision depends on various factors; the type of substrate and temperature is one of them. Grover *et al*. (1999); Lettinga *et al*. (2001) also stated that the decision of a suitable OLR for a stable digestion process is temperature-dependent [311], [312]. Dev *et al*. (2019) found that ambient temperature and OLR are crucial factors and can affect the unheated long-term CH_4 generation [313]. Luo *et al*. (2017) stated that an unheated anaerobic reactor, especially when it is exposed to drastic fluctuated temperatures, may get affected by in terms of CH_4 production [314]. An unsuitable OLR for any AD generally leads to various complications such as accumulation of VFA, low biogas yield, odor and foaming, and hence process failures [315].

In the present study, the anaerobic reactor was operated at ambient temperature. There were significant atmospheric temperature fluctuations (low mesophilic and psychrophilic) daily (during day and night time) and seasonal basis. Hence, in the preliminary stage, due to the drastic temperature fluctuations, it was very challenging to decide a suitable OLR to initiate the process.

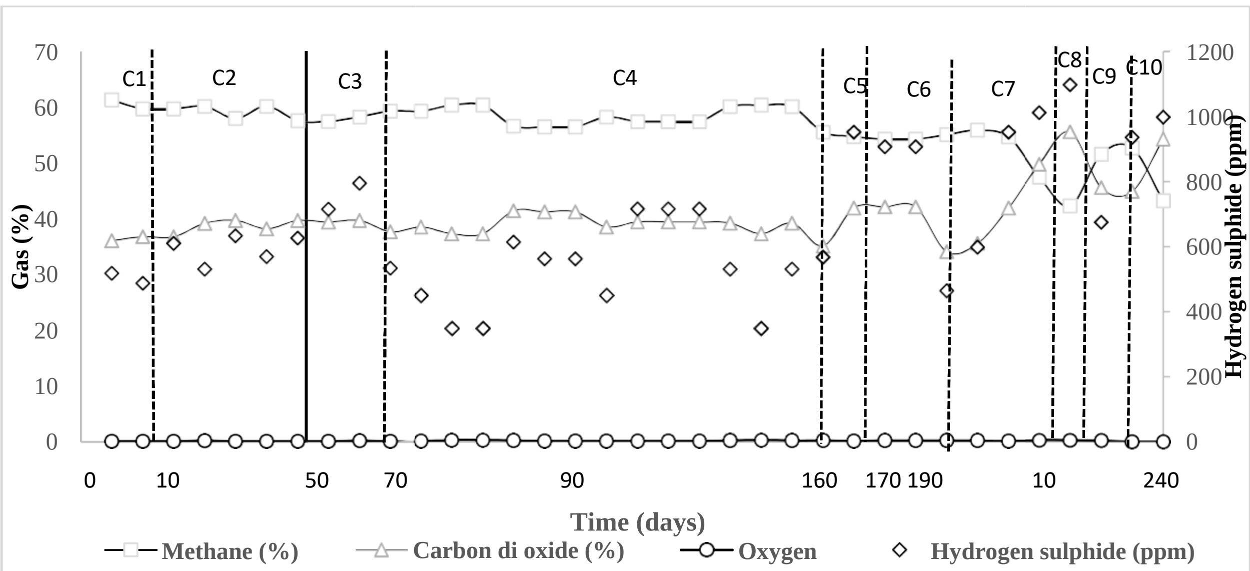
As discussed in Chapter-3, OLR was decided based on a study conducted by Safley and Westerman (1994) [316] and experience gained during the accomplishment of Objective-1. During the optimization study, in the beginning *i.e.* during the C1, a moderate OLR equal to 0.067 g VS/L/d was decided to adopt which is lesser than that suggested by Safley and Westerman (1994). This is attributed to the fact that AD of FW has a low buffering capacity and its digestate is more prone to low pH [317].

This OLR is relatively less when compared to other various studies. Generally, an alternate strategy employed by the researchers to employ high OLR is to go for co-digestion of FW with any dung/manure so that it could strengthen buffering to the AD process [160], [318] but the availability of dung in some of the urban and rural areas is difficult. This is attributed to the fact that generally in rural India dung is either used as manure during the farming or dung cake is prepared which used while cooking. On the other hand, in urban areas generally, people don't keep farm animals such as cows, horses, pigs, buffalo, and goats.

Figure 4.3 (a) depicts time variation of temperature, pH, and biogas generated and (b) biogas composition. From Figure 4.3 (a), it can be seen that the temperature inside the anaerobic reactor has always been reported more when compared to the ambient temperature. This is attributed to the fact that the night temperature used to be significantly low during the whole experiment. HRT has a great influence on the production of VFA and its distribution [319]. In this study, HRT was recorded between 10-42 days. However, the optimized HRT was reported 10 and 17 days in summer and winter, respectively.



(a)



(b)

Figure 4.3: (a) Variation of Temperature, pH and Biogas and (b) Biogas Composition

4.3.2 Optimization of the process

The summary of the optimization study has been shown in Table 4.1. After the experimental studies, it was found that the maximum OLR in summer and winter was achieved as 0.34 and 0.21 g VS/L/day in C7 and C9, respectively. Dev *et al.* (2019) carried out a study and reported the OLR in the range of 0.56 to 1.06 g VS/ L/d while investigating the feasibility of the fruit and vegetable waste as a substrate in kind of similar environmental conditions [313]. Dev *et al.* (2019) successfully operated the rector at a maximum OLR of 1 g VS/L/day (approximately) however the maximum CH_4 potential recorded at an OLR of 0.57 g VS/L/d [313].

Table 4.1: Summary of the optimization study

Cycle No.	HRT (day)	Duration time (day)	OLR (g VS/L/day)	Average CH_4 (%)	Average BOD_5 reduction (%)	Average VS reduction (%)	Average VFA/alkalinity
C1	42	1-9	0.06	60.5±1.1	68.85±8.45	95.79±1.27	-
C2	28	10-47	0.12	59.1±1.2	67.69±9.53	96.72±0.90	0.220±0.075
C3	21	48-66	0.17	57.8±0.4	58.15±5.97	95.94±0.49	0.291±0.042
C4	17	67-164	0.21	58.6±1.5	60.26±10.10	96.09±2.78	0.239±0.082
C5	14	165-173	0.25	57.9±3.2	52.71±4.41	89.73±0.85	0.377±0.002
C6	12	174-192	0.29	54.7±0.6	63.97±7.96	93.28±2.26	0.307±0.095
C7	10	193-214	0.34	55±0.6	61.56±2.27	94.67±0.30	0.287±0.018
C8	28	215-222	0.38	44.9±3.6	25.60±2.0	52.61±1.80	1.267±0.105
C9	17	223-235	0.21	52.1±0.8	50.36±1.21	92.36±1.86	0.261±0.030
C10	20	236-240	0.25	43.21±0.8	44.6±3.40	75.2±3.40	1.34±0.21

During summer, C2-C7 the OLR increased from 0.06 to 0.34 g VS/L/day, and the weighted average of pH was reported 7.0. As well, in the same interval CH_4, CO_2 and H_2S were reported 57.93%, 38.84%, and 608.8 ppm, respectively. Destruction of VS and BOD_5 and was achieved 93.578%, and 61.88%, respectively. Besides, the VFA/Total Alkalinity ratio was found 0.314 and total alkalinity was found 2,357 mg/L which indicates a stable AD.

Further increase in the value of OLR in cycle C8, from 0.34 to 0.38 g VS/L/d a significant drop in the pH (6.5) was reported. Also, the VFA/Total alkalinity ratio increased to a value of 1.3 and total alkalinity dropped to a value of 1,312 mg/L. During this period, the reduction of VS and BOD also dropped to a value of 52.6 and 53%, respectively. Moreover, the level of CO_2 was reported maximum (52.7%) while CH_4 was reported a minimum (44.9%). Therefore, after observing pH, VFA/Total alkalinity ratio, CO_2 and CH_4 it can be stated that the reactor has become unstable while increasing the OLR 0.34 to 0.38 g VS/L/d.

Similarly, when, OLR was increased from 0.21 to 0.25 g VS/L/d while moving C9 to C10, during winter season again anaerobic reactor has shown a kind of similar characteristics as shown from moving from C7 to C8. Again, the total alkalinity/VFA ratio exceeded the permissible limit (*i.e.*, 0.8) and sudden drop in pH and CH_4, and the rise in CO_2 was observed. Therefore, after observing pH, VFA/Total alkalinity ratio, $CO_{2,}$ and CH_4 it can be stated that the reactor has become unstable while increasing the OLR 0.21 to 0.25 g VS/L/d in winter. The summary of overall OLR, VS, BOD_5, and variation of VFA/Alkalinity ratio is shown in Figure 4.4.

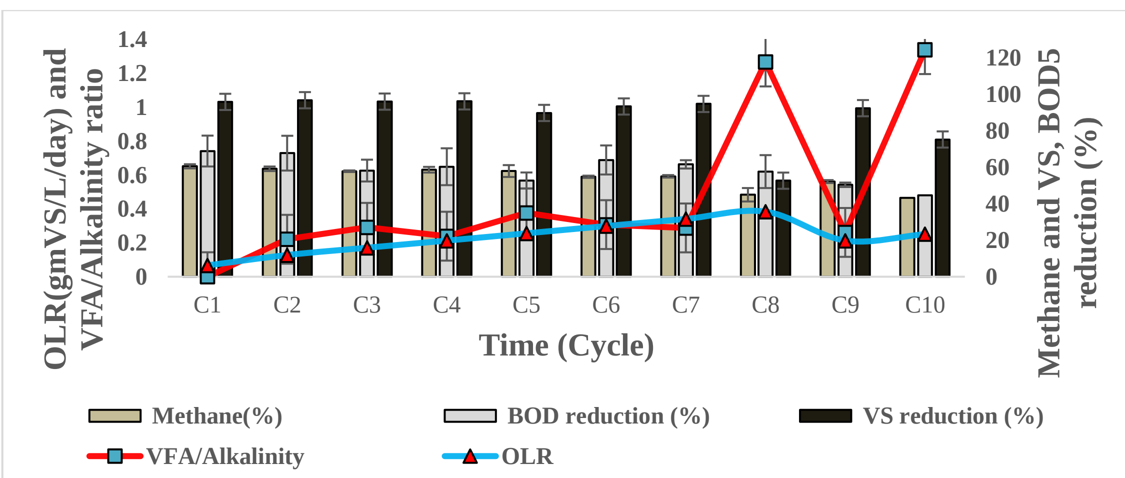


Figure 4.4: Variation of VFA/Alkalinity ratio, OLR and VS, BOD_5 reduction

Based on the temperature and OLR of various substrates a comprehensive comparison of several studies has been shown in Table 4.2. Rajagopal *et al.* (2017) have conducted a lab-scale batch study at 20°C in the context of North America. In this study, FW was mixed with cow dung and performed at OLR in the range of 0.8-4.2 g VS/L/d and a CH_4 yield of 0.477 ± 0.088 m^3 CH_4/kg VS was reported [183]. To the best of our knowledge, only one study is performed in India in which FW (mono-digestion) is utilized. In this study, Lou *et al.* (2012) performed all the experiments in natural ambient conditions in a pilot-scale semi-continuous anaerobic reactor without heating. However, this study was carried out in southern India at a place named Trivandrum (10 m above MSL) and there is considerable assortment in FW composition between northern and southern India [320]. In this study, the reactor was successfully operated at OLR in the range of 0.50-1.38 g VS/L/d.

Table 4.2: Comparative performance of mono and co-digestion of FW

Feed Type	VS%	OLR (g VS/L/d)	Temperature and operating conditions	Biogas (%)	CH_4 potential (mL/g VS)	Reference
Domestic FW without dung (batch)	13–37.5	0.8–4.2	20°C (lab study)	64.0–69.0	0.477 ± 0.088	[183]
FW with various dungs (lab scale; batch)	20.3 ± 3.2	1.0 g COD g^{-1} VS	30°C (lab study)	Not provided	0.227 (Maximum for cow dung)	[43]
Kitchen waste Inoculated with cattle slurry and grass silage (batch)	28.0	NA	37°C (lab study)	NA	0.467 - 0.529	[112]
FW with dairy manure (semi-continuous)	14.6	stepwise from 0.67 to 3 g/L/d	36°C (lab study)	63.0-74.0	0.140-0.460	[5]
FW (MD)	19.6	6.4-21.8	35 ± 1°C (lab study)	50.0-54.0	0.377-0.465	[321]
Kitchen waste (MD; batch)	22.7	3 g/L/d	37°C (lab study)	60.0	0.683	[317]

FW (MD; semi continuous)	17.0 ± 0.1	8 10 12	35°C (lab study)	61.2 58.0 35.0	0.347 0.277 0.096	[160]
Fruit and Vegetable waste (Pilot-scale; Continuous plug flow reactor)	26.3	0.5	Field Study Natural field conditions	43.0 CH4, 50.0 CO_2, and 176 mg/L of H_2S	0.150	[322]
Kitchen waste (MD; continuous)	NA	0.50-1.38	Field Study Natural field (22-34°C)	63.1–66.8 $CH_4$27.4–33.3 CO_2	0.249	[320]
Kitchen FW (MD; semi-continuous)	14.95	0.342 (summer) 0.214 (winter)	Field Study Natural field conditions (11-30°C; day time temperature)	55.2 CH_4 37.2 CO_2 672 mg/L H_2S	0.210-0.589	Present study

4.3.3 Kinetic Modeling

The hydrolysis rate constant '*k*', was determined from the First order Kinetic model with the help of non-linear regression. The observed biogas production was used as an input parameter to determine the value of *k*. Figure 4.5 shows the curve fitting relation between experimentally observed biogas yields and predicted biogas yields. During the curve fitting, a significantly strong co-relation was noticed. From the regression analysis, the *k* value was obtained 0.073 d^{-1} with (*R-squared value = 0.999*).

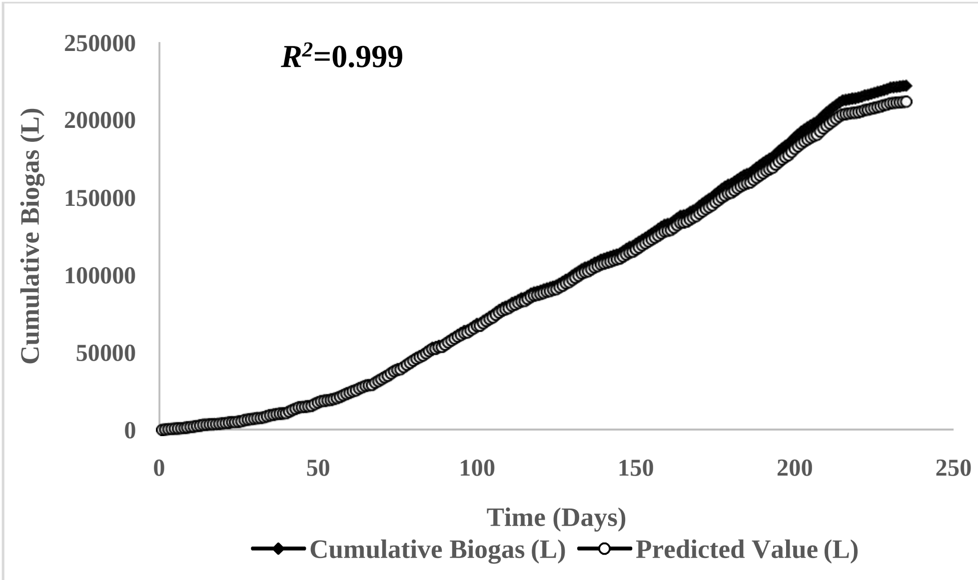


Figure 4.5: The Correlation between observed and predicted values of Biogas

A comparison of '*k*' for various substrates at different temperatures from various studies has been shown in Table 4.3. Browne and Murphy (2013) determined the *k* for FW and reported it in the range of 0.056-0.364 d^{-1}[112]. In another study, Bala *et al*. (2019) determined the *k* of organic fraction of MSW in the range of 0.143–0.182 d^{-1}[221]. Form Table 4.3; we can see that in several studies for other than FW, the *k* is reported relatively towards the higher side when compared to other substrates. This is due to the reason that FW is a rapidly digestible substrate when compared to others and therefore it has a higher hydrolysis rate. Besides, temperature and type of waste are some of the major performance bottlenecks for any digestion process and influence hydrolysis rate decisively [323]–[325].

Table 4.3: Comparative hydrolysis rate constants for various substrates and temperature ranges

Feed	**Temperature**	**Hydrolysis rate Constant (*k*;day^{-1})**	**Reference**
FW	Natural ambient temperature (11-30°C; day time temperature)	0.073	Present study
Erythromycin removal	55°C and <20°C	0.290 and 0.005	[223]

FW	37℃	0.056-0.364	[112]
Granular sludge	35℃	0.059–0.068	[224]
Olive mill wastewater	35℃	0.718	[222]
Cellulose	25	0.110-0.400	[226]
	15	0.030-0.110	
	10℃	<0.010-0.100	
Nitrogen rich material	55℃ and 37℃	0.261 and 0.234	[225]
OFMSW	20-40℃	0.143–0.182	[221]
Flocculent sludge	35℃	0.100 to 0.168	[224]

4.3.4 Techno-economic aspects of the Anaerobic Digestion of Food Waste in Northern Hilly States

In one of the previous sections of this chapter, the OLR of FW based anaerobic reactor has been optimized for summer and winter in natural ambient conditions. Based on these results, an assessment of CH_4 potential from FW generated in these hilly states has been performed. In the present study, it is presumed that CH_4 generated from FW will partially replace the LPG and it generates a source of revenue.

The summary of TEA of the proposed AD process in terms of *CI, NPV, O&MC, PBT, and IRR* is shown in Table 4.4. In the analysis, the assessment of NPV is performed by assuming a discount rate of 12%. Besides, a conversion factor of 6.25 is used while converting biogas (per m^3) into energy in KWh as suggested by Blat and Balat, (2009) [326]. The TEA showed an NPV of 128 billion INR by the end of 25 years and the *CI* will return within 5.9 years (*PBT*). However, the first positive net present values will appear in the 7th year after the beginning of the project. The results of the sensitivity analysis are shown in Figure 4.6. Analysis has shown that *PBT, IRR,* and *NPV* will change by ±30%, ±34%, and approximately ±9%, respectively when *CI* will vary by ±30%. In the same way, *PBT, IRR,* and *NPV* will vary by about ±9-10% when *O&MC* will vary by ±30%. Hence, *CI* has a significant dependency on the economic indices of the project when compared to *O&MC*.

Table 4.4: Economic Analysis of the proposed process

Economic Indices	Value
Capital cost	41.43 billion INR
Operation and maintenance cost	1.73 billion INR
NPV (25th year)	128 billion INR
IRR	4.6 %
PBT	5.9 Years

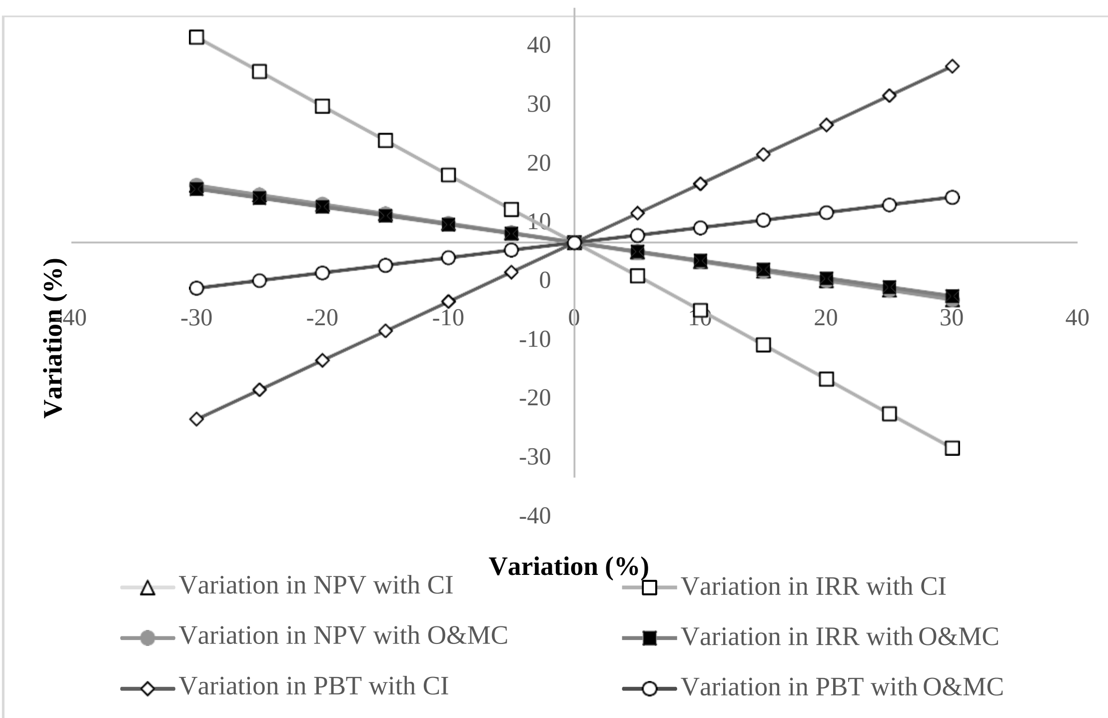


Figure 4.6: Sensitivity analysis of Net Present Value with variation in Capital Investment and Operation and Maintenance Cost

4.3.5 Greenhouse Gases Emissions from Food Waste

Generally, in the past few decades, it is noticed that unhygienic and unsafe environment has been created due to the mismanagement of waste in various parts of the country. A similar kind of situation is also developed in the northern hilly states of India. All hilly states are well-known tourist areas and therefore there is a huge number of restaurants and hotels. The details of waste generation, population, area (in Km^2), Global warming potential from various processes, and energy potential of the respective state are shown in Table 4.5.

Table 4.5: Ecological aspects of all hilly states of Northern India during 2019-2029

Name of State	Area (Km^2)	MSW generation per day (TPD)*	Current Waste to energy facility*	Landfilled (TPD)#	$(GWP) Anaerobic Digestion 10^3 tonnes CO_2 eq	$(GWP) Landfilling 10^3 tonnes CO_2 eq	$(GWP) Compost 10^3 tonnes CO_2 eq	$Estimated Energy Potential through of FW in 10 years (GWh)
Himachal Pradesh	55,673	342.5	NIL	308.2	74.7	581.3	125.2	375
Jammu and Kashmir	222,236	1,634.5	NIL	1,471.0	356.6	2,765.6	597.3	1,794
Uttarakhand	53,483	917	NIL	825.3	200.1	1,549.7	335.1	1,006
Sikkim	7,096	49	NIL	44.1	10.7	82.6	17.9	53
Arunachal Pradesh	83,743	13	NIL	11.7	2.8	21.8	4.8	14
Assam	78,438	7,920	NIL	7,128	1,728.1	13,385.9	2,894.2	8,693
Meghalaya	22,429	187	NIL	1,68.3	40.8	315.9	68.3	205
Nagaland	16,579	344	NIL	309.6	75.1	581.2	125.7	377
Manipur	22,347	176	NIL	158.4	38.4	297.3	64.3	193
Mizoram	21,087	552.6	NIL	497.3	120.6	933.8	201.9	606
Tripura	10,491	414	NIL	372.6	90.3	21,210.8	151.3	454
Total	287,623	12,549.6	NIL	11,294.6#	2,738.2	41,726.2	4,585.9	13,770

* as per CPCB 2015-2016, # assumed that 90% of MSW is directly dumped on landfill

A recently published report has revealed that despite a huge generation of waste in these states, there is neither any engineering landfill nor any other facility is available here [302], [306]. Also, being hilly states, these states witness significant rainfall every year as a result of that waste generally carries high moisture content. To decide the most suitable treatment method between AD and composting, renewable energy generation potential and GHG emissions are used as a decision-making tool. The GHG emissions from landfilling have also been analyzed so that a comparison between AD, composting, and existing scenarios could be made. The analysis shows that if a similar scenario remains *i.e.*, open dumping then in the coming 10 years emissions of 41,726 Gg CO_2-eq will take place. While, if FW is managed with the help of composting then the emission of 4,585 GgCO_2 eq will take place in the coming 10 years. On the other hand, if FW is managed with the help of AD then the emission of 2,738.2 Gg CO_2-eq will take place which significantly less when compared with composting and open dumping. Therefore, a curtailment of about 93% is possible if FW is managed with the help of AD. Moreover, if FW is managed with the help of AD it has a huge potential of renewable energy *i.e.*, 1,377 GWh/year. State-wise energy potential is shown in Figure 4.7. Hence in such ambient conditions, an AD of FW as a waste management method is very much recommended. From Figure 4.8, It can be seen that there is a linear correlation between GWP and population with $R^2 = 0.92$. The state with the highest population (Assam) has shown the maximum GWP whereas states like Mizoram and Meghalaya have shown the opposite trend.

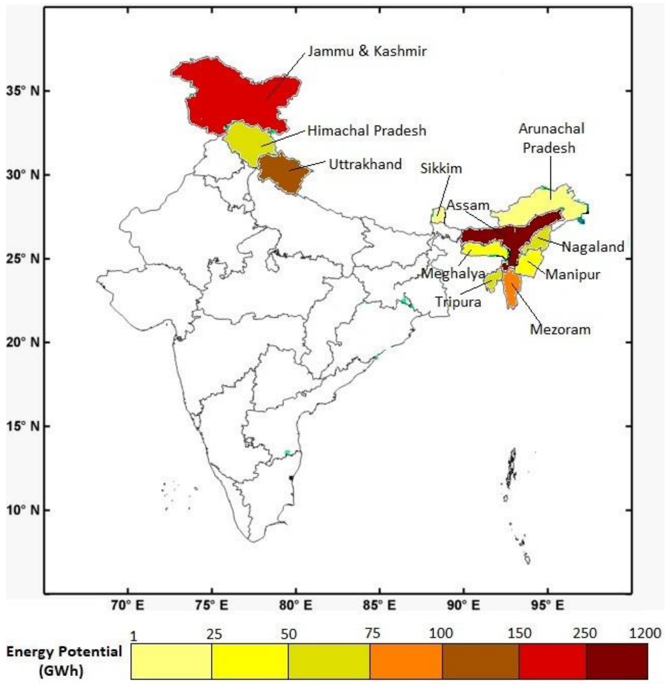


Figure 4.7: Spatial distribution of estimated Energy Potential from Food Waste across the Northern Hilly region of India

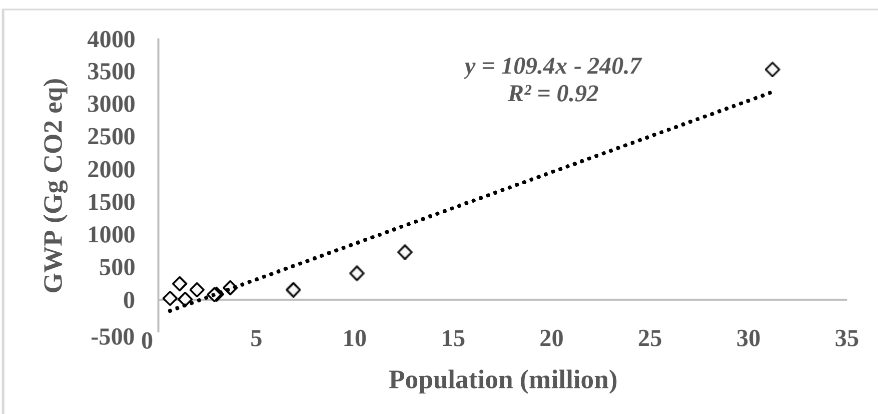


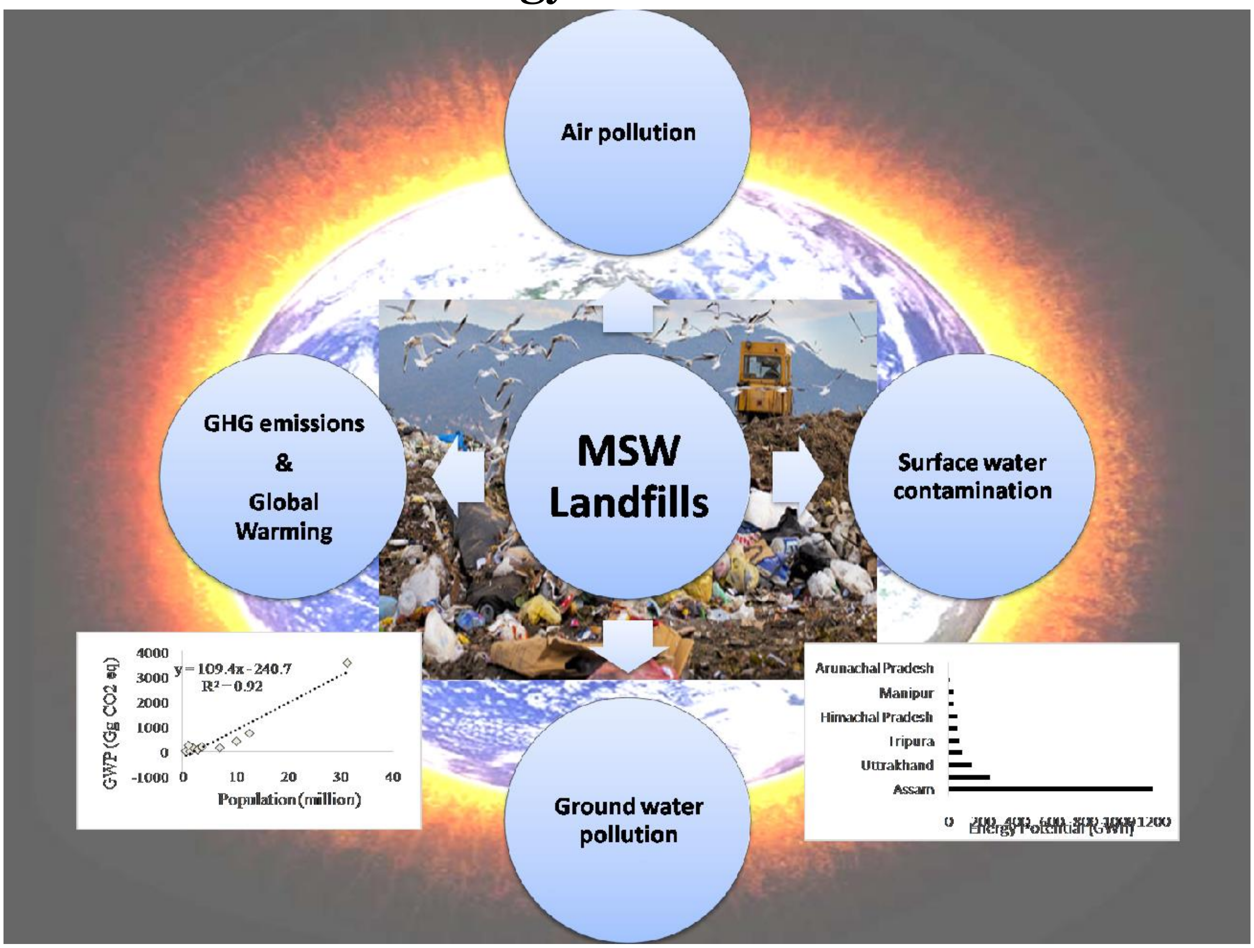
Figure 4.8: Co-relation between Global Warming Potential of Hilly States of Northern India with a population

4.4 Concluding Remark

The results of AD of FW at continuously varied psychrophilic and low-mesophilic temperatures at the pilot-scale without external heating, and co-digestion in the hilly area of northern India are presented here. FW is a source for RER and can be managed through AD even at continuously varied psychrophilic and low-mesophilic temperatures. This study also concludes that an AD of FW can be reached up to an OLR of 0.32 g VS/L/day in summer and 0.21gVS/L/day in winter. Based on the optimized OLR, an AD process for all northern hilly states is analyzed. It is estimated that capital investment on AR will return in 5.9 years with an IRR of 4.6%. Besides a shorter PBT, successful implementation of the AD process for the next ten years in these hilly states will curtail 93.4% and 89% GWP from AD and composting, respectively when compared to landfill. This recognized concept is the first in terms of energy generation and waste management in a hilly area through anaerobic mono-digestion process across the country. Further, simple floating drum type semi-continuous reactor is a low investment and cost-effective solution for management of FW and can be used for small-scale or large-scale reactors in villages, towns or cities of hilly areas of north India or any developing country having similar climatic conditions, which are usually lacking with funds. In a nutshell, a similar or maybe a worse scenario of GHG emissions can be seen in the coming decade if appropriate management of FW is not made. The result of the study will be helpful for the decision-makers and planners dealing with waste management.

CHAPTER - 5

The State-wise Energy Potential of MSW in India



~ Energy conservation is the foundation of energy independence.

\- **Tom Allen**

CHAPTER-5

STATE-WISE ENERGY POTENTIAL OF MSW IN INDIA

5.1 Introduction

Amongst several problems worldwide, global warming is one of the major problems today. Global warming is a process in which GHG absorbs the sun's radiation and as a result, there is a gradual increase in earth's temperature. The augmentation of GHG in the atmosphere is a consequence of the various human activities. Generally, GHG comprises nitrous oxide (N_2O), carbon mono-oxide (CO), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), CO_2 and CH_4 which are accountable for environmental degradation [327]–[330]. Various studies have concluded that only CH_4 and CO_2 have a noteworthy contribution to global warming. Therefore, massive emission of CO_2 and CH_4 in the last few decades has prompted the worry for almost all developed and developing countries, [331]. In this course, the Global Methane Initiative (GMI), an international public-private partnership, has taken initiative and defined anthropogenic methane potential. GMI stated that global anthropogenic methane potential is 6.88 Gt CO_2-eq and is expected to escalate the value of 8.59 Gt CO2-eq by 2020 if appropriate measures will not be taken in the future [332]. CO_2 is also a major greenhouse gas, in a general review of global CO_2 emissions, Nejat *et al*. (2015) stated that India contributes 5% in total CO_2 emissions by producing 1626 million tonnes [333]. Studies found that the uses of fossil fuels, burning of various waste material, rice cultivation, and anaerobic degradation of biomass are the prime sources of anthropogenic methane emissions [334]. After oil &gas operations (24%) and enteric fermentation (27%), landfills due to anaerobic degradation of organic fraction of Municipal Solid Waste (MSW) contributes the third-highest *i.e.*, 11% of global anthropogenic CH_4 emissions into the atmosphere [335]. From the last few years, there is a huge MSW generation due to urbanization, increased population, and economic growth. The population of India was 1.347 billion in 2017 and is increasing with an annual growth of 1.33% [336]. Moreover, today India is the second-largest populated country and second fastest economy in the world. As of now the urban population of India has witnessed a growth of 17.6% to 28% in the last 50 years and further it is expected to increase by 38% till 2026 [56].

Consequently, Indian cities generated eight times more MSW than that in 1947. A recent report submitted by the central pollution control board (CPCB) stated that there is a generation of approximately 135,198 tonnes of MSW per day as a result of various domestic, institutional, commercial and industrial activities and out of that about 82% is collected [302]. Besides, various studies indicated that due to inadequate funds and lack of knowledge among workers, nearly every Municipal Corporation is disposing of a huge amount of the total MSW openly without considering further treatment [54], [241], [337]. This is one of the main causes of contamination in nearby surface & groundwater resources and air present in the vicinity and henceforth affects humans living. Moreover, inappropriate disposal is also responsible for losing recyclable nutrients as well as reusable materials.

It is a well-known fact that the MSW in dumpsites is subjected to natural degradation by microorganisms. In the initial phase, it undergoes aerobic digestion where few or no CH_4 is produced. After a few months, O_2 present in the pores of MSW is utilized by the aerobic microorganism, and the establishment of anaerobic conditions takes place where emissions of CO_2, CH_4, H_2S, and other gases occur [338]–[343]. Methane is a dominating landfill gas (LFG) emitted during anaerobic degradation and constitutes approximately 50-55% of the total emission. Besides, methane has 31 times more GWP when compared to CO_2 [344]. Consequently, CH_4 is more hazardous for the environment than CO_2. However, CH_4 is a green fuel that can be utilized in electricity generation, heat source, *etc*. Certainly, well-managed landfills, having efficient LFG collection systems detain landfill gases and enable it to convert into energy in terms of heat or electricity. This makes it more attractive from an economic point of view as the energy generated (in terms of heat or electricity) onsite at landfill sites can be channelized and hence utilized. Hence it leads to economically better investment that helps giving aid to investors and in turn making environment pollution free [345]. Therefore, it is important to do methane quantification of any landfill before the implication that can be estimated with diversity of methods.

A huge number of studies have been performed in numerous regions of different developing and developed countries for the estimation of GWP and energy potential through MSW. Researchers used *in-situ* methods such as flux chamber technique, tracer gas correlation, micrometeorological, differential absorption light detection and ranging (LiDAR), and vertical plume mapping methods [337], [346]–[349]. On the other hand, the Intergovernmental Panel on Climate Change (IPCC) also developed analytical methods such as zero-order also known as default methods ($IPCC_{DM}$)[242], [350], and first-order decomposition or decay models ($IPCC_{FOD}$). United States Environmental Protection Agency (USEPA) developed LandGEM inventory ($LandGEM_{inventory}$) and LandGEM clean air act ($LandGEM_{CAA}$). The modified triangular method (MTM) is also a renowned method and generally used by various authors [242]. There has been extensive development in computing methane emissions from MSW in India. Very recently Ghosh *et al*. (2019) conducted a study to know CH_4 emission and energy potential for three landfill sites of the capital of India (Delhi). They performed a comparative analysis by utilizing three different models *i.e.*, $IPCC_{DM}$, $IPDD_{FOD,}$ and LandGEM models, and predicted methane potential in the range of 11-51 Gg/y in the year of 2015 [250]. Gollapalli and Kota (2018) performed a comparative analysis among $LandGEM_{CAA}$(Clean Air Act), $LandGEM_{inventory}$, $IPCC_{FOD}$, MTM, and *in-situ* method *i.e*. flux chamber method. Based on study for a city in north-India (Guhawati), they concluded that MTM, $LandGEM_{CAA}$, $LandGEM_{inventory,}$ and $IPCC_{FOD}$ predicted 1.9, 3.3, 1.6 and 1.4 times more emissions when compared to the actual emissions reported on landfill site [351]. To study various landfill sites of Delhi; Kumar and Sharma (2014) used $IPCC_{DM}$, MTM, IPCC $_{FOD}$, LandGEM and *in-situ* closed chamber method and noticed that emissions observed in the field has a good correlation with $IPCC_{FOD}$ but LandGEM was found to be the best suitable method for the estimation of CH_4 emission. They also concluded that an 11.1 and 26.2 Gg/y of CH_4 and CO_2, respectively can be curtailed from the environment if MSW of Delhi is managed scientifically [352]. Kumar and Sharma (2014) conducted one more study in which they have considered 23 Indian metro cities for a period of 2001-2020 and quantification of methane emissions were done using LandGEM model. They found a total GWP of 189,984 Gg CO_2eq [249].

The greatest benefit of their investigations was that studies have used updated methods and compared the simulation made by the models with field observation. However, they have taken the default input values suggested by IPCC 2006 or LandGEM for the assessment of energy potential and GHG emissions. In the region-specific studies, it is better to calculate these parameters such as degradable organic carbon (*DOC*), half-life (k), and CH_4 production capacity (L_0) as per site condition rather than utilize default values as suggested by IPCC 2006 or LandGEM. Moreover, in the literature survey, it was found that the studies in India are city-specific. As per our knowledge, no study is available on energy and GWP possibility of any state, region, or national inventory for India. So, keeping in mind in the present chapter an attempt has been made to investigate energy potential possibilities of MSW for all Indian states.

Therefore, taking care of the gaps found in the previous studies, predictions of MSW CH_4 emissions from 2015 to 2040 has been done. Besides, in the same duration, GWP of MSW from landfills also computed. Based on the results obtained income abilities from MSW were also estimated.

5.2 Material and Methods

5.2.1 Municipal Solid Waste generation and Compositions in India

In India, MSW management is accountable under the Ministry of Environment and Forest (MOEF). There are 4,002 urban local bodies [25] working under the supervision of 28 State Pollution Control Boards (SPCB)/Pollution Control Committees in accordance to manage the waste described in Solid Waste Management rules 2016. Although, the Government of India is trying to improve management of MSW still most of the SPCBs are unable to decipher proper composition and the amount of generation of the MSW in the states.

The National Action Plan for MSW management 2015 stated that India produces approximately 135,197 TPD out of which 82% of the total waste is collected and only 27% is processed due to various challenges mainly due to lack of funds [25]. A state-wise MSW generation is reported in Table 5.1. A study conducted by CPCB in collaboration with National Environmental Engineering Research Institute (NEERI) on 59 cities across India concluded that the waste generation rate varies in the range of 0.12-0.60 Kg/capita/day [353]. In a similar study, a physical analysis showed that compostable matter varied in the range of 40-60%, and a recyclable fraction varied in the range of 10-25%. In an analysis of the determination of moisture content in MSW, it was found that recyclable fraction varied in a range of 30-60% while the Carbon/Nitrogen (C/N) ratio was observed in the range of 20-40.

The base year for this study is assumed 2015 and predictions have been for the next 25 years *i.e.*, by 2040. The state-wise data regarding the MSW generation in 2015 and 2040 is shown in Table 5.1. This data is further utilized for the analysis purpose. The state-wise MSW generation in 2040 has been computed with the help of the growth rate of MSW in each state and it was calculated with the help of data obtained from Joshi and Ahmed (2016) [1] and CPCB (2015) [25].

Table 5.1: Municipal Solid Waste generation, collection, treatment, and Waste to Energy scenario of Indian states and Union Territories

States and Union Territories	MSW generation (2015-2016)*	Per year growth in MSW (%)	MSW generation (2040)	No of Landfills in operation (2015-16)*
Andaman Nicobar	70	8	210	-
Andhra Pradesh	6,440	0	6,440	2
Arunachal Pradesh	13	18.2	72	0
Assam	7,920	-8.6	7,920	0
Bihar	1,670	0	1,670	0
Chandigarh	370	-2.1	370	1
Chhattisgarh	2,245	12.9	9,257	0
Daman Diu	85	21.4	541	-
Delhi	9,620	2.7	16,173	4
Goa	450	-1.0	450	6
Gujarat	10,480	5.0	23,603	3
Haryana	4,837	109.98	137,841	10
Himachal Pradesh	276	-0.2	276	-
Jharkhand	3,570	21.7	22,985	0
Jammu and Kashmir	1,634	0	1,634	2
Karnataka	8,842	7.0	24,376	134
Kerala	1,339	-16.3	1,339	-
Nagaland	344	8.7	1,094	-
Lakshadweep	21	0	21	-
Madhya Pradesh	6,678	2.5	10,974	-
Maharashtra	21,867	7.9	65,227	5

Manipur	176	11.1	666	-
Mizoram	552	17.6	552	-
Meghalaya	187	-1.1	187	0
Orissa	2,574	1.9	3,844	0
Punjab	4,456	8.5	13,993	0
Puducherry	513	6.0	1,289	1
Rajasthan	5,037	0	5,037	-
Sikkim	49	4.0	104	-
Tamilnadu	230	3.2	416	0
Telangana	6,628	3.0	11,599	1
Tripura	414	2.6	684	1
Uttarakhand	917	6.9	2,508	0
Uttar Pradesh	15,192	13.1	64,990	9
West Bengal	9,500	-6.1	9,500	-
Total/Average	135,197	+6.7	447,849	179

* CPCB, "The National Action Plan for Municipal Solid Waste Management," 2015 [25]

5.2.2 Methodology for Methane Emission, Global Warming Potential, and Energy estimation

For estimation of CH_4 emissions from MSW of all the states and union territories, $IPCC_{DM}$, $IPCC_{FOD}$, $LandGEM_{inventory}$, LandGEM with state-specific data ($LandGEM_{SSV}$) and $LandGEM_{CAA}$ have been utilized. A comparative assessment is also conducted from 2015 to 2040. Apart from that GWP of India between 2015 and 2040 has been analyzed by $LandGEM_{SSV}$, $LandGEM_{inventory}$, and $LandGEM_{CAA}$ models and further compared with each other. Energy potential computation is done based on the CH_4 calorific value equal to 55,530 kJ/kg. [338] Description of all these above-mentioned models is given below:

(a) The default method (DM) IPCC 1996

Bingemer and Crutzen developed an approach-based model on the mass balance to calculate the production of CH_4 from solid waste [354]. Further, this method was recommended by IPCC in 1996; named IPCC default methodology ($IPCC_{DM}$) for determining emissions of methane from landfills. CH_4 emission from total waste deposited at any particular landfill site at that instant of time is calculated using Eq. 5.1 [228].

$$CH_4\ emissions = MSW_t * MSW_f * MCF * DOC * DOC_f * F * \left(\frac{16}{12} - R\right) * (1 - OX) \qquad (5.1)$$

Where MSW_t is total waste generated in the year, MSW_f is a fraction of total waste which is disposed on the landfill (80%), *MCF* is CH_4 correction factor, *DOC* is degradable organic carbon, DOC_f is a fraction of *DOC* dissimilated (0.77), *F* is a fraction of CH_4 in total landfill gas (0.5), *R* is recovered CH_4 (default value=0), *OX* is Oxidation factor (default value=0). The values of MSW_f, DOC_f, *F*, *R*, and *OX* are used as suggested by Chakraborty *et al.* (2011) and Ghosh *et al.* (2019) [243], [250]. *MCF* and *DOC* are computed by using the method suggested by IPCC (2006). State-wise *MCF* and *DOC* values are shown in Table 5.2.

(b) First-order Decay method (FOD)

In the year of 2006, IPCC developed a model to determine CH_4 emissions for all the countries. $IPCC_{FOD}$ assumes that emissions of CH_4 do not take place immediately after the dumping. Hoeks in 1993 stated that the generation of LFG during the degradation of organics can be approximated to first-order kinetics [355]. Consequently, CH_4 emitted in the first few years after the deposition has a substantial fraction and then started reducing gradually as available organic content in waste also start depleting by the microorganisms during the period of landfilling [242] (IPCC, 2006). The CH_4 emissions are estimated with the help of Eq. (5.2) [228].

$$A = \sum_{y-b}^{T-1} \left\{ Q_x L_o \left(e^{-k(T-y-1)} - e^{-k(T-y)} \right) \right\} \qquad (5.2)$$

Where *A* is CH_4 production per year (Mg/year), *y* is the year of waste disposal, *b* is the beginning year of inventory, *T* is the year for which the emission is to be determined, Q_x is the waste quantity (Mg), L_0 is CH_4 production potential and *k* is decay rate constant (y^{-1}). '*k*' has been estimated by a method suggested by Mohsen R.A. *et al*. (2019) [356]. 'L_0' has been estimated by a method suggested by Staley and Barlaz (2009) [357]. Table 5.2 represents the various ecological parameters computed for the estimation of methane emission.

(c) US EPA's LandGEM

United States Environmental Protection Agency (USEPA) has developed a programmed tool for the predictions of LFG such as CH_4, CO_2, and non-methane organic compounds (NMOC) from the landfill. Like $IPCC_{FOD}$, LandGEM also assumes degradation of MSW as kinetic first-order decay, therefore, the peak of LFG emissions due to the degradation of waste comes after years of disposal of waste. Once LFG attains its peak then its emission starts reducing overtime and continues even after the closing of the landfill. Further, this model assumes that in LFG, CH_4 and CO_2 contributes equally. $IPCC_{FOD}$ and LandGEM work almost similar, however, the only difference between both the models is LandGEM requires L_0 value but on the other hand, $IPCC_{FOD}$ requires *DOC* and DOC_f as input parameters. Equation (5.3) shows the equation suggested by USEPA 2005. Determination of LFG form the model requires various inputs parameters like an opening year of the landfill, landfill closure year, and CH_4 potential. LandGEM, either uses land specific data, default parameters as inventory or as clean air act (CAA). The equation for the estimation of methane production suggested by USEPA 2005 is as:

$$A_{CH_4} = \sum_{t=1}^{m} \sum_{p=0.1}^{1} k L_o \left(\frac{N_i}{10}\right) e^{-kX_{ip}} \tag{5.3}$$

Where,

A_{CH_4} = methane production per year in the year of the calculation (Mg/y)

i = Increment in time (1 year)

m = (calculation year) - (initial year of waste dumping)

p = 0.1 year time increment

L_o= methane production capacity (m^3/Mg)

N_i= mass of waste accepted in the i^{th} year (Mg)

X_{ip} = age of the j^{th} section of waste mass M_i accepted in the i^{th} year

Table 5.2: Computed parameters

States	***DOC***	***MCF***	***L_0* (m^3/Mg)**	***k* (y^{-1})**
Andaman Nicobar	-	0.4	-	0.102
Andhra Pradesh	0.112	0.8	31.7	0.038
Arunachal Pradesh	0.138	0.4	58.2	0.097
Assam	0.138	0.4	58.2	0.096
Bihar	0.128	0.4	41.2	0.045
Chandigarh	0.118	0.8	31.3	0.021
Chhattisgarh	0.150	0.4	61.6	0.051
Daman Diu	-	0.4	-	0.074
Delhi	0.128	0.8	33.7	0.021
Goa	0.157	0.8	63.1	0.098
Gujarat	0.130	0.8	37.7	0.041
Haryana	-	0.8	-	0.021
Himachal Pradesh	0.194	0.4	70.6	0.032
Jharkhand	-	0.4	-	0.047
Jammu and Kashmir	0.124	0.8	48.0	0.050
Karnataka	0.137	0.8	46.0	0.038
Kerala	0.141	0.4	52.1	0.095
Nagaland	0.138	0.4	58.2	0.065
Lakshadweep	-	0.4	-	0.065
Madhya Pradesh	0.152	0.4	44.4	0.035
Maharashtra	0.147	0.8	41.5	0.037
Manipur	0.138	0.4	58.2	0.066
Mizoram	0.138	0.4	58.2	0.133
Meghalaya	0.138	1	58.2	0.096
Orissa	0.128	0.4	83.7	0.053
Punjab	0.112	0.4	36.0	0.025
Puducherry	0.181	0.8	95.5	0.041

Rajasthan	0.133	0.4	40.9	0.026
Sikkim	0.138	0.4	58.2	0.095
Tamilnadu	0.137	0.4	39.8	0.041
Telangana	0.136	1	40.4	0.036
Tripura	0.144	0.8	93.5	0.116
Uttarakhand	0.136	0.4	97.7	0.057
Uttar Pradesh	0.128	0.8	39.1	0.030
West Bengal	0.139	0.4	44.2	0.060
Total/Average	0.139	0.6	54.1	0.058

5.2.3 Estimation of Global Warming Potential

$LandGEM_{SSV,}$ $LandGEM_{inventory,}$ and $LandGEM_{CAA}$ models are used for the evaluation of GWP due to MSW in India. Biodegradation of any biomass on the landfill produces various gas emissions though CO_2 and CH_4 contribute a significant fraction. Moreover, amongst all LFG, the GWP of CO_2 and CH_4 is more when compared to other gases. Therefore, to compute GWP, only CO_2 and CH_4 have been used for the analysis purpose. The GPW of CH_4 is taken 31 for the analysis as suggested by [238]. Further, the GWP is computed with the help of Eq. (5.4) as suggested by [358].

*GWP Gg (CO_2-eq) = CO_2 emissions in Gg *1(CO_2-eq) + CH_4 emissions in Gg *31 (CO_2-eq)* Eq. (5.4)

5.3 Result and Discussions

5.3.1 Current scenario of Sanitary Landfill facilities and Energy generation in India

In India, out of total MSW, 82% of the total waste is collected and only 27% is processed due to various challenges mainly due to lack of funds [25] and a significant amount is dumped on the landfills or open dumps. This dumped MSW neither undergoes any treatment nor is the biogas generated from these open dumps captured. If captured, biogas can further be utilized for heat or electricity generation. Hence, open dumps need to be replaced with sanitary landfills with leachate and landfill collection facilities. Presently, a maximum number of landfills in the country are not sanitary hence causing the generation of leachate and emissions of LFG, hence, polluting the environment. Today there are only 179 sanitary landfills are available which works scientifically [25]. In a sanitary landfill, LFG produced during the AD of waste can be captured and utilized as a source of renewable energy. At present across the country, there are only 12 landfills from which the LFG is captured and further utilized for energy or heat generation [25]. However, the energy potential from MSW needs to be estimated by the researchers, and LFG plants should be proposed to policymakers in the country. The energy potential in 2030 and 2040 of all the states are shown in the Table. 5.3. Based on the analysis, Haryana is the state with maximum energy potential *i.e.*, 288 MW followed by Maharashtra and Uttar Pradesh by generating 198 and 150 MW in 2040, respectively. Further, in the analysis, it was found that all the states collectively have huge energy potential *i.e.*, 1,387MW in 2040.

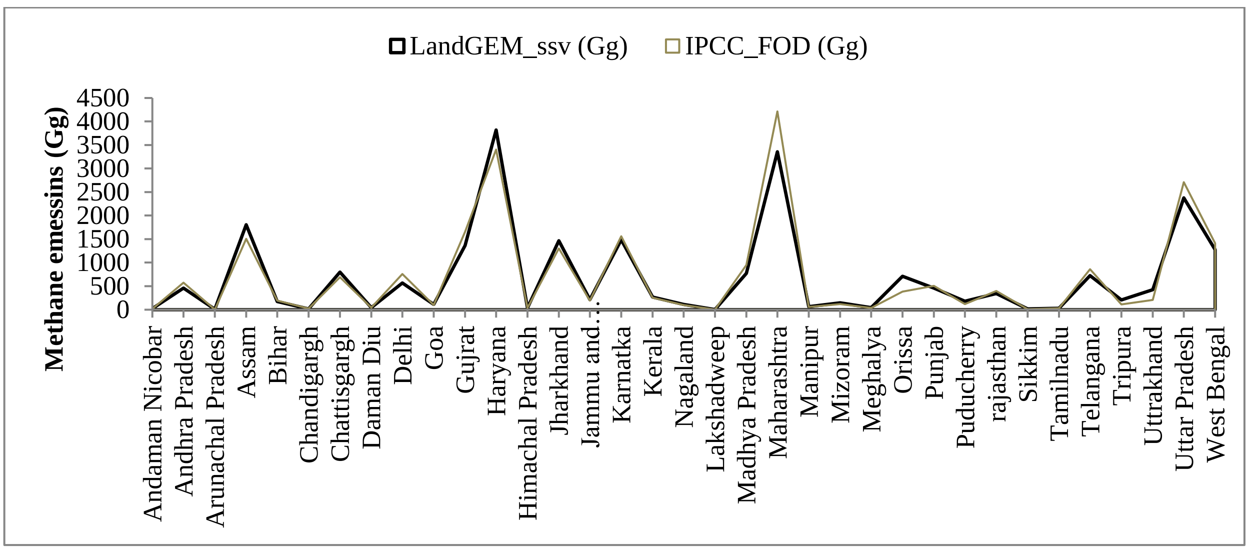
Table 5.3: Energy Potential in 2030 and 2040 in the Indian States

States	Waste to Energy Potential in 2030 (MW)	Waste to Energy Potential in 2040 (MW)
Andaman Nicobar	0.8	1.4
Andhra Pradesh	15.4	21.7
Arunachal Pradesh	0.2	0.5
Assam	60.8	72.4
Bihar	5.8	8.1
Chandigarh	0.5	0.8
Chhattisgarh	25.4	48.5
Daman Diu	1.5	2.9
Delhi	18.5	31.4
Goa	3.8	4.5
Gujarat	44.0	75.4
Haryana	113.2	288.0

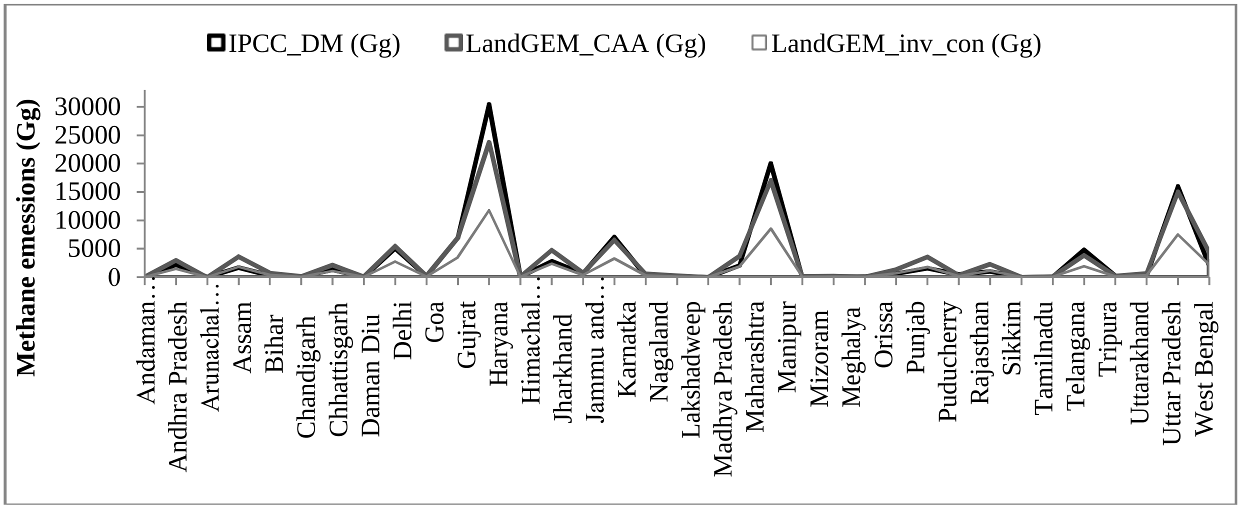
Himachal Pradesh	1.3	1.9
Jharkhand	45.7	95.0
Jammu and Kashmir	7.2	9.7
Karnataka	47.5	86.1
Kerala	9.1	10.9
Nagaland	3.7	6.5
Lakshadweep	0.1	0.2
Madhya Pradesh	25.3	40.8
Maharashtra	107.0	198.0
Manipur	2.1	3.9
Mizoram	4.8	5.4
Meghalaya	1.4	1.7
Orissa	23.5	35.1
Punjab	14.6	28.2
Puducherry	5.7	10.0
Rajasthan	11.4	17.0
Sikkim	0.5	0.8
Tamilnadu	0.9	1.5
Telangana	23.7	38.8
Tripura	6.8	9.2
Uttrakhand	13.8	23.8
Uttar Pradesh	74.3	150.9
West Bengal	43.0	56.2
Total/Average	764	1387

5.3.2 Estimation of Methane Emissions/Potential

Figure 5.1 illustrates a comparison between CH_4 emissions predicted by various methods at the end of 2040 for the states of India. In the analysis (based on $LandGEM_{SSV}$), it was found that Haryana is the state which will have the maximum CH_4 potential (3,820 Gg) amongst all states in India. After Haryana, Maharashtra and Uttar Pradesh will have a CH_4 potential equal to 3,354 and 2,377 Gg, respectively. Figure 5.2 illustrates the temporal (2015-2040) distribution of CH_4 potential. In Figure 5.2, it is very interesting to note that except for $IPCC_{DM}$, all other models have not predicted any emission in the year 2015. On the other hand, $IPCC_{DM}$ has predicted a certain emission. It is due to the reason that $IPCC_{DM}$ works on the principle of Zero- order Kinematics, while other methods work on the principle on First order kinematics. All other models predicted the emissions after 12-13 months. In the analysis, it is also observed that between 2015 and 2040 $LandGEM_{CAA}$ has predicted the highest emissions amongst all models. $LandGEM_{CAA}$ has simulated the results 4.60, 4.72, 2.00, and 1.03 times the simulations made by $IPCC_{FOD}$, $LandGEM_{SSV}$, $LandGEM_{inventory,}$ and $IPCC_{DM}$, respectively. For the same duration $IPCC_{FOD}$, $LandGEM_{inventory}$, $IPCC_{DM}$, $LandGEM_{CAA}$, and $LandGEM_{SSV}$ has predicted the total cumulative CH_4 potential as 24,541, 56,520, 109,693, 112,913 and 23,936 Gg/y, respectively. Table 5.3 shows the state-wise energy potential of all the states in India. Based on results obtained by $LandGEM_{SSV}$ in 2030 and 2040, the total energy potential of India will be 764 and 1,387 MW, respectively.



(a)



(b)

Figure 5.1: Comparison of various models used in Methane emissions from all the States of India at the end of 2040 by using (a) $\text{LandGEM}_{\text{SSV}}$ and IPCC_{FOD}, and (b) $\text{LandGEM}_{\text{inventory}}$, $\text{LandGEM}_{\text{CAA,}}$ and IPCC_{DM}

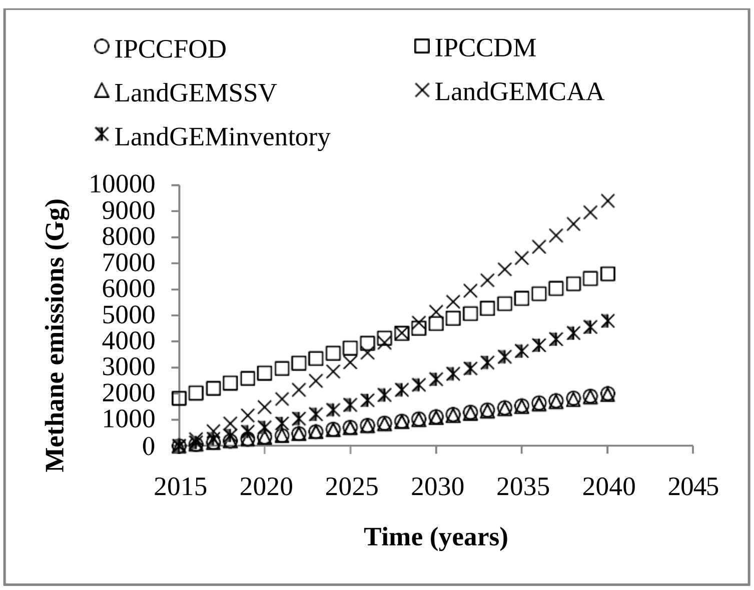


Figure: 5.2 Temporal distributions of Methane Emissions of India

5.3.3 Uncertainties in the estimation of emissions

Various researchers found that there are considerable uncertainties in the *in-situ* estimation of emissions which are attributed to the fact that in the process of sampling, a portion of emissions remains unaccounted therefore *in-situ* method under predicts the emissions.

Similarly, in estimation with the help of these analytical models, there exist various uncertainties. In this context, many researchers have worked and found that these models always over predict the emissions when compared to the actual emissions measured by various *in-situ* methods. Kumar *et al*. (2004) utilized $IPCC_{DM}$ and MTM methods to estimate CH_4 yield during degradation of waste on the landfill and found that simulations made by $IPCC_{DM}$ were much more when compared to the actual emissions observed *in-situ* [359]. Jha *et al*. (2008) also found similar trends and concluded that the emissions observed in the field measurement were 5-6 times lower when compared to the $IPCC_{DM}$ [241]. Chakraborty *et al*. (2011) reported a similar pattern, they found 7- and 2-times higher emissions from $IPCC_{DM}$ and $IPCC_{FOD}$ when compared to the *in-situ* measurement [243]. They reported that relatively $IPCC_{FOD}$ models simulate emissions much more appropriately than $IPCC_{DM}$. Very recent research conducted on the biggest city in north-east India (Guwahati) found that those predicted emissions were 1.4 and 1.6 times higher for $IPCC_{DM}$ and LandGEM, respectively. In a comparative analysis of $IPCC_{DM}$, $IPCC_{FOD}$, MTM, and $LandGEM_{inventory}$, methods, $LandGEM_{inventory}$ found to be best suitable [352]. Nonetheless, these uncertainties generally occurred due to unavailability or lack of data. Recently, Ghosh *et al.* (2019) considered small variations or uncertainties in the input parameters. They observed that a variation of ±0.1 in *F* (0.5), a variation of ±10% in MSW_f (80%), and found a variation of 10-20% in the results predicted by these models [250]. Thus, based on the discussion, this study also states that predictions made may have uncertainties based on the variation in any input parameter used in this study.

5.3.4 Global Warming Potential and relationships between MSW Methane and GDP

As discussed in material and section methods, $LandGEM_{SSV,}$ $LandGEM_{inventory,}$ and $LandGEM_{CAA}$ models were used for the evaluation of GWP due to MSW in India. Figure 5.3 depicts temporal distribution Global warming potential of India for a period from 2015-2040. It can be seen that during the phase of 2015-2040, the GWP has an increasing trend. In the year 2030, 2035, and 2040 a GWP of 36,599, 50,989, and 66,443 Gg CO_2-eq, respectively was predicted by $LandGEM_{SSV.}$ To determine the correlation between CH_4 emissions, and GDP simulation-based on the $LandGEM_{SSV}$ was utilized for methane emissions and plotted with the GDP ("All India Gross Domestic Product at Current Prices from 2011-12 to 2016-17") [360] which can be seen in Figure 5.4.

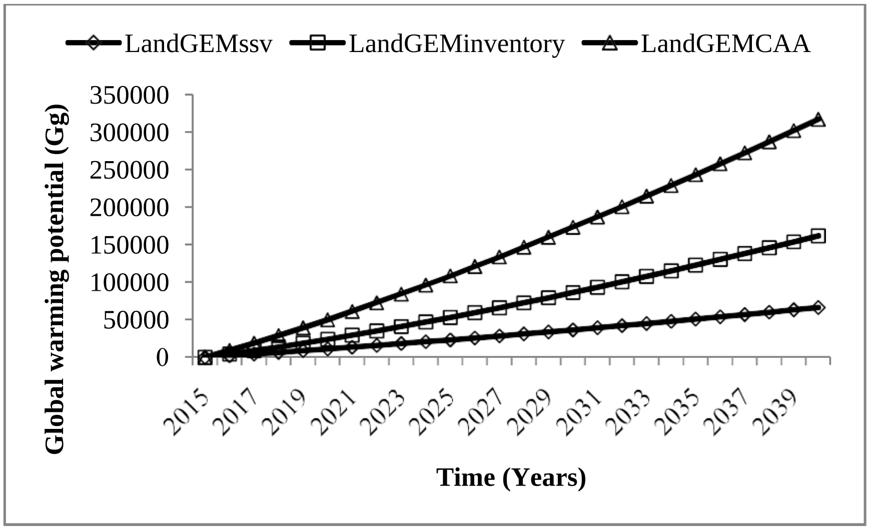


Figure: 5.3 Temporal distribution Global Warming Potential of India

The finding of this study shows that methane emissions are significantly correlated ($R^2=0.998$) with economic development. GDP is also a primary factor affecting CH_4 emissions. This study believes that higher GDP indicates higher human activity, leading to the production of much greater volumes of MSW.

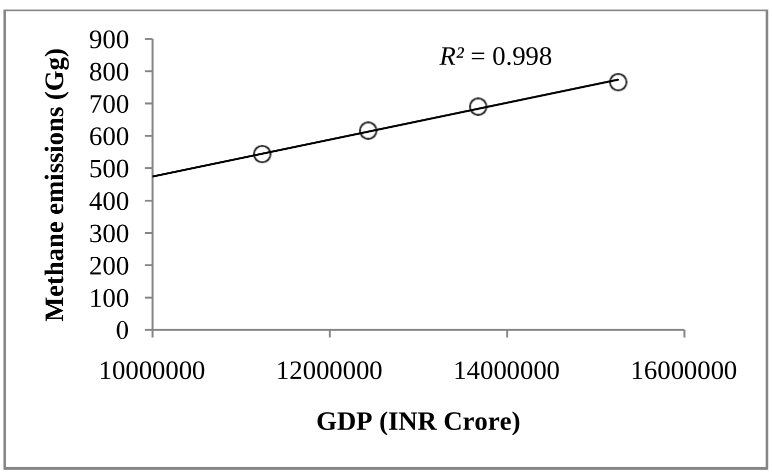


Figure 5.4 Regression curve for Municipal Solid Waste methane emissions and GDP for 2011-17

5.3.5 Environmental and Economic benefits of Methane capture

Release of LFG specifically, CH_4 can create huge problems for the environment in which global warming is a significant one. Apart from its contribution to global warming, it plays a decisive role in the depletion of the ozone layer. So, its collection and utilization from the landfills will not only help the environment but also make it more attractive to the policy, decision-makers, and investors. Table 5.4 summarizes the environmental and economic benefits of CH_4 capturing via gas collection mechanism on the landfills. If GHG is captured (*i.e.*, CH_4) during the landfill emissions, under Clean Development Mechanism (CDM) programs, it could attract an income of 483, 673 and 877 million US $ in 2030, 2035 and 2040 through carbon credit from carbon reduction based on the US$13.20/tonnes of CO_2. If gas engine efficiency is assumed 40% (as suggested by Shin *et al*. (2005)) then energy equivalent to 305, 425, and 554 MW can be produced in 2030, 2035, and 2040, respectively [344]. Moreover, based on the assumed electricity price *i.e.*, 5 INR/kWh, the profits equivalent to approximately 478, 666, and 867 million US$ in 2030, 2035, and 2040, respectively can be attracted.

Table: 5.4 Economic and environmental benefits of Methane produced from Indian MSW.

Parameter	**2030**	**2035**	**2040**
[#]Methane Potential (Gg)	1,084	1,511	1,969
[#]GWP CO_2 eq (Gg)	36,599	50,989	66,443
[a] Revenue from carbon credit (million USD)	483	673	877
[b] Equivalent electricity generation (GWh)	6,692	9,324	12,150
[d,b]Equivalent electricity generation (MW)	305	425	554
[c]Revenue from electricity sale (billion USD)	478	666	867

[a]USD ($) 13.2/tonne of equivalent emission

[b]Based on the methane calorific value 55,530 kJ/kg

[c]Price of electricity 1 kWh/5 INR and assuming 1 US$= 70INR

[d]calculated assuming 40% efficiency of LFG

#Calculated with the help of $LandGEM_{ssv}$

5.4 Concluding Remark

Due to several reasons, in India major part of MSW is directly being dumped on the landfills without any scientific treatment. On the open dumping sites, MSW naturally undergoes the AD process where emissions of GHG take place. GHG emissions, if not captured by any mechanism; ultimately harm the environment in one or another way and global warming is one of them. On the contrary, if these GHG emissions are captured then not only it will be beneficial for the environment but also it will help to achieve the nation's quest for the development of renewable energy. In the present study, the MSW energy and GWP potential for a period of 2015-2040 are computed. Analysis reveals that MSW has a huge potential as a source of renewable energy. If the MSW landfill is managed as sanitary landfills with landfill gas collection mechanism then 1,387 MW of energy can be conserved in 2040. Besides, the revenue of 877million USD can be generated via carbon credit from carbon reduction. Moreover, the revenue of 867 million USD can be generated vie selling the electricity at a nominal price of 5 INR/kW·h. This study also concludes that there is a prompt need for minimization of waste load on the landfill by reducing the generation at a household level, reuse, recycling. The sanitary landfills with gas collection mechanisms are need of the hour, otherwise, incoming few decades India will be one of the biggest GHG (due to MSW) emitter across the world.

CHAPTER - 6

Conclusions

Every new beginning come from some other beginning end. – Seneca

CHAPTER-6
CONCLUSIONS

6.1 General

One of the broad aims of the present investigation was to manage food waste of the hilly terrain of Northern India at natural ambient conditions and check its economic and ecological feasibility. To achieve the objectives of the study experiments were conducted in a pilot-scale (3,000 L) anaerobic reactor at a natural ambient condition. Experimental work was focused on the feasibility aspect and optimization of the organic loading rate of the anaerobic digestion of food waste. Besides the optimization of OLR, techno-economic feasibility, and ecological aspects of this process in comparison to open dumping and composting were also evaluated. An attempt has also been made to estimate the energy and global warming potential of MSW of states of India.

Keeping in mind the broad objectives following general conclusions can be drawn based on this study:

(a) Characterization of food waste utilized in this study has shown that it has substantial volatile fraction therefore it can be treated with the help of anaerobic digestion.

(b) From the initial investigation, it can be concluded that food waste can be used as a substrate for sustainable methane production via anaerobic digestion using a floating drum type single- stage reactor at an ambient temperature range in the hilly terrain of North India.

(c) The information on the optimized organic loading rate obtained during this study will be very beneficial for the people who want to run a family scale, medium scale, and pilot-scale anaerobic reactors in such environmental conditions for stable anaerobic digestion and optimum methane generation.

(d) Due to significantly higher energy production potential and lesser generation of GHG emissions, anaerobic digestion is found to be the most suitable method for the management of food waste in hilly terrain.

The specific conclusions arrived at are summarized below:

6.2 Feasibility Study of Food Waste based anaerobic reactor at continuously varied low mesophilic and psychrophilic temperature

a. It can be concluded that anaerobic digestion of food waste at continuously varied psychrophilic and low mesophilic temperatures (at an altitude 1,544 m above MSL) is not as similar as at mesophilic and thermophilic temperatures (at an altitude ≤ 1,000 m above MSL).

b. The maximum and minimum biogas was reported in June and January, respectively. In the winter season, the production of biogas decreased drastically (approximately 55%). Although, after February, a significant improvement in the stability of digester and biogas production was attained.

c. Production of methane per month has a linear dependency ($R^2 = 0.9283$) on the average monthly temperature.

d. Despite such adverse environmental conditions (at such low temperature *i.e.* -2.6°C) the AD process was not inhibited. As far as AD in Himachal Pradesh is concerned, more substantial studies are required for the special environmental conditions in HP due to very large temperature fluctuations in day and night.

e. Among all the mathematical methods used in the present study, FOM was the most accurate model with k =0.007 day^{-1} and with R^2=0.990, P= 32.951 L CH_4/g VS, and R=134.51 L CH_4/g VS/day MGM was the best mathematical model.

6.3 Optimization, Techno-economic, Ecological feasibility of Food Waste based Anaerobic Digestion process at continuously varied low mesophilic and psychrophilic temperature

a. From the optimization study, it can be concluded that anaerobic digestion of food waste can be achieved up to an organic loading rate of 0.34 g VS/L/day in summer and 0.21gVS/L/day in winter.

b. Based on the optimized organic loading rate, an anaerobic digestion process for all northern hilly states is analyzed. It is estimated that capital investment in such a process will return in 5.9 years with an *IRR* of 4.6%.

c. Besides a shorter PBT, successful implementation of the AD process for the next ten years in these hilly states will curtail 93.4% and 89% GWP from AD and composting, respectively when compared to landfill.

d. FW has a huge potential of renewable energy i.e., 1,327 GWh/year if managed with the help of AD in all hilly states of North India

e. This recognized concept is the first in terms of energy generation and waste management in a hilly area through anaerobic mono-digestion process across the country. In a nutshell, a similar or maybe a worse scenario of GHG emissions can be seen in the coming decade if appropriate management of FW is not made.

6.4Municipal Solid Waste Energy and Global Warming Potential in India

a. It was noticed that during the phase of 2015-2040, the GWP has an increasing trend. In the year 2030, 2035, and 2040 a GWP of 36,599, 50,989, and 66,443 Gg CO_2-eq, respectively was predicted by $LandGEM_{SSV.}$ If these GHG emissions are captured then not only it will be beneficial for the environment but also it will help to achieve the nation's quest for the development of renewable energy.

b. Analysis reveals that MSW has a huge potential as a source of renewable energy. If the MSW landfill is managed as sanitary landfills with landfill gas collection mechanism then 1,387 MW of energy can be conserved in 2040.

c. Besides, the revenue of 877million USD can be generated via carbon credit from carbon reduction. Moreover, the revenue of 867 million USD can be generated via selling the electricity at a nominal price of 5 INR/kW·h.

Simple floating drum type semi-continuous reactor is a low investment and cost-effective solution for optimization of OLR of FW and can be used for small-scale or large scale reactors at households, hotels, canteens, etc. in villages, towns or cities of hilly areas of north India or any developing country having similar climatic conditions, which are usually lacking with funds. The results of the present study will be helpful for researchers and industries who want to work in the field of AD at low mesophilic and psychrophilic temperatures conditions. Moreover, it will help in the safe disposal of household, hotel, restaurant, and institutional leftover food waste and will provide a rich source of energy in the kitchen and generation of nutrient-rich bio-slurry which can be utilized in field for optimum growth of crops.

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PUBLICATIONS

“Every accomplishment starts with the decision to try.” —
Brian Littrell

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- Choudhary, A., Kumar, A., and Kumar, S. (2020). “Techno-economic analysis, kinetics, global warming potential comparison and optimization of a pilot-scale unheated semicontinuous anaerobic reactor in a hilly area: For north Indian hilly states.” Renewable Energy,155, 1181–1190, https://doi.org/10.1016/j.renene.2020.04.034

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