UTILIZATION OF ORGANIC WASTE GENERATED BIO METHANE FOR TRANSPORTATION APPLICATION

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by

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CERTIFICATE

This is to certify that the thesis entitled **"Utilization of Organic Waste Generated Bio Methane for Transportation Application,"** submitted to the Delhi Technological University, Delhi -110042, for the fulfillment of the requirements for the award of a degree of Doctorate of Philosophy in Mechanical Engineering, embodies the original research work carried out by **Mr. PRADEEP KUMAR MEENA,** Enrollment No: 2K18/Ph.D./ME/08 under our supervision. This work has not been submitted in part or full for any other degree or diploma of this or any other University.

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DECLARATION

I certify that the work which is being presented in this thesis entitled "**Utilization of Organic Waste Generated Bio Methane for Transportation Application"** in fulfillment of the requirement for the award of the degree of Doctorate in Philosophy submitted in the Department of Mechanical Engineering at Delhi Technological University is an authentic record of my own work carried out during a period from August 2018 to May 2023, under the supervision of PROF. AMIT PAL and PROF. SAMSHER, Department of Mechanical Engineering, Delhi Technological University, Delhi. The matter presented in this thesis has not been submitted in any other University/Institute for the award of any degree or diploma.

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ABSTRACT

Municipal waste management has been a persistent issue in India for decades, with the increasing urbanization and population leading to an alarming rise in daily waste generation. Unfortunately, most of this waste is not segregated, leading to environmental and health hazards as the organic waste gets mixed with non-biodegradable waste. This also makes recycling and reusing waste materials challenging, leading to natural resource depletion and environmental degradation. Therefore, immediate action is required to address this issue. In present work a case study was conducted at Delhi Technological University to tackle the problem, where organic waste was collected from the university campus. For easy segregation, 750 dustbins labeled organic and inorganic waste were distributed across the canteen, mess, and all residential apartments, with a holding capacity of up to 13 kg of garbage. Over 12 months, 24 sample sets of household organic waste were studied, with a sample size of 1620 waste bags. The study found 73 types of organic waste, with raw vegetable waste (RVW), fruit waste (FW), and mixed cooked waste (MCW) being the most common, weighing 518.53 kg, 263.57 kg, and 249.94 kg, respectively. The relationship between these waste types was analyzed using the regression method. The result suggested that the coefficient of determination (R^2) of RVW and FW, RVW and MCW, and FW and MCW were 0.90, respectively 0.91, and 0.94, respectively, with $p < 0.05$.

Firstly, it analyzes the relationship between different types of organic waste, and then experiments are conducted to optimize biogas production. The Taguchi method is used, which involved nine experimental anaerobic digesters (ADs) with a total capacity of 10 liters. The design of experiment data tumbling and without tumbling processes was used to determine the best combination of parameters for optimal biogas production. It investigated FW, RVW, and MCW at different proportions (1:1, 1:1.5, and 1:2) with varying temperatures (35°C, 40°C, and 45°C) and multiple feeds. It evaluated the tumbling effect for 0,10, and 20 minutes at 15 rpm. The Taguchi method gave coefficient of determination (R^2) values of 94.76% and 98.48% for experiments without tumbling and with tumbling, respectively. At 40°C and a 1:1.5 ratio, the average optimum CH_4 gas generation in FW without the tumbling effect was 37.12%. The ratios of 1:1.5 and 1:2 in RVW and MCW and the value of CH_4 at 35°C were estimated to be 26.7% and 26.68%, respectively. Our findings indicate that tumbling can enhance the amount of CH_4 gas produced. Specifically, CH_4 gas production in FW increased by 11% and 6% after 10- and 20-min tumbling, respectively, compared to without tumbling. Tumbling resulted in 31.1% and 47.9% more CH_4 gas production after 10 and 20 minutes in RVW, and 25.7% and 12.2% more were produced after 10 and 20 minutes in MCW, respectively. Overall, the Taguchi method was an effective tool for determining the optimal parameters for biogas production, and our study highlights the importance of tumbling in enhancing biogas production. To explore the potential of alternative fuels in spark-ignition (SI) engines, pure biogas is compressed and blended with gasoline, ethanol, methanol, and methyl acetate alcohol. It measured the engine performance parameters (BTE, ITE, BP, BSFC, BSEC), combustion phenomenon (Cylinder pressure, Crank angle, Cylinder volume, Mass fraction burned, Mean gas temperature, Rate of pressure rise), and emission characteristics (HC, CO, CO_2, NOx). The study included using 10%, 20% (Ethanol, Methanol, Methyl Acetate), and 100% Compressed Biogas (CBG) as alternative fuels. CBG produced the highest BTE of 23.33% compared to all other fuels. The minimum fuel consumption rate of 1.72 kg/h at maximum rpm achieved a BSFC value of 0.44 kg/kWh and an ISFC value of 0.261 kg/kWh. The G90M10, with a cylinder volume of 48.58 cc, achieved the highest cylinder pressure of 67.9 bar. The G80E20 had the highest mean gas temperature (MGT) of 390.20°C. The G90M10 achieved a maximum rate of pressure rise of 0.14 bar/degree at a crank angle of 374°. CBG had the lowest emission gases at both minimum and maximum RPM, indicating its potential for producing the best emission results with engine performance compared to all other alternative fuels.

Installing biogas plants in urban societies and university campuses can play a vital role in reducing the amount of solid waste produced by utilizing household organic waste to produce green energy. Biogas plants can convert organic waste into eco-friendly green energy, which helps solve the problem of solid waste. CBG fuel is the most effective solution for solid organic waste and a better alternative to gasoline fuel, as it burns cleaner and produces fewer harmful emissions. Waste-to-energy technologies, such as biogas plants, give a reliable renewable energy source and contribute to achieving carbon neutrality goals. CBG fuel can play a key role in reducing dependence on fossil fuels and mitigating climate change. The findings of this study have significant implications for policymakers and waste management authorities as it promotes sustainable waste management practices and the use of renewable energy sources. Governments and industries can collaborate to encourage the development and deploy biogas and CBG technologies to promote sustainable energy practices.

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NOMENCLATURE

AD	Anaerobic digester
BG	Biogas
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CBG	Compressed Biogas
R^2	Coefficient of Determination
CR	Compression ratio
EOB	End of burning
FF	Fluid Flow
FW	Fruit waste
G100	Pure gasoline fuel
G80E20	80% gasoline, 20% ethanol
G80M20	80% gasoline, 20% methanol
G80MA20	80% gasoline, 20% methyl Acetate
G90E10	90% gasoline, 10% ethanol
G90M10	90% gasoline, 10% methanol
G90MA10	90% gasoline, 10% methyl Acetate
ISFC	Indicated specific fuel consumption
ITE	Indicated thermal efficiency
ME	Mechanical efficiency
MFB	Mass fraction burned
MGT	Mean gas temperature
MCW	Mixed cooked waste
MSW	Municipal Solid Waste
NHR	Net heat release
RVW	Raw vegetable waste
RPR	Rate of pressure rise
S1(10), S2(15), S3(20), S4(25), S5(30), S6(35), S7(40), S8(45), S9(50), S10(55), S11(60), S12(65), S13(70), S14(75),	Sample Sets (Sample Size)

S15(80), S16(85), S17(90), S18(95), S19(100), S20(105), S21(110), S22(115), S23(120), and S24(125)	
SOB	Start of burning
TDC	Top dead center
BDC	Bottom dead center

CHAPTER 1

INTRODUCTION

Biogas is a renewable energy source through the anaerobic digestion of organic waste materials. In India, biogas technology has a long history and has been widely adopted by rural communities, small-scale industries, and households. This chapter provides an overview of the history of biogas plants in India, their impact on the country's energy sector, and the current status of biogas technology and its barriers.

1.1 History of biogas plants in India

The history of biogas plants in India dates back to the mid-1950s when the National Dairy Development Board (NDDB), under the leadership of Dr. Verghese Kurien, started promoting biogas plants to provide clean and renewable energy to rural areas. The NDDB, in collaboration with the Khadi and Village Industries Commission (KVIC), established the first biogas plant in a small village called Gobar Tirth in Gujarat in 1959 [1]. The success of the first biogas plant led to the establishment of biogas development centers (BDCs) in various states to promote the technology and provide training to interested individuals. The BDCs played a crucial role in disseminating information about the technology and building the capacity of rural communities to install and maintain biogas plants.

In the early 1980s, biogas technology gained momentum, and the government established the National Biogas and Manure Management Program (NBMMP) in 1981 to promote biogas plants in rural areas—the program aimed to install one million biogas plants by 1987. However, the target was not met, and by 1990, only 125,000 biogas plants had been established under the program [2]. Despite the slow progress of the NBMMP, biogas technology continued to grow in popularity. In the 1990s, the government introduced several policies to promote renewable energy, including biogas. In 1992, the Ministry of Non-Conventional Energy Sources (MNES) was established to promote developing and using renewable energy sources, including biogas. The MNES introduced the Biogas Power (Off-grid) Generation Program in 1994, which aimed to encourage electricity generation from biogas [3]. Under the program, subsidies were provided for installing biogas-based power generation units.

1.2 Impact of biogas plants on India’s energy sector

Biogas has the potential to contribute significantly to India's energy sector by reducing dependence on fossil fuels, increasing energy security, and mitigating greenhouse gas emissions. This essay will discuss the impact of biogas plants on India's energy sector.

Firstly, biogas production can help to reduce dependence on fossil fuels. India relies heavily on imported fossil fuels, mainly crude oil and natural gas, to meet its energy demands. However, the country has significant biomass resources, including agricultural waste, which can be used to produce biogas. By using biogas as a fuel source, India can reduce its dependence on imported fossil fuels and improve its energy security. According to the Ministry of New and Renewable Energy report, biogas production in India can potentially replace 17.5 million tonnes of firewood and provide energy access to 60 million households by 2022 [4]. Secondly, biogas production can help to mitigate greenhouse gas emissions. Organic waste, such as agricultural and municipal solid waste, produces methane emissions when decomposing in landfills. Methane is a potent greenhouse gas, 28 times more powerful than carbon dioxide over a 100-year timescale [5]. India can reduce methane emissions and mitigate its contribution to global warming by diverting organic waste from landfills and using it to produce biogas. According to a study by the International Energy Agency (IEA), biogas production in India can reduce greenhouse gas emissions by up to 20 million tonnes of CO_2 equivalent per year by 2020 [6].

Thirdly, biogas production can provide economic benefits to rural communities in India. Biogas plants can be set up on farms, where agricultural waste can be used to produce biogas. Farmers can generate an additional income stream by utilizing biogas for cooking and heating purposes and selling surplus biogas to other users. Biogas plants can also provide employment opportunities in rural areas, particularly for women who can be involved in the maintenance and operation of the plants [7]. Finally, biogas production can improve the health and well-being of rural communities in India. Traditional cooking methods, such as burning firewood and cow dung, produce indoor air pollution that can have severe health impacts, particularly for women and children who spend more time indoors. By providing biogas as a cooking fuel, India can reduce indoor air pollution and improve the health and well-being of rural communities [8].

1.3 Biogas

Biogas is a type of renewable energy produced through the anaerobic digestion of organic materials such as agricultural waste, food waste, sewage, and animal manure. It is composed mainly of methane (CH_4) and carbon dioxide (CO_2), with small amounts of other gases such as hydrogen sulfide (H_2S), nitrogen (N_2), and oxygen (O_2). Biogas can be used as an energy source for heating, cooking, and electricity generation.

The biogas production process is a complex biological process that involves four distinct stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

- Hydrolysis is the initial stage of biogas production, in which hydrolytic bacteria enzymatically degrade complex organic compounds like carbohydrates, proteins, and lipids. Through the secretion of enzymes, these bacteria break down the complex organic matter into soluble organic compounds such as sugars, amino acids, and fatty acids. The temperature range for the hydrolysis stage usually falls within the mesophilic range, approximately 25°C to 40°C [9].

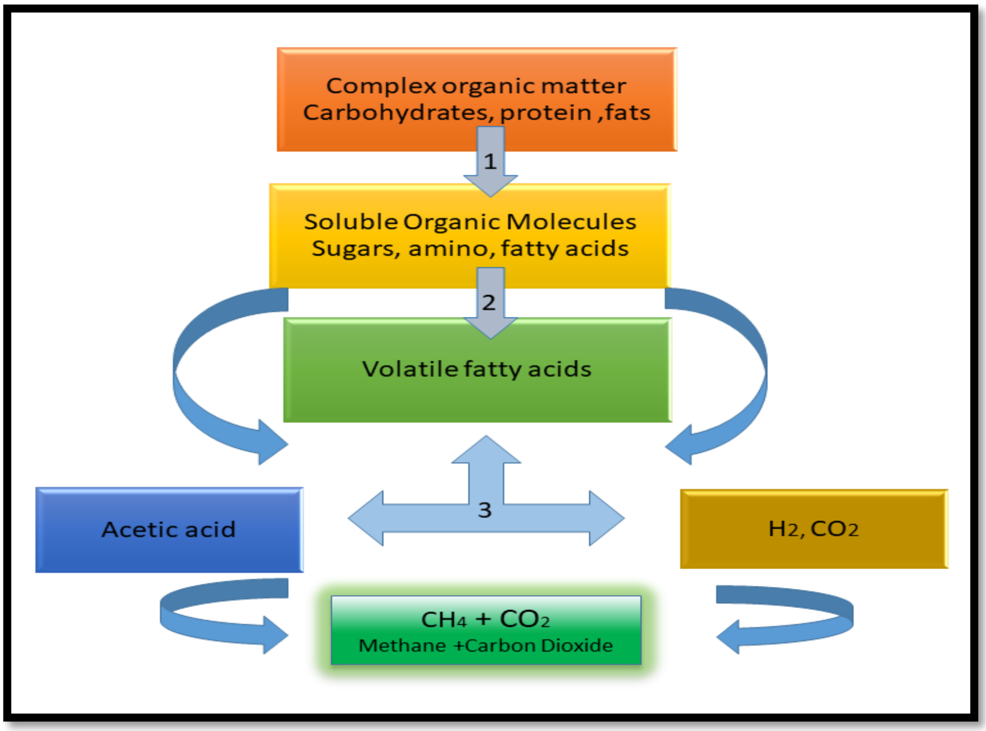


Figure 1.1: Biogas Production Process

Hydrolytic bacteria exhibit optimal enzymatic activity within this temperature range, ensuring efficient degradation of complex organic materials. The mesophilic conditions provide a favorable environment for the enzymes to effectively break down the organic compounds into smaller, soluble forms. This breakdown of complex compounds into simpler molecules facilitates the subsequent stages of biogas production, such as acidogenesis and methanogenesis. Proper temperature control in the hydrolysis stage is crucial for maximizing the conversion of complex organics and ensuring a steady supply of substrates for further biogas production.

- Acidogenesis is the second stage of biogas production, where the simple organic compounds generated during hydrolysis undergo further transformation. In this stage, acidogenic bacteria facilitate the conversion of these compounds into volatile fatty acids (VFAs), alcohols, and other intermediate products. The production of carbon dioxide, hydrogen, and VFAs such as acetic acid, propionic acid, and butyric acid accompanies this process. The temperature range for acidogenesis typically falls within the mesophilic range, approximately 25°C to 40°C. At these temperatures, mesophilic acidogenic bacteria are most active and efficient in metabolizing organic compounds.
  However, acidogenesis can also occur under thermophilic conditions, with a temperature range of 50°C to 60°C [10]. Thermophilic acidogenic bacteria thrive in these elevated temperatures, enhancing metabolic activity. During acidogenesis, the organic compounds are further broken down, releasing VFAs that serve as essential substrates for the subsequent methanogenesis stage. The production of VFAs, hydrogen, and carbon dioxide sets the stage for the subsequent conversion of these compounds into methane by methanogenic microorganisms. By maintaining the appropriate temperature range, biogas plant operators can optimize the activity of acidogenic bacteria, ensuring the efficient breakdown of organic compounds and the production of valuable intermediates necessary for the subsequent stages of biogas production.

- Acetogenesis is the third stage of biogas production, where the volatile fatty acids (VFAs) generated during acidogenesis undergo further transformation. In this stage, acetogenic bacteria play a crucial role in converting VFAs into acetic acid, hydrogen, and carbon dioxide through acetogenesis. Acetogenesis can occur under mesophilic conditions, with a temperature range of approximately 30°C to 45°C.

Mesophilic acetogenic bacteria exhibit optimal metabolic activity in converting VFAs into acetic acid within this range. Alternatively, acetogenesis can occur under thermophilic conditions, with a temperature range of 55°C to 65°C [11]. Thermophilic acetogenic bacteria thrive in these higher temperatures, leading to accelerated conversion of VFAs.

The conversion of VFAs into acetic acid, hydrogen, and carbon dioxide during acetogenesis sets the stage for the final stage of biogas production, methanogenesis. By maintaining the appropriate temperature range, biogas plant operators can optimize the activity of acetogenic bacteria and ensure the efficient conversion of VFAs into valuable intermediates for subsequent methane production.

- Methanogenesis represents the final stage of biogas production, where the products of acetogenesis, namely acetic acid, hydrogen, and carbon dioxide, are further transformed into methane and carbon dioxide. This pivotal stage is facilitated by methanogenic bacteria, which utilize the acetic acid and hydrogen generated during earlier steps to produce methane and carbon dioxide. Methanogenesis can occur under mesophilic conditions, typically within a temperature range of 35°C to 40°C. Within this range, mesophilic methanogenic bacteria display optimal metabolic activity, ensuring efficient conversion of intermediates into methane. Alternatively, methanogenesis can occur under thermophilic conditions, with a temperature range of 50°C to 60°C [12]. Thermophilic methanogenic bacteria thrive in higher temperatures, producing accelerated methane.

  The biogas production process is intricate and relies on the coordinated activities of different microbial groups. Various factors influence the process's efficiency, including substrate availability, temperature, pH, and retention time. Proper monitoring and control of these factors are essential for maintaining optimal conditions and promoting the growth and activity of the microorganisms involved in biogas production. By understanding and optimizing the interplay between different stages and microbial communities, biogas plant operators can enhance the overall efficiency of the process and maximize the production of methane, a valuable renewable energy source.

1.4 Current status of biogas plants in India

The current status of biogas plants in India shows varying distribution across different zones. Over the years, there has been a notable growth rate in the number of biogas plants across all zones, with advancements in technology, government support, and increasing awareness about renewable energy contributing to this growth.

1.4.1 West Zone

The West zone of India comprises five states and one UT: Rajasthan, Madhya Pradesh, Gujrat, Maharashtra, Goa, and Dadra Nagar Haveli and Daman Diu (UT). This zone contains 151 districts and 21265 wards, but only 7273 receive door-to-door waste pickup. Goa is the only state in the zone that provides 100% door-to-door waste collection from all wards. The West region of India has the highest number of biogas plants installed, totaling 1.81 million. Maharashtra has about 0.92 million biogas plants, almost 50% of the total in the West Zone.

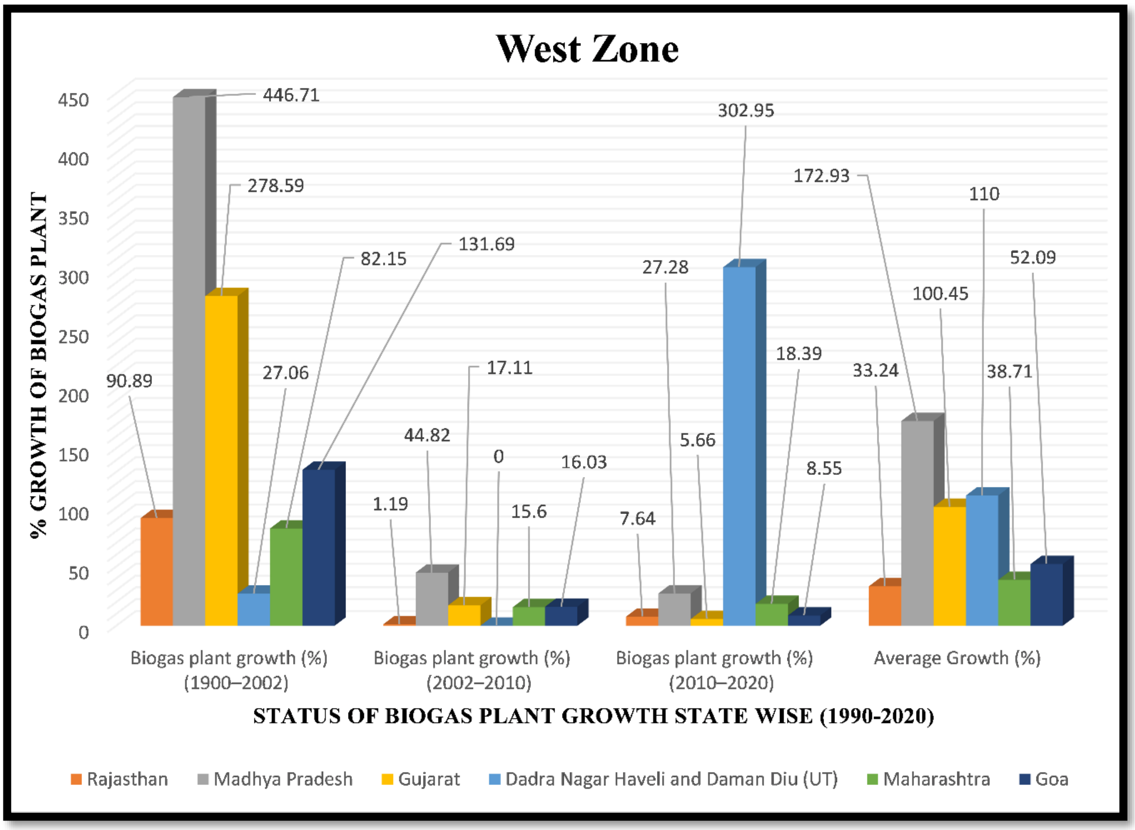


Figure 1.2: Biogas Plant Status and Growth Rate in West Zone (1990 to present)

On the other hand, the union territories of Dadra Nagar Haveli and Daman Diu have the lowest number of biogas plants installed. Figure 1.2 shows the growth rates of biogas plants in Rajasthan, Madhya Pradesh, Gujarat, Dadra Nagar Haveli and Daman Diu (UT), Maharashtra, and Goa from 1990 to 2002. During this period, the growth rates of biogas plants in these states were 90.89%, 446.71%, 278.59%, 27.06%, 82.15%, and 131.69%, respectively.

Table 1.1: State location in the Western Zone and details about biogas plant in the region

	State/Uts	**Districts**	**No. of Wards with 100% door-to-door Collection, Out of Total No. of Wards**	**Area (km^2)**	**Biogas plant, (1990)**	**Biogas plant, (2002)**	**Biogas plant, (2010)**	**Biogas plant, (2020)**
(a) West Zone	Rajasthan	35	1300, (5247)	3,42,239	34,864	66,552	67,348	72,497
	Madhya Pradesh	50	3602, (6999)	3,08,245	37,332	2,04,100	2,95,580	3,76,221
	Gujarat	26	1658, (1730)	1,96,024	92,908	3,51,745	4,11,950	4,35,287
	D & N Haveli and Daman Diu	3	13, (43)	603	133	169	169	681
	Maharashtra	35	508, (7054)	3,07,713	3,70,662	6,75,177	7,80,527	9,24,092
	Goa	2	192, (192)	3702	1448	3355	3893	4226
	Total	**151**	**7273, (21,265)**	**11,58,526**	**5,37,347**	**13,01098**	**15,59467**	**18,13,004**

Source: [13], [14]

The average growth rate of biogas plants in the West Zone during this period was 176.18%. From 2002 to 2010, the growth rates of biogas plants in these states were 1.19%, 44.82%, 17.11%, 0%, 15.6%, and 16.03%, respectively. The average growth rate during this period was 15.29%. From 2010 to 2020, the growth rates of biogas plants in these states were 7.64%, 27.28%, 5.66%, 302.95%, 18.39%, and 8.55%, respectively. The average growth rate during this period was 61.74%. From 1990 to 2020, the states of the West Zone of India increased the number of biogas plants at an average growth rate of 84.57%. Madhya Pradesh had the highest growth rate among the states, at 172.93%, while Maharashtra had the highest increase in biogas plants based on the number of biogas plants installed. The West Zone of India has made significant progress in increasing the number of biogas plants in the region over the past 30 years. The growth rate of biogas plants in the West Zone has been consistently high, with an average growth rate of 176.18% from 1990 to 2002.

However, there has been a decrease in the growth rate of biogas plants from 2002 to 2010, with an average growth rate of only 15.29%. The growth rate of biogas plants increased again from 2010 to 2020, with an average growth rate of 61.74%. Maharashtra has been a key player in the growth of biogas plants in the West Zone, with almost more than half of the total biogas plants installed in the region. The state has been prosperous in promoting biogas plants and has implemented several policies and schemes to encourage the use of biogas. The state government has also provided financial incentives and subsidies to farmers and other individuals to install biogas plants. Madhya Pradesh has also made significant progress in increasing the number of biogas plants in the state, with the highest growth rate at 172.93%.

1.4.2 North Zone

According to climate conditions, states in this zone, including Himachal Pradesh, Jammu and Kashmir, and Uttarakhand, are called cold states since their annual average temperature is 15 to 20°C. Uttar Pradesh is the largest state in population, districts, wards, and land area. Regarding land area, Jammu and Kashmir are the smallest Indian states in the northern zone. Only 4327 wards out of 18473 are serviced by door-to-door waste collection in this zone.

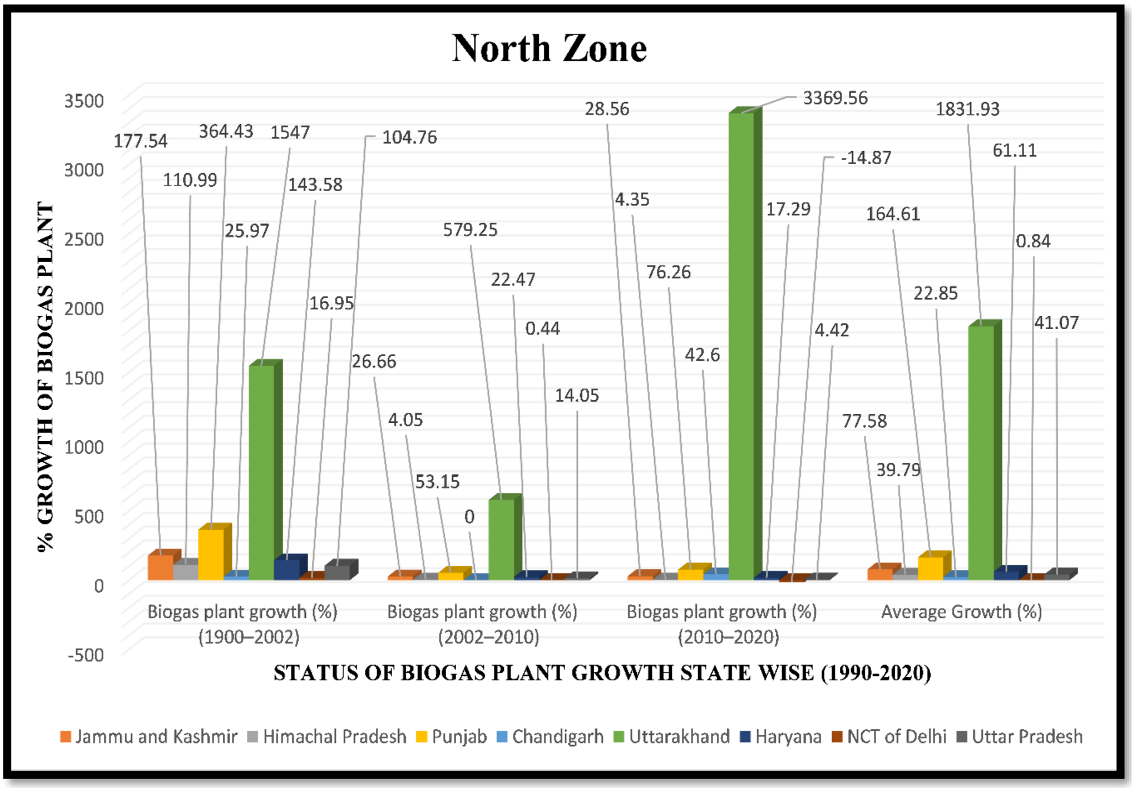


Figure 1. 3: Biogas Plant Status and Growth Rate in North Zone (1990 to present)

Chandigarh is a UT which is the only one in the north zone of India that provides 100% door-to-door waste collection in all 26 wards. There are 1.106 million biogas plants erected in the North Zone; Uttar Pradesh has the most significant number of biogas plants in this zone, accounting for almost 40% of the total biogas plants constructed there.

Table 1.2: State location in the Northern Zone and details about biogas plant in the region

	State/Uts	**Districts**	**No. of Wards with 100% door-to-door Collection, Out of Total No. of Wards**	**Area (km^2)**	**Biogas plant, (1990)**	**Biogas plant, (2002)**	**Biogas plant, (2010)**	**Biogas plant, (2020)**
(b) North Zone	Jammu and Kashmir	22	989, (1163)	42,241	708	1965	2489	3200
	Himachal Pradesh	12	167, (502)	55,673	20,822	43,933	45,716	47,706
	Punjab	22	2000, (3065)	50,362	14,802	68,745	1,05,289	1,85,583
	Chandigarh	1	26, (26)	114	77	97	97	169
	Uttarakhand	13	90, (706)	53,483	0	1547	10,508	3,64,582
	Haryana	21	332, (1449)	44,212	18,129	44,160	54,083	63,436
	NCT of Delhi	8	232, (272)	1484	578	676	679	578
	Uttar Pradesh	75	491, (11290)	2,40,928	1,80,806	37,0219	4,22,269	4,40,949
	Total	**174**	**4327, (18,473)**	**4,88,497**	**2,35,922**	**53,1342**	**6,41,130**	**11,06,203**

Source: [15], [16]

- It's important to note that our data is current up to 2019-2020, when Jammu and Kashmir was still a state, although it is now a union territory.

Jammu & Kashmir and the Union Territory of Chandigarh have established the least number of biogas plants in the region. Growth of Biogas Plants in Jammu & Kashmir, Himachal Pradesh, Punjab, Chandigarh, Uttarakhand, Haryana, NCT of Delhi, and Uttar Pradesh from 1900 to 2002 was 177.54%, 110.99%, 364.43%, 25.97%, 1547%, 143.58, 16.95% and 104.76% respectively, which can be seen in Figure 1.3. During this period of twelve years, the average annual growth rate was 311.40%. Because Uttarakhand was split from Uttar Pradesh and established as an independent state during this period, the state saw tremendous growth in biogas plants. From 2002 to 2010, the growth rates of biogas plants in these states were 26.66%, 4.05%, 53.15%, 0%, 579.25%, 22.47%, 0.44%, 14.05%, respectively, and the average growth rate of biogas plants in all states during this period was 87.5%. Not a single biogas plant was built in Chandigarh during this period.

Over the period 2010 to 2020, the growth rate for biogas plants in the states of this zone was 28.56%, 4.35%, 76.26%, 42.6%, 3369.56%, 17.29%, 14.87%, 4.42%, with an average growth rate of 441.02% over the time. During this time, the already established biogas plants in Delhi were shut down, resulting in a negative rise in the number of biogas plants in Delhi. The average annual growth rate of biogas plants in the North Zone has been 279.97% during the 30 years from 1990 to 2020, with the state of Uttarakhand, which has built biogas plants, seeing the most significant annual growth rate of 1831.93% over this period.

1.4.3 South Zone

The South Zone of India is the third-largest region in terms of land area, but it has the smallest population compared to other regions. This zone is composed of five states and three union territories. Still, the data of Telangana state is considered with Andhra Pradesh, and the data of Lakshadweep union territory has been added in Table 1.3. In this zone, four states and two union territories have been considered. The overall number of wards in this region is 25659; 100% door-to-door waste collection is 19220. Tamil Nadu has the most significant number of wards and districts, while Kerala has the smallest number.

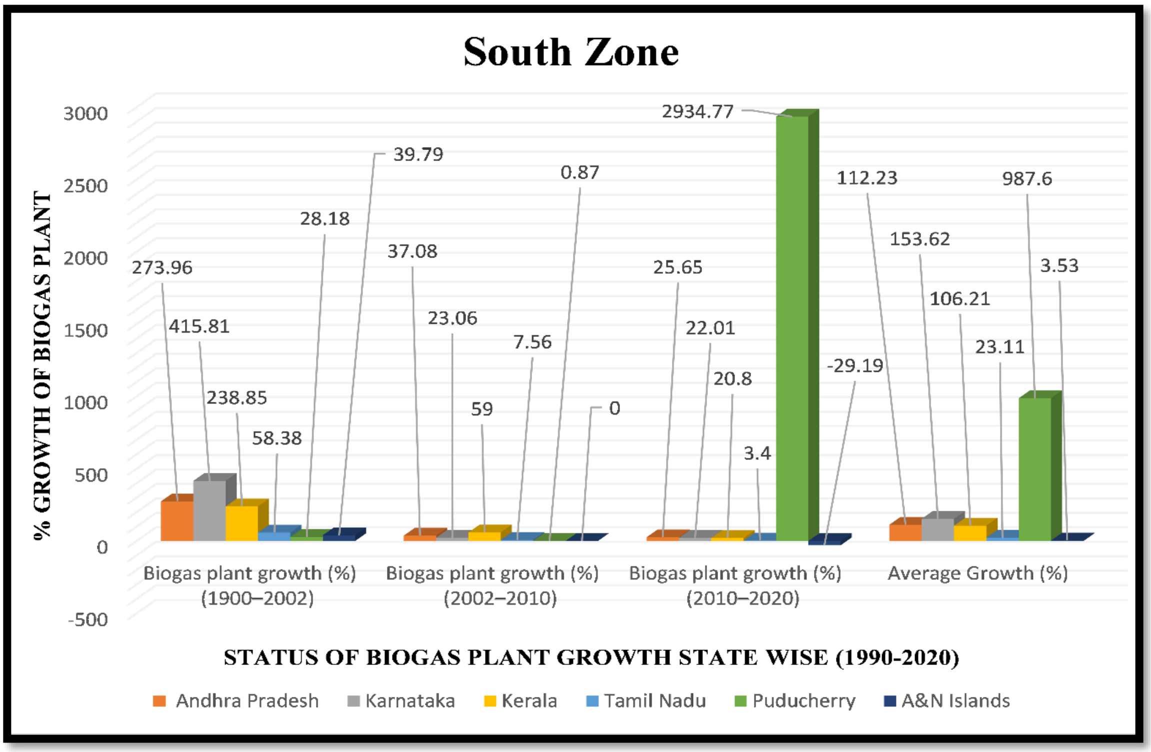


Figure 1. 4: Biogas Plant Status and Growth Rate in South Zone (1990 to present)

Biogas production is a critical aspect of waste management, and the South Zone has made considerable progress in this area. From 1990 to 2002, this region's states and union territories experienced significant growth rates in biogas plants. Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Puducherry, Andaman, and Nicobar Islands have recorded growth rates of 273.96%, 415.81%, 238.85%, 58.38, 28.18%, and 39.79%, respectively.

Table 1.3: State location in the Southern Zone and details about biogas plant in the region

	State/Uts	**Districts**	**No. of Wards with 100% door-to-door Collection, Out of Total No. of Wards**	**Area (km^2)**	**Biogas plant, (1990)**	**Biogas plant, (2002)**	**Biogas plant, (2010)**	**Biogas plant, (2020)**
(c) South Zone	Andhra Pradesh	23	4697, (5356)	2,75,045	89,327	3,34,054	4,57,938	5,74,988
	Karnataka	30	3962, (5252)	1,91,791	65,968	3,40,270	4,18,759	5,10,942
	Kerala	14	1280, (2096)	38,863	23,471	79,532	1,26,463	1,52,771
	Tamil Nadu	32	9182, (12802)	1,30,051	1,27,096	2,01295	2,16,516	2,23,894
	Puducherry	4	81, (129)	479	447	573	578	17,541
	A & N Islands	3	18, (24)	8249	98	137	137	97
	Total	**107**	**19,220, (25,659)**	**6,44,478**	**3,06407**	**9,55,861**	**12,20,391**	**14,80,233**

Source: [16], [17], [18]

- Lakshadweep does not have a biogas plant at the moment. However, one district from Lakshadweep has been incorporated into the southern zone, and the data for Telangana and Andhra Pradesh have been amalgamated.

During this period, the average growth rate of biogas plants in this region was 175.82%. Between 2002 and 2010, the average growth rate of biogas plants in these states and union territories was 37.08%, 23.06%, 59%, 7.56%, 0.87%, and 0%, and the average growth rate was 21.26%. However, no new biogas plants were constructed in the Andaman and Nicobar Islands Union territory during this time. As a result, the growth rate for this region was zero percent during this period. From 2010 to 2020, the growth rate of biogas plants in these states and union territories was 25.65%, 22.01%, 20.8%, 3.4%, 2934.77%, -29.19%, and the average growth rate for this period was 496.24%. This is an excellent example of how growth rates can vary significantly over time. For example, some existing biogas facilities in the Andaman and Nicobar Islands Union territory were closed during this time, resulting in a negative growth rate for this sector. Over 30 years, from 1990 to 2020, the South Zone experienced an average growth rate of 231.05% in biogas plants. This growth rate indicates that the region has successfully promoted the adoption of biogas technology in waste management. Karnataka and Puducherry recorded the highest growth rates.

In conclusion, the South Zone of India has significantly progressed in biogas production and waste management. The growth rates in biogas plants in this region have varied substantially over time. Some states and union territories are experiencing high growth rates, while others have experienced negative growth rates. However, the overall trend over 30 years has been positive, indicating that the South Zone is on the right path toward sustainable waste management.

1.4.4 East Zone

The East Zone of India is the second-largest zone in terms of area and comprises 11 states. The data of these 11 states, including Bihar, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, Assam, West Bengal, Jharkhand, and Odisha, are used to analyze the growth of biogas plants in the region from 1990 to 2020.

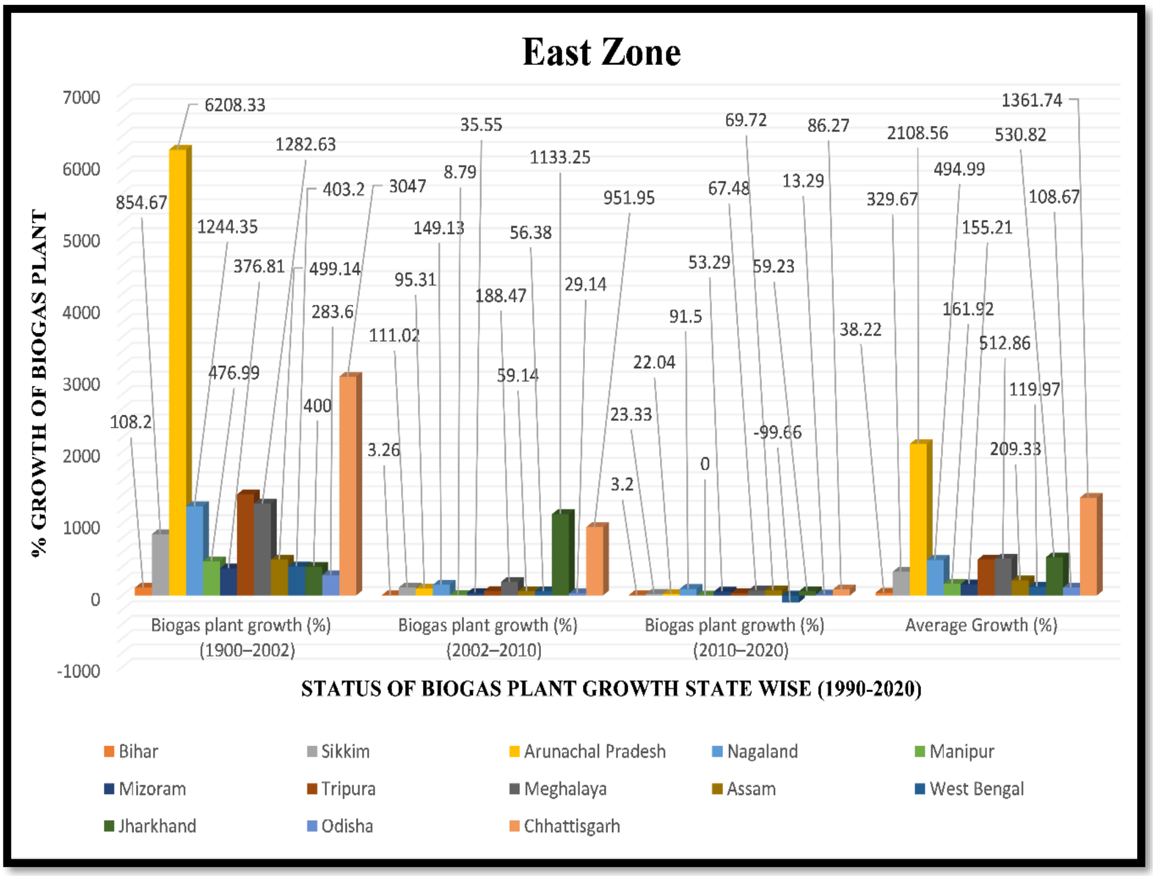


Figure 1. 5: Biogas Plant Status and Growth Rate in East Zone (1990 to present)

The zone has 13236 wards, of which only 3439 have 100% door-to-door waste collection. Interestingly, Tripura is the only state where no society has door-to-door waste collection, which is a matter of concern as proper waste management is necessary for maintaining a healthy environment. The growth rates of biogas plants in the East Zone from 1990 to 2020 have been remarkable, with an average growth rate of 1276.37%. During this period, Arunachal Pradesh has shown the highest growth rate of 6208.33%, followed by Nagaland (1244.35%), West Bengal (403.2%), and Chhattisgarh (3047%). Bihar and Sikkim also saw growth rates of 108.2% and 854.67%, respectively. Fig 1.5 depicts the growth rates of biogas plants in the East Zone from 1990 to 2020.

Table 1.4: State location in the Eastern Zone and details about biogas plant in the region

	State/Uts	**Districts**	**No. of Wards with 100% door-to-door Collection, Out of Total No. of Wards**	**Area (km^2)**	**Biogas plant, (1990)**	**Biogas plant, (2002)**	**Biogas plant, (2010)**	**Biogas plant, (2020)**
(d) East Zone	Bihar	39	519, (3229)	94,163	58,553	1,21,913	1,25,888	1,29,925
	Sikkim	4	4, (48)	7096	364	3475	7333	9044
	Arunachal Pradesh	16	18, (42)	83,743	24	1514	2957	3609
	Nagaland	11	165, (234)	16,579	124	1667	4153	7953
	Manipur	9	130, (315)	22,327	339	1956	2128	2128
	Mizoram	8	66, (193)	21,081	591	2818	3820	5856
	Tripura	8	0, (244)	10,486	114	1719	2793	3710
	Meghalaya	7	6, (114)	22,429	167	2309	6661	11,156
	Assam	27	45, (883)	78,438	8557	51,269	81,592	1,38,483
	West Bengal	19	1130, (2875)	88,752	40,474	2,03,669	3,18,510	1072
	Jharkhand	24	161, (815)	79,714	0	400	4933	7855
	Odisha	31	456, (1012)	1,55,707	48,407	1,85,690	2,39,818	2,71,690
	Chhattisgarh	27	739, (3232)	1,35,191	0	3047	32,050	59,700
	Total	**230**	**3439, (13,236)**	**8,15,706**	**1,57,714**	**5,81,446**	**8,32,636**	**6,52,181**

Source: [18], [19]

From 2002 to 2010, the growth rates of biogas plants in the East Zone have been lower than in the previous decade, with an average growth rate of 221.83%. However, some states have shown tremendous growth rates, such as Tripura with 1407.89%, Meghalaya with 1282.63%, and West Bengal with 1133.25%. Meanwhile, Mizoram and Odisha have seen a growth rate of 35.55% and 29.14%, respectively. The period from 2010 to 2020 saw a mixed trend in the growth rate of biogas plants in the East Zone. While some states saw growth rates of 67.48%, 69.72%, and 86.27%, others saw negative growth rates, with Manipur and West Bengal seeing a fall of 99.66% and 99.62%, respectively. Overall, the average growth rate of biogas plants in the East Zone from 2010 to 2020 was 32.5%. It is important to note that during this period, no new biogas plants were built in Manipur, and some existing biogas plants in West Bengal were shut down, leading to a fall in the growth rate of biogas plants in the region. Odisha, with the most biogas plants installed, has seen a growth rate of 23.33% from 2010 to 2020.

In conclusion, the East Zone of India has seen remarkable growth in biogas plants from 1990 to 2020. While some states have shown impressive growth rates, others have seen a mixed trend in the growth rate of biogas plants. Proper waste management is necessary for maintaining a healthy environment, and steps should be taken to increase door-to-door waste collection in all the states of the East Zone, especially Tripura.

1.5 Present status of solid municipal waste in India

Solid municipal waste management (SWM) is a significant challenge for India due to its population and rapid urbanization. A lack of proper infrastructure and financial resources further compounds the issue of solid waste management in India. This essay will discuss the present status of solid municipal waste generation in India, including its sources, composition, and management. India generates around 62 million tonnes of solid waste annually, which is expected to increase to 165 million tonnes by 2030 [20]. The per capita generation of waste in India is around 0.5 kg per day, which is lower than in developed countries, but it is increasing at an alarming rate. According to the World Bank, India is the world's fifth largest generator of municipal solid waste (MSW) after the United States, China, Brazil, and Japan [21].

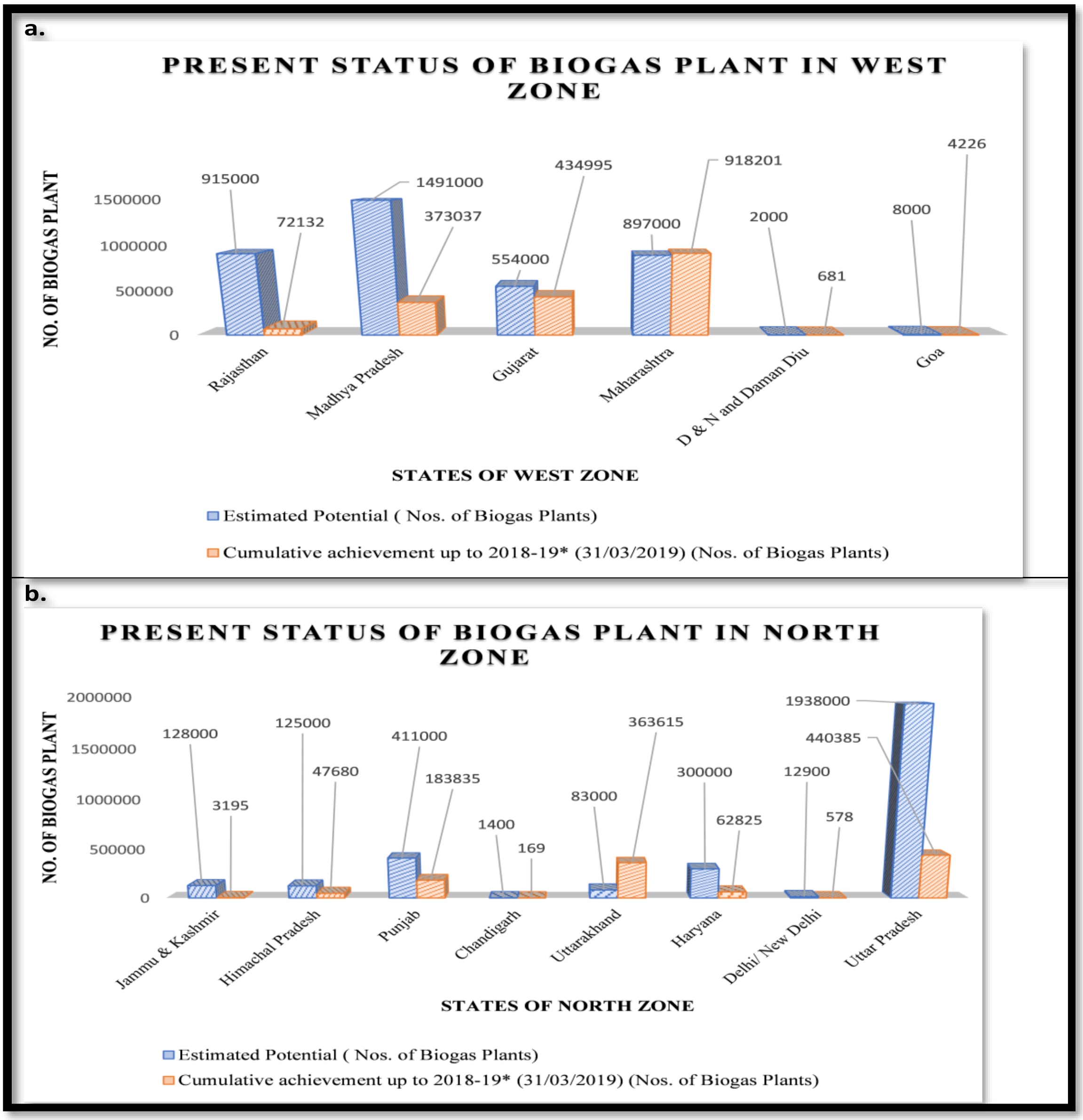
The primary sources of solid municipal waste in India are households, commercial establishments, and industries. Household garbage is India's most significant component of solid waste, accounting for around 62% of the total waste generated [20]. The garbage generated by commercial establishments and industries accounts for approximately 5% and 7% of the complete waste generated in the country. The composition of solid municipal waste in India varies from region to region and depends on several factors, such as population density, economic activities, and lifestyle. However, in general, the solid waste in India is composed of organic waste (50-60%), paper and cardboard (15-20%), plastics (10-12%), metals (5-6%), and others (5-7%). Organic waste is India's most significant component of solid waste, including kitchen, garden, and other biodegradable materials [20]. The management of solid municipal waste in India is complex due to the lack of public awareness.

In many parts of India, solid waste is either burned openly, dumped in landfills, or disposed of in water bodies, leading to environmental pollution and health hazards. The government has implemented various policies and programs to address the country's solid waste management issue. One of the significant initiatives taken by the Indian government is the Swachh Bharat Abhiyan [22], launched in 2014. The mission aims to achieve a 100% open defecation-free India, 100% scientific and sustainable management of solid waste, and 100% behavioral change in the country regarding sanitation practices. Under this mission, the government has provided financial assistance to local bodies to construct toilets and solid waste management facilities. Another initiative the government takes is the National Green Tribunal [23], established in 2010 to handle environmental disputes and enforce environmental laws. The NGT has been actively monitoring and enforcing the solid waste management rules in the country.

The government has also introduced the Solid Waste Management Rules, 2016, which replace the earlier rules of 2000. The new rules aim to promote the concept of waste to wealth and reduce the amount of waste going to landfills. The regulations make it mandatory for all urban local bodies to segregate waste at the source, set up waste processing and disposal facilities, and encourage waste recycling [24]. Despite the government's efforts, solid waste management in India still faces several challenges. The government's significant challenges are the lack of proper infrastructure and funding, inadequate public awareness, and weak enforcement of rules and regulations.

1.6 Present status of estimated and cumulative achievement of biogas plants in states of different zones

As seen in Figure 1.6(a), Rajasthan, the westernmost state of India, has installed just 7.89% of its total potential for biogas plants. Similarly, Madhya Pradesh, Gujarat, Dadra Nagar Haveli, and Daman Diu & Goa have only installed 25.02%, 78.52%, 34.05%, and 52.83% of their potential biogas plants. Maharashtra is the only state in the area that installed 102.36% more biogas plants than expected [25]. Thus, this state has the most biogas plants in this zone and the most in India. Based on their projected potential, Table 1.5(a) shows that two states, one UT, have installed less than half of their biogas plants in the West Zone.



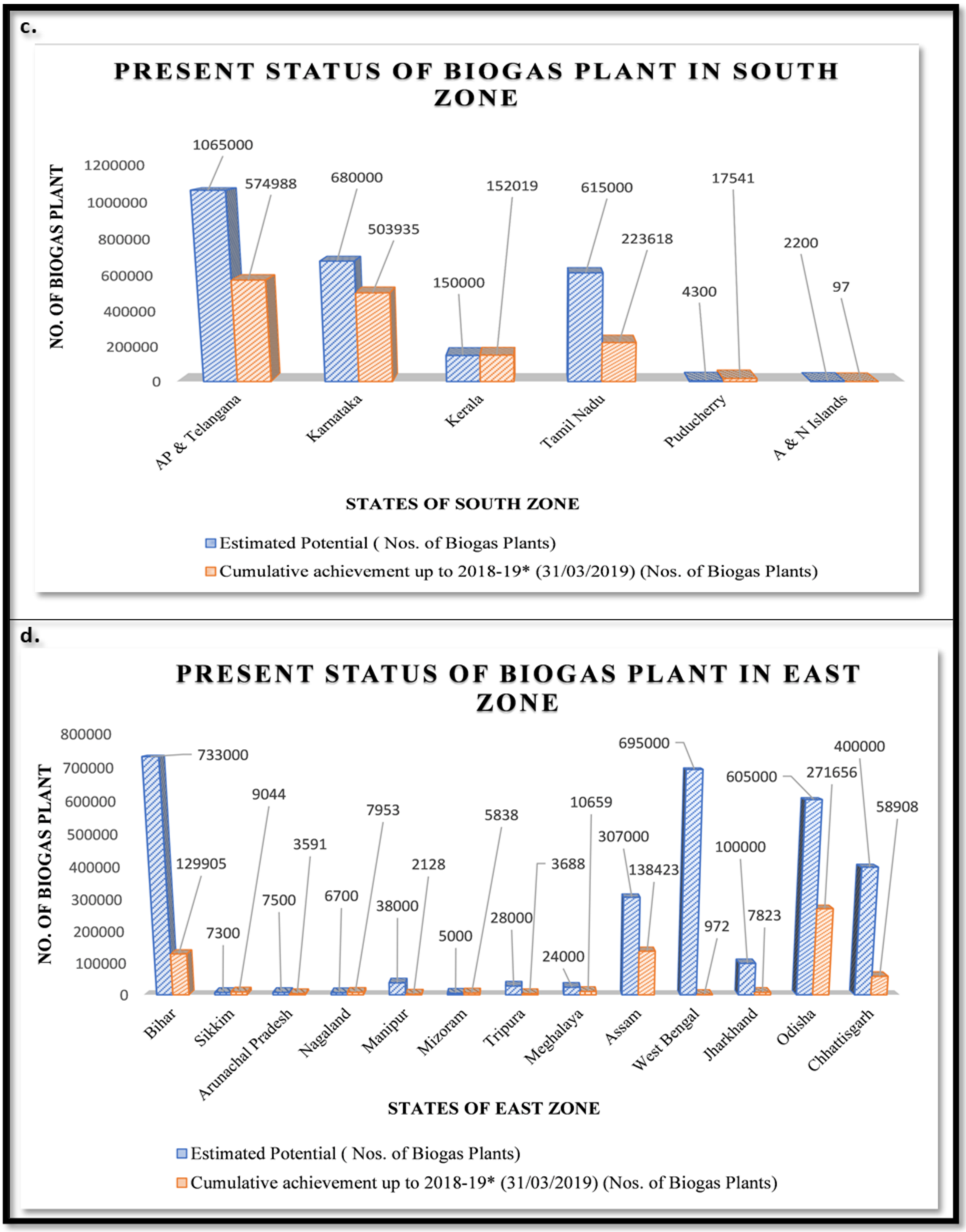


Figure 1.6: Estimated Potential and Cumulative Achievement of Biogas Plants in (a) West Zone, (b) North Zone, (c) South Zone, (d) East Zone [27]

Only two states in the moderate category have established more than 50% biogas plants. Only one state in the excellent category has built more biogas plants than expected. Figure 1.6(b) shows that Jammu, Kashmir, Delhi, and Chandigarh have installed biogas plants at just 2.49 %, 4.48 %, and 12.07 % of their anticipated capacity [26]. Himachal Pradesh has installed 38.14 % of its potential biogas plants, whereas Punjab, Haryana, and Uttar Pradesh have installed 44.72 %, 20.94 %, and 22.72 %, respectively.

Table 1. 5: Worst, moderate/Good, and excellent categories in biogas installation by states in different zones

(a) West Zone	0-50% Biogas Plants Established by States/UTs (Worst Condition)	51%-100% Biogas Plants Installed by States/UTs (Moderate/Good Condition)	Above 100% Biogas plant installed by State/UTs (Excellent Condition)
	Rajasthan	Gujarat	Maharashtra
	Madhya Pradesh	Goa	_
	D & N and Daman Diu	_	_
(b) North Zone	Jammu & Kashmir	_	Uttarakhand
	Delhi/ New Delhi	_	_
	Chandigarh	_	_
	Himachal Pradesh	_	_
	Punjab	_	_
	Haryana	_	_
	Uttar Pradesh	_	_
(c) South Zone	A & N Islands	AP & Telangana	Kerala
	Tamil Nadu	Karnataka	Puducherry
	_	_	_
	_	_	_
(d) East Zone	Manipur	_	Sikkim
	West Bengal	_	Nagaland
	Chhattisgarh	_	Mizoram
	Jharkhand	_	_
	Tripura	_	_
	Bihar	_	_
	Arunachal Pradesh	_	_
	Meghalaya	_	_
	Assam	_	_
	Odisha	_	_

Uttarakhand is the only state in the area with 438.09 % biogas plants, more than expected [27]. As shown in Table 1.5(b), the North Zone has eight states and UTs, seven of which are in the worst category, meaning it has installed less than half its anticipated biogas capacity. Uttarakhand is the only state in this zone to have established nearly four times as many biogas plants as its potential. Figure 1.6(c) shows that AP & Telangana, Karnataka, Tamil Nadu, and A & N Islands have installed 53.98%, 74.1%, 36.36%, and 4.4% biogas plants, respectively, although their percentages are considerably below the potential of 100% [28]. Kerala and Puducherry have installed up to 101.34 % and 407.93 % of their potential biogas plants. Table 1.5(c) shows two states in excellent and two in moderate categories. Puducherry has installed four times the estimated full potential of biogas plants.

East zone states like West Bengal, Jharkhand, and Manipur have installed 0.13 %, 7.82 %, and 5.6 % of biogas plants, respectively, much below the 100% potential [27]. Between 2010 and 2020, over 99 % of West Bengal's biogas facilities closed owing to bad government policies and neglect of facility upkeep. Bihar, Arunachal Pradesh, Tripura, Meghalaya, Assam, Odisha, and Chhattisgarh have all struggled to establish biogas facilities. It has only built 17%, 47%, 13%, 44%, 44%, and 14% of its total capacity [27]. Only Sikkim, Nagaland, and Mizoram have installed more than 100% of their projected potential biogas plants in this zone. These states have built 123.89, 118.7, and 116.76 % of biogas facilities [27]. Ten of the thirteen states are in the worst group, while three are in the excellent category, as seen in Table 1.5(d).

1.7 Status of waste-to-energy plants and biogas production in different states of the regions

2014-15, India produced around 20,757 lakh cubic meters of biogas, comparable to 66 million home LPG cylinders. It accounts for 5% of overall LPG use in the country. As Figure 1.7(a) indicates, Maharashtra leads the way with 3578 lakh cubic meters of biogas produced yearly in 2014-15, followed by Andhra Pradesh with 2165 lakh cubic meters. The 26 various categories of garbage shown in Figure 1.7(b) are projected to have the ability to create energy equivalent to 5690 MW, and the majority of urban solid waste generates energy. Every day, around 50% of municipal garbage produced in India is food and other biodegradable waste, 29% is inert silt and building waste, and 21% is textiles, paper, plastic, and glass waste [29].

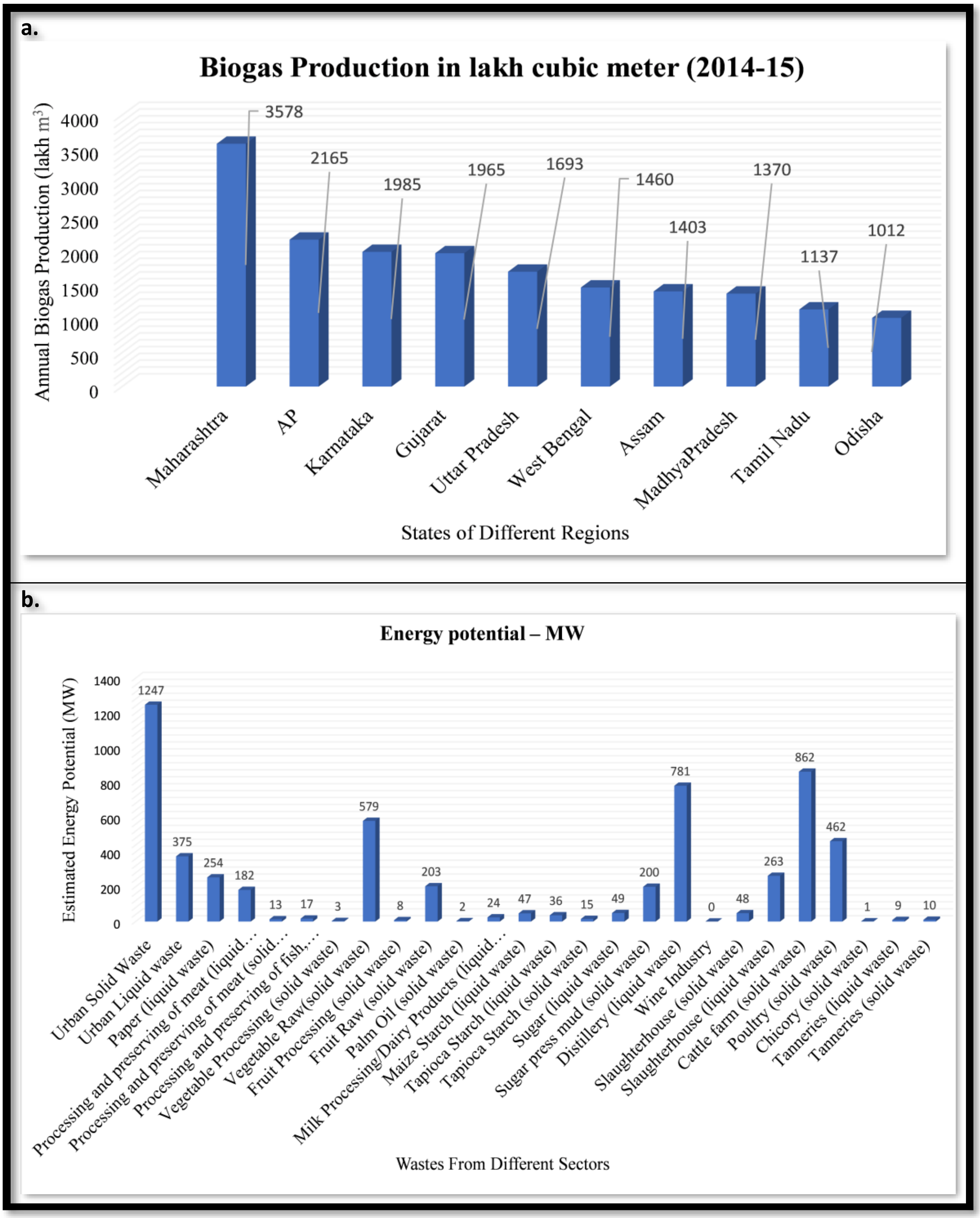


Figure 1. 7: (a) Biogas production state-wise [30] (b) Estimated energy potential by different sectors of waste [25]

Table 1.6: Status of biogas production, MSW generation, and power generation from waste to energy plants in the states of different zones [31]

State/UT		Municipal Waste generation (metric tonnes/day)	Biogas generation Plants M^3/day (No. of Plants), (A)	Bio-CNG generation plants kg/day (No. of plants), (B)	Power generation plants MW (No. of Plants), (C)	Total MWeq, (A+B+C)
(a) West Zone	Rajasthan	5247	-	4000 (2)	3.0 (1)	3.83 (3)
	Madhya Pradesh	5079	27,014 (5)	1200 (1)	15.4 (3)	17.90 (9)
	Maharashtra	26820	1,09,636 (10)	27,723 (4)	28.713 (15)	43.63 (29)
	Gujarat	9277	24,800 (4)	28,338 (5)	11.275 (10)	19.25 (19)
	Total	**46,423**	**1,61,450 (19)**	**61,261(12)**	**58.38 (29)**	**84.61 (60)**
(b) North Zone	Delhi	8400	-	-	52.00 (3)	52.00 (3)
	Haryana	3490	-	4250 (3)	4.0 (2)	4.89 (5)
	Punjab	3900	34,800 (5)	1847 (1)	14.92 (7)	18.20 (13)
	Uttarakhand	1400	67,260 (5)	5880 (2)	1.89 (2)	8.72 (9)
	Himachal Pradesh	300	12,000 (1)	-	-	1.00 (1)
	Uttar Pradesh	19180	62,320 (6)	2000 (1)	44.63 (22)	50.24 (29)
	Total	**36,670**	**1,76,380 (17)**	**13,977 (7)**	**117.44 (36)**	**135.05 (60)**
(c) South Zone	Andhra Pradesh	6141	90,540 (7)	-	40.82 (15)	48.365 (22)
	Karnataka	8784	58,060 (3)	9521 (3)	7.8 (5)	14.62 (11)
	Kerala	1576	2760 (1)	-	-	0.23 (1)
	Tamil Nadu	15,272	1,50,218 (28)	-	10.45 (6)	22.97 (34)
	Telangana	8634	37,100 (5)	-	19.5 (4)	22.59 (9)
	Total	**40,407**	**3,38,678 (44)**	**9521 (3)**	**78.57 (30)**	**108.775 (77)**
(d) East Zone	West Bengal	8675	14,000 (2)	-		1.17 (2)
	Bihar	3703	12,000 (1)	-	-	1.00 (1)
	Chhattisgarh	1896	-	-	0.33 (1)	0.33 (1)
	Total	**12,378**	**26,000 (3)**	**-**	**0.33 (1)**	**2.5 (4)**

Maharashtra's western area creates a maximum of 26820 metric tons of solid trash daily. Table 1.6(a) shows the substantial trash from which organic waste is separated and the more than one lakh cubic meters of biogas created daily in 10 facilities. Four plants utilize raw biogas, remove CO_2 and H_2S from biogas, purify it, compress it to 200 bar pressures, and generate approximately 27723 kg of Bio-CNG daily. Other 15 garbage plants produce 28.71 MW of power. Thus, Maharashtra generates the most incredible power in the western area, 43.63 MW, from 29 garbage facilities. Rajasthan's state generates a negligible amount of energy. As a result, 1.6 lakh cubic meters of biogas are generated daily from the West Zone's 19 biogas facilities. Twelve units produce over 61 thousand kg of Bio-CNG gas each day. Twenty-nine waste facilities yield 58.38 MW of power, for a total of 84.61 MW of energy created by 60 waste plants in this zone. According to Table 1.6(b), the northern portion of Uttar Pradesh generates the most MSW. Using organic waste, six units produce 62,320 cubic meters of biogas daily. One waste plant has 2000 kg of bio-CNG gas daily, while the other twenty-two waste plants use solid waste. This generates around 44.63 MW of electricity. In this manner, the twenty-nine-waste facility generates 54.24 MW of electricity. Delhi generates a maximum of 52 MW of electricity utilizing three waste facilities, whereas Himachal Pradesh generates up to 1 MW.

As a result, 36670 metric tons of trash generated in North Zone states create 1.7 lakh cubic meters of biogas from 17 plants and 13977 kg of bio-CNG gas produced daily from 7,117.44 MW from 36 additional waste facilities. The total electricity generated by the 60 waste facilities is 135.06 MW, the highest in all zones. According to Table 1.6(c), organic waste segregation generates 6141 metric tons of waste per day in the South Zone state of Andhra Pradesh. Seven biogas plants produce ninety thousand five hundred forty cubic meters of biogas, while 15 waste plants generate 40.81MW of electricity. This state generates 48.36 MW of electricity utilizing 22 waste facilities. Tamil Nadu generates 1.5 lakh cubic meters of biogas daily from 28 biogas plants and 22.97 MW of electricity from 34 plants using 15272 MT MSW. Kerala generates at least 2760 m^3 of biogas annually, providing just 0.23 MW of power. Thus, 40407 MT MSW is utilized in the South Zone, and 3.38 lakh m^3 of biogas is generated in forty-four facilities. Three plants produce 9521 kg of bio-CNG. Thirty waste treatment facilities have 78.57 MW of electricity.

As a result, the 77 plants generate 108.775 MW of electricity. From 2010 to 2020, most biogas facilities in West Bengal's State of East Zone were shut down. Currently, just two biogas plants produce 14000 m^3. It is substantially smaller in quantity, and these biogas plants generate 1.17 MW of power. Only one biogas plant in Bihar State has 12000 m^3 of biogas, generating 1MW of energy. In Chhattisgarh, only one waste energy plant generates 0.33 MW of power. Thus, all three biogas plants in the East Zone produce 26000 m^3 of biogas. Only 0.33 MW of power is caused by one plant. As a result, four waste facilities generate 2.5 MW of power. This way, 83 biogas plants throughout all zones produce 7.02 lakh m^3 biogas daily, while 22 plants have 84759 kg of bio-CNG daily. Power is generated by 96 waste facilities totaling 254.33 MW. Table 1.6(d) shows 201 waste facilities that create 330.93 MW of electricity.

1.8 Problem of organic waste in the developing country

India is facing a significant challenge when it comes to managing organic waste. The problem is mainly due to the lack of waste segregation at the source, where most households collect all types of garbage in a single dustbin. This situation increases in solid organic waste daily, creating several environmental and health issues. Organic waste includes all food, garden, manure, animal and plant-based material, and degradable carbon such as paper, cardboard, and timber. According to a report by [32], organic materials comprise 51% of Municipal Solid Waste (MSW) in India. The Food and Agriculture Organization of the United Nations (FAO) estimates that 1.3 Gigaton (Gt) of food is wasted annually, about one-third of all food produced globally [33]. This is a significant concern, especially in countries like India, where food insecurity is still prevalent.

The problem is exacerbated by the lack of efficient waste management systems, leading to large quantities of organic waste ending up in landfills. Organic waste in landfills produces methane, a potent greenhouse gas contributing to global warming and climate change. Another significant challenge is India's lack of infrastructure and resources for proper waste management. The country's waste management system has been unable to keep up with the rapid growth of urbanization and industrialization, leading to an increase in waste generation. The limited availability of landfills has led to illegal waste dumping in open spaces, rivers, and other water bodies, leading to environmental degradation and public health hazards.

According to [34], organic waste is a significant portion of solid waste in India. An estimated 70% of solid waste in the country contains organic waste, including food waste, kitchen waste, green waste, and sewage sludge. In addition, India is the second-largest producer of fruits and vegetables globally, which contributes significantly to the organic waste generated in the country. According to a study by [35], India produces over 300 million metric tons of fruits and vegetables annually, which amounts to significant organic waste. Efficient waste management strategies are crucial to managing this waste and preventing environmental degradation and public health hazards. Recycling organic waste can provide several benefits, such as reducing greenhouse gas emissions, producing biogas, and generating organic fertilizers.

Figure 1. 8: Household waste and Municipal solid waste

Anaerobic digestion is a popular method for recycling organic waste, where microorganisms break down organic material to produce biogas, which can be used as a source of energy. The remaining material, after anaerobic digestion, called digestate, can be used as organic fertilizer. In conclusion, given the country's high food production, population, and inadequate waste management systems, organic waste management is a crucial issue in India. A comprehensive approach is required to tackle this challenge, including waste segregation at the source, efficient waste management infrastructure, and organic waste recycling.

By addressing the organic waste problem, India can improve public health, reduce greenhouse gas emissions, and promote sustainable development. If people in India know the importance of organic waste generated at home and started segregating their waste, biogas could be produced, which would help solve the municipal waste problem. This would reduce the amount of waste going to landfills and provide a clean and renewable energy source for households. It is crucial to educate people about the benefits of the segregation of waste and incentivize the production of biogas to make it a sustainable solution.

1.9 Challenges or barriers to biogas implementation

The barriers to biogas implementation in developing countries that will be discussed include limited financial resources and funding options, lack of infrastructure and technical expertise, and challenges related to feedstock availability and quality. Additionally, regulatory obstacles, cultural acceptance, and awareness about the benefits of biogas technology will be considered in the discussion.

1.9.1 Technical barriers

According to several studies, the establishment of biogas facilities in underdeveloped countries is hindered by several technical barriers. These include a lack of information and training among householders, leading to inadequate maintenance of biogas digesters and insufficient knowledge of feedstock compatibility [36]. Inappropriate garbage disposal, inadequate waste collection, and defective supply chains can impede biogas generation [37]. In rural areas where not all households have livestock or poultry, biogas generation is further hampered by the shortage of animal manure [38]. Farmers in agro-biogas plants need to be educated so that biogas slurry can be utilized for organic farming in addition to biogas utilization [39]. However, a lack of technical expertise among biogas operators, including experienced and qualified personnel, presents significant challenges to establishing long-term biogas plants.

Moreover, most operators lack the necessary technical training and course certificates, making connecting biogas with eco-agriculture and reducing biogas output challenging [40]. As a result, most biogas plants are shut down before their full operational potential due to a lack of setup and operation expertise [41]. In addition to technical barriers, the failure of biogas initiatives due to poor management, lack of technical knowledge, and lack of experience have led to an overly pessimistic view of biogas technology [42]. Biogas production is also accompanied by the generation of harmful poisonous gases, such as carbon dioxide, ammonia, and hydrogen sulfide, which can impede biogas production [43]. Biomass is abundant in developing nations but underutilized due to a lack of infrastructure and technology [44]. A lack of R&D to manufacture high-quality digesters, a lack of information about effective digester management, and a failure to embrace technology on time are other causes of digester failure [45]. Larger-scale biogas production has proven to be a substantial impediment in many countries due to water scarcity experienced by many developing nations [44]. In desert regions like Rajasthan or Rann of Kutch, where water scarcity is a significant problem, biogas plants grown are on the verge of closing, and biogas generation efficiency has dropped drastically [46]. In addition, the daily organic waste-to-water ratio in a biogas digester is crucial to producing biogas. It can be completely stopped when the quantity is too much or too little [45]. In metropolitan environments, where organic and inorganic waste segregation is not done appropriately, biogas production is also negatively impacted. Many waste-to-energy facilities in medium-sized cities have been shut down due to inadequate trash collection and uncoordinated waste transportation by municipalities [47].

Furthermore, due to municipal and government neglect of trash collection and segregation, there are insufficient waste-to-energy facilities in India's cities, towns, and villages. Adopting biogas technologies is also a difficult challenge. Many private enterprises are reluctant to invest in new construction and technology for biogas plants due to the costly investment and market risk associated with biogas technology [48] [49].

1.9.2 Financial barriers

According to several studies, financial barriers pose a significant challenge to adopting and proliferating biogas systems. Biogas systems are expensive to install and maintain, making them unaffordable for low-income individuals and households. A self-built home-scale bio-digester with a daily input capacity of 50 kg can cost more than $1500, a significant investment [50]. The cost of treatment and transportation of feedstock can further reduce the economics of biogas power plants, especially over long distances [37]. Moreover, producing pure biogas from raw biogas requires expensive equipment such as H_2S scrubbers, CO_2 scrubbers, and gas conditioners [51], and mechanical pretreatment for optimal biogas generation is also costly [52]. Access to commercial capital to invest in biogas infrastructure is severely restricted in poor countries, mainly rural areas. As a result, subsidies, financial assistance programs, and low-interest loans are significant economic barriers that make biogas projects less attractive to investors [49].

Lack of long-term finance and high-interest rates also impair the economic viability of biogas plants [53]. Additionally, the lack of government incentives for adopting biogas technology and favoring fossil fuels over renewable fuels in many developing nations' financial structures delay or prevent the implementation of biogas initiatives [54] [55]. Corruption, lack of political will, and insufficient government policies further hinder the performance of biogas systems [56]. The shortage of skilled researchers due to a lack of financing also poses a challenge [57]. More funds for research and development would enhance technology innovation [58], and institutional networking for R&D and coordinated efforts in solving R&D obstacles should be established to improve biogas processes, reduce the cost of biogas technologies, make them available to more imperfect investors, and expand training and consulting opportunities.

In conclusion, financial barriers pose a significant challenge to adopting and proliferating biogas systems. To overcome these barriers, government policies, subsidies, financial assistance programs, and low-interest loans should be implemented to encourage biogas technology adoption and make it affordable for low-income individuals and households. Moreover, more funds should be allocated to research and development, and institutional networking for R&D should be established to enhance technological innovation and reduce the cost of biogas technologies.

1.9.3 Social barriers

The major sociocultural hurdle for biogas adoption is the lack of public participation and consumer interest. In India, households typically do not sort their organic waste, instead dumping it all in the same container due to a lack of knowledge and time. As a result, most people are unaware that biogas can be produced from home organic waste [59], [60]. In rural areas, several social and cultural barriers prevent the adoption of biogas. For example, there is a social taboo surrounding the use of human excrement in biogas plants, which contains plant owners and individuals from using this source. Although farm households are involved in developing these new technologies, it is not held accountable for their use, maintenance, or the environmental and economic benefits biogas consumption delivers [61]. In addition, women in rural households are more likely to cook, which means it is more likely to be exposed to indoor air pollution caused by burning solid fuels.

However, due to rural women's lack of decision-making authority, adopting clean energies is slow. Furthermore, small-scale biogas installations are often ignored because people in these areas typically cook with dung, and local communities are unwilling to embrace the consumption of biogas due to cultural beliefs surrounding waste, excrement, or any other form of fecal material [62]. There are also problems with feedstock and slurry management, as many users hesitate to do the required daily dung mixing because it is an unpleasant burden [63]. Similarly, using human excrement in biogas plants is socially undesirable due to filthy conditions within the home [64]. Some religions also have rigorous hygiene standards, particularly surrounding people and animal excrement [65]. Finally, the adoption and implementation of biogas plants may be affected by consumers' preference for existing brands over new ones, as it can be difficult for them to evaluate the quality of a new product [66]. This knowledge affects the adoption and implementation of biogas plants.

1.9.4 Market barriers

The high cost of biogas compared to natural gas is a significant market barrier, making it difficult for new companies to enter the bioenergy technology market [67]. Government regulations further complicate the market entry process, as licensing, raw material access, environmental requirements, and product testing are all subject to government oversight [68]. To make biogas competitive in the public sector, its price must be lowered to match other available fuels [69]. Additionally, biogas faces competition from other, cheaper cooking alternatives, such as traditional solid biomass, firewood, and cow dung, all locally available [70]. While biogas can potentially increase natural gas imports, customers are not interested in using 100% enhanced biogas due to its high cost. However, blending natural gas with biogas makes the fuel more acceptable to the general public [71]. Biogas also faces competition from other fuel sources, such as bioethanol and electric cars. The success of electric vehicles has been linked to the increase in biogas use [71].

The study's interviews indicate that municipalities prefer electric vehicles over biogas vehicles due to a lack of fueling infrastructure, internal mistrust, and a fear of accidents caused by a lack of knowledge [72]. Additionally, established soil and organic fertilizer businesses compete with digestate-based product makers, as merchants and garden centers prefer providers with varied product offerings and the capacity to provide large volumes [66]. Despite the excellent market potential for organic fertilizer, no substantial efforts have been made to develop and commercialize the non-energy products of the biogas process [73]. These market barriers may hinder the participation of biogas plant developers [74].

1.9.5 Institutional barriers

The lack of government support and specific efforts is one of the primary impediments [75]. Additionally, the energy sector has been ignored in emerging country policy discussions [42]. The National Biogas and Manure Management Program (NBMMP), launched by the Central Government, has too many formal requirements and administrative and legal processes, hindering biogas plant installation [76]. The program's capital subsidies require the possession of two to three cattle, making it difficult for most low-income rural families to secure a grant and impeding the application of biogas technology [36]. As a result, low-income families resort to using locally available biomass for cooking.

Several agencies implement the national biogas development effort. A lack of collaboration and competition for incentives has been identified as a reason for poor performance and limited dissemination of biogas technology in rural regions [56]. The policy environment's volatility and uncertainty are also tricky [76], and cooperation between national and subnational governments is minimal. While standard pricing for electricity produced by biogas and waste-to-energy plants was established in 2016, state electrical regulatory commissions have not yet developed everyday prices for energy produced by anaerobic digestion power plants (SERCs), making it difficult to evaluate the project's feasibility during the pre-investment evaluation phase due to the uncertainty of pricing for the SERCs' power purchase agreement [77].

Private investment in large-scale biogas plants is discouraged without government initiatives such as specific guidance and stakeholder involvement, making risks associated with income sources, technology, and feed supplies essentially the responsibility of private parties[69]. Moreover, political instability inhibits the usage of biogas as a source of energy. Challenges in India also arise with the availability and quality of feedstock due to inadequate supply networks and low collection efficiency [78]. Limited financial and technical resources make it challenging for municipal organizations to expand solid waste quantities in an integrated manner without corporate entity support [37]. According to several studies, the future of biogas taxes, incentives, and government support in India is mainly unpredictable [69] [78]. Regulatory restrictions, such as the need for permits from several government ministries, including the Petroleum Explosives Safety Organization (PESO) and the Ministry of Environment and Forest, inhibit the improved biogas industry [37]. The private sector is crucial for delivering biogas energy to the market and ensuring economic viability [79].

1.9.6 Information barriers

The lack of information and knowledge dissemination on biogas technology is a significant factor in its low adoption as a primary cooking fuel in rural areas [80]. The general public, including rural communities, financial institutions, and enterprises, lacks access to appropriate information and necessary tools. This results in a lack of awareness and understanding of the numerous feedstock choices and how digesters might use them [36]. This lack of information and technological, infrastructural, and user limitations have hindered biogas technology adoption in rural regions [37]. Despite decades of government efforts, adopting biogas technology in rural areas remains challenging. This is due to the poor performance of biogas technology, leading to its unsuitability and unreliability in meeting households' daily or seasonal cooking energy demands [37]. This results in rural families resorting to alternate, easily accessible fuels. Additionally, NGOs, corporate groups, microfinance institutions, and governments are often unaware of the advantages of bioenergy, resulting in a stronger push for renewable energy alternatives such as wind and solar [81].

Raising awareness is one of the three components of the integrated policy package necessary to combat climate change, alongside carbon pricing and innovation assistance [82]. However, agencies struggle to collect consistent information on biogas plant utilization and mitigation potential, hindering capacity-building efforts. Developing a sample plan for routine monitoring of biogas consumption in different regions can be a suitable solution. The long-term acceptability of biomass gasifiers and biogas facilities is hindered by a lack of information and awareness about proper operation and maintenance [68]. Overall, the lack of available information and understanding regarding biogas technology has contributed to its low adoption in rural areas, emphasizing the need for better dissemination of information and capacity-building efforts.

1.9.7 Environmental barriers

Biogas production is not without its potential drawbacks and environmental concerns. One prominent challenge biogas plants face is the need for a significant amount of water, which is necessary for anaerobic digestion and maintaining the ideal water-to-manure ratio of 1:1 [83]. Biogas production can become challenging during dry seasons or in areas where water is scarce [76]. In addition, colder temperatures can negatively impact biogas production. For instance, temperatures below 15°C can reduce biogas output, making it difficult for farmers in colder regions to use it as an energy source [84]. Furthermore, the potential for environmental harm exists in noise pollution, odor concerns, and gas leakage.

In particular, broken digester lids and leaking gas valves can release a mixture of methane, carbon dioxide, and hydrogen sulfide, leading to increased greenhouse gas emissions and groundwater contamination [58], [85]. Certain African countries, such as Zambia, may face water shortages that could compound the challenge of operating biogas plants [57]. To mitigate these environmental risks, using leak-proof feedstock and digester storage areas and identifying hazardous locations is essential. Waste gas outlets should also be appropriately managed to protect groundwater and prevent unpleasant odors [85].

1.9.8 Policy barriers

The renewable energy industry faces significant obstacles due to government policies, particularly energy price distortion, which favors fossil fuels over renewable energy sources [86]. In addition, low agricultural rates lead to excessive electricity and groundwater usage, and energy subsidies prevent progress in replacing inefficient agricultural pump sets [87]. The lack of environmental policy and a defined policy on renewable energy utilization also hinders the spread of biofuel technologies [88]. Although the Electricity Act of 2003 mandates the establishment of a National Electricity Plan and a National Tariff Policy, tariff levels for renewable energy vary across different states, leading to developers' complaints about the system's fairness [89] [90]. The absence of a reliable waste collection and sorting infrastructure in most developing countries also impedes the growth of renewable energy.

Waste management businesses often dispose of wastewater effluents in uncontrolled landfills or publicly burn them, causing environmental problems [91]. Land-tenure policies are another issue that limits the ability of farmers and municipalities to enter long-term contracts to acquire wood fuel for bioenergy [70]. Corruption is also a significant barrier that decreases the rate of return on investment in implementing biogas investments and operating expenses [92]. Furthermore, the lack of government commitment and inadequate continuity of previous biogas program initiatives across successive governments also hinder the adoption of biogas technology [93]. In India, energy pricing regulations that favor existing technologies and heavily subsidize electricity use for farming further stifle the growth of biogas, as farmers lack incentives to invest in biogas technology [86]. These policies, combined with a lack of environmental policy and weak government commitment, impede the spread of biofuel technologies and hinder the renewable energy industry's development.

1.10 Conclusions

India is one of the world's most populous countries, and the rapid growth of its population is putting a tremendous strain on its resources, including its waste management systems. Organic waste is generated in large quantities in households and institutions, but most are not segregated at the source, leading to a significant amount of municipal solid waste. This waste causes various environmental problems, including air and water pollution, greenhouse gas emissions, and health hazards. In light of this, it has been conducted a case study at Delhi Technological University to explore the potential of using organic waste to generate biogas and solve the problem of solid waste. The primary purpose of this study is to raise awareness among Indians about the benefits of segregating organic waste at the source and utilizing it to produce biogas. If every Indian realizes the value of organic waste generated in their homes and institutions, it can contribute to solving the problem of solid waste and developing renewable energy simultaneously.

The household organic waste is collected in 1620 garage bags, generated from residential areas and canteens, and categorized into 73 types: vegetable, fruit, and cooked food. This study took around one year, and after the waste categorization, the researchers optimized the biogas production process at a small scale. Finally, it produced biogas at a larger scale with the best parameters. The raw biogas was purified by eliminating CO_2 and H_2S, and it was compressed up to 200 bar for use in a four-stroke multi-cylinder SI engine. The results of this study suggest that biogas can be produced from household organic waste and used as fuel for electricity generation and transportation. This would reduce the amount of waste going to landfills, reduce the dependence on fossil fuels, and promote renewable energy. Furthermore, installing biogas plants in universities and societies where more people live can solve the problem of solid waste and generate renewable energy simultaneously. These plants can be established at a small scale initially, and with proper optimization and scaling-up, it can provide a significant amount of energy and contribute to sustainable development.

In conclusion, this study highlights the potential of utilizing organic waste to generate biogas and solve the solid waste problem in India. It emphasizes the importance of segregating waste at the source and raising awareness about the value of organic waste. By utilizing biogas as a renewable energy source, India can reduce its dependence on fossil fuels and promote sustainable development. Additionally, compressing the biogas can be used in various applications, including fuel for vehicles and power generation. Installing biogas plants in universities and societies can provide a sustainable solution to the problem of solid waste and contribute to a greener future.

CHAPTER 2

LITERATURE REVIEW

The literature review analyzed the factors that affect the production of biogas, the performance of biogas in internal combustion engines (IC engines), and the types of biogas plants (digesters) currently in use. Several factors influence biogas production, impacting the efficiency of the biogas production process and the quality of the biogas produced. The performance of biogas in IC engines depends on several factors, including the composition of the biogas, engine design, and operating conditions. Biogas can be a renewable energy source for IC engines, and optimizing its performance requires understanding these factors and their interactions. The literature review also examined the different types of biogas digesters. Every digester has advantages and disadvantages, depending on factors such as the type of feedstock used, the desired biogas output, and the operating conditions. Overall, the literature review provides essential insights into the factors that affect the production and performance of biogas, as well as the different types of biogas digesters currently available.

2.1 Types of biogas plants (digesters)

Several biogas plants are designed to suit different purposes and feedstocks. Here are the most common types of biogas plants:

2.1.1 Continuous Stirred Tank Reactor

Continuous Stirred Tank Reactors (CSTRs) are one of the most widely used biogas plants due to their simple design, versatility, and efficient production. The reactor consists of a closed, cylindrical tank equipped with a mechanical stirring mechanism that mixes the substrate and microorganisms. The substrate is continuously fed into the reactor, while the biogas produced is constantly removed. CSTRs operate at a constant temperature, usually between 35°C and 40°C, which is optimal for the activity of the microorganisms involved in digestion. This consistency in temperature ensures that the microorganisms are active throughout the digestion process, leading to a higher efficiency in biogas production. The stirring mechanism in the reactor ensures that the substrate and microorganisms are well mixed, creating a homogenous environment that promotes efficient digestion.

One of the primary advantages of CSTRs is their versatility in handling a wide variety of feedstocks. The reactor can process solid and liquid organic waste, including agricultural waste, municipal solid waste, and sewage sludge. The efficiency of the digestion process is also high, with the potential to convert up to 90% of the organic matter in the feedstock to biogas. In a study conducted by [94], the performance of a CSTR in treating food waste was investigated. The results showed that the CSTR could effectively degrade the food waste, producing a high yield of biogas with a methane content of over 60%. The study concluded that CSTRs are a promising technology for treating food waste and producing biogas.

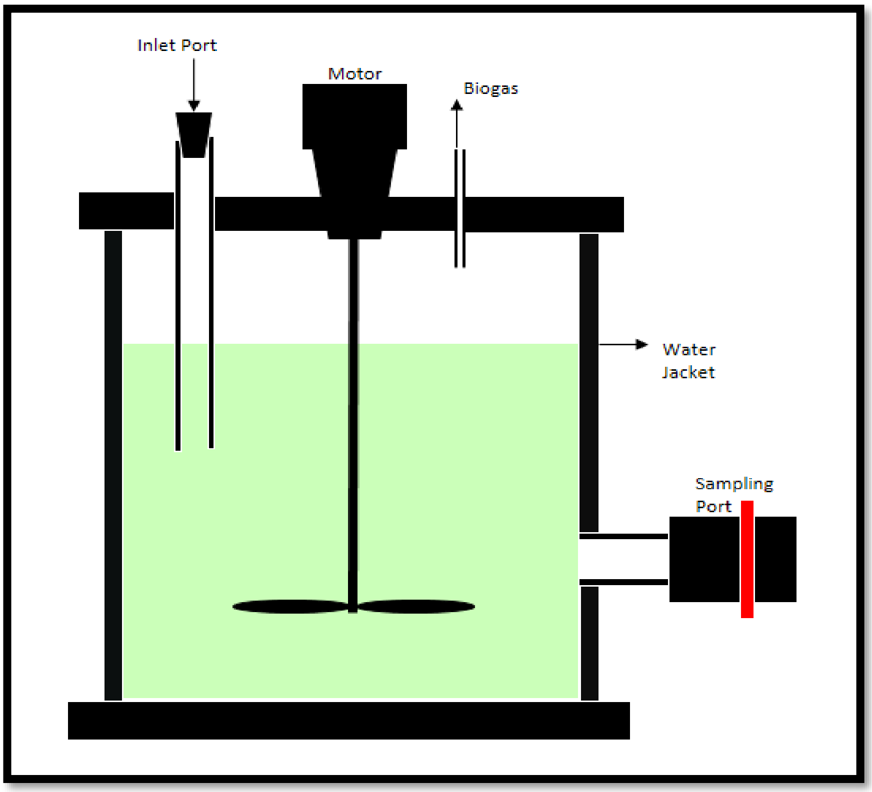


Figure 2.1: Schematic diagram of Continuous Stirred Tank Reactor

Another study by [95] compared the performance of CSTRs and Plug Flow Digesters (PFDs) in treating cattle dung. The results showed that the CSTRs had a higher biogas production rate and yield than the PFDs, indicating that CSTRs are a more efficient technology for biogas production. However, there are also some limitations to CSTRs. One of the main challenges is maintaining a consistent feedstock supply, as the reactor requires a continuous feed of organic waste to ensure optimal biogas production. Additionally, the feedstock must be screened to remove non-biodegradable materials that could interfere with digestion. In addition, CSTRs require a significant amount of land and energy to operate and can produce odors if not properly maintained.

2.1.2 Plug Flow Digester

The Plug Flow Digester (PFD) is an anaerobic digester widely used to produce biogas from organic waste. It is a continuous-flow digester designed to process high-solids substrates and makes a consistent supply of biogas. The PFD is particularly suitable for processing agricultural, food, and industrial waste. The PFD consists of a long, narrow tank made of concrete or steel. The tank is typically buried in the ground so the substrate can be loaded from the top. The substrate is introduced at the feed end of the digester and gradually moves toward the gas outlet end.

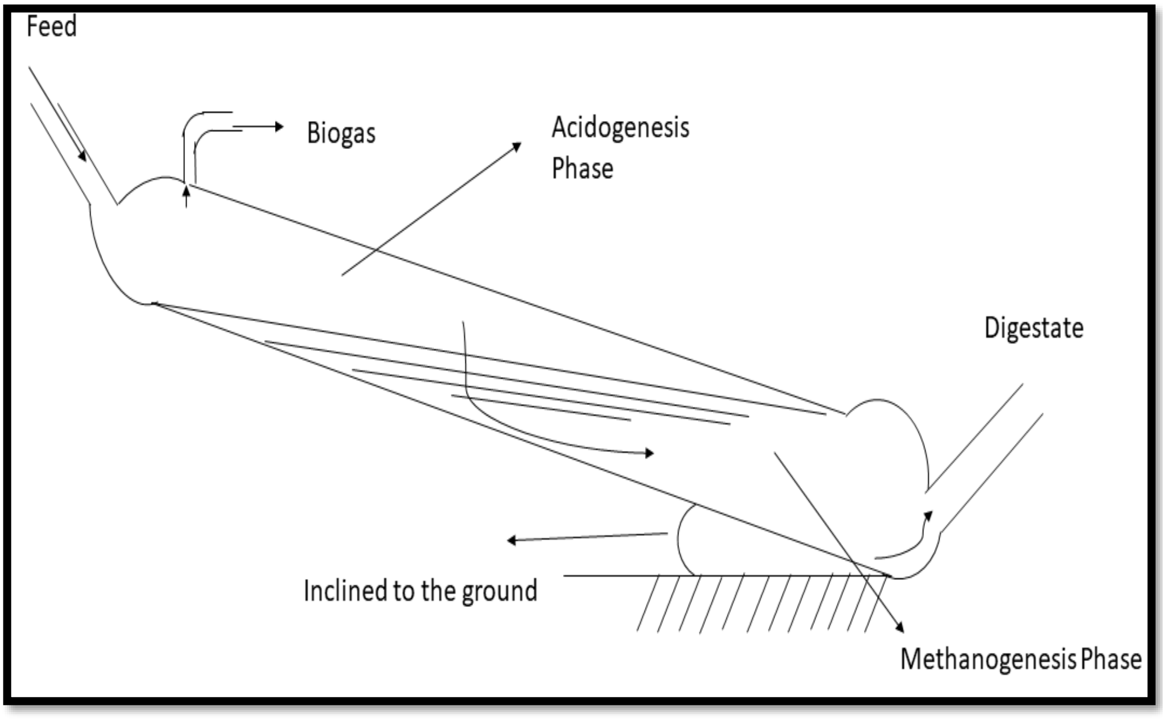


Figure 2. 2: Schematic diagram of Plug Flow Digester

The digester is designed to ensure that the substrate stays in the digester for a set amount of time, which allows the microorganisms to break down the organic matter and produce biogas. The PFD is operated continuously, with new substrates added regularly and biogas produced constantly. The digester is equipped with a mixing system, which ensures that the substrate is thoroughly mixed and heated to ensure the microorganisms have the best conditions for producing biogas. The digester also has a gas collection system, which captures the biogas and stores it in a gas holder or a storage tank.

One of the main advantages of the PFD is its high efficiency and reliability. The digester ensures the substrate is processed, controlled, and efficiently, maximizing biogas production and minimizing waste. The PFD is also relatively easy to operate and maintain, which makes it a popular choice for large-scale applications. According to a study conducted by the Indian Institute of Technology (IIT Delhi), Plug Flow Digesters (PFDs) are suitable for the Indian context due to their low capital cost and high efficiency in processing a variety of substrates, including agricultural waste and urban solid waste [96]. The study also found that PFDs have a shorter hydraulic retention time than other digesters, making them more suitable for Indian conditions, where water availability is often challenging. Another study conducted by the Indian Agricultural Research Institute (IARI) found that PFD is effective in producing biogas from various substrates, including cattle dung, poultry waste, and vegetable waste [97]. The study found that the PFD had a high biogas production rate and yield and was relatively easy to operate and maintain.

2.1.3 Fixed Dome Digester

A Fixed Dome Digester (FDD) is a biogas plant that converts organic waste into usable biogas and fertilizer. It is a simple and cost-effective solution for managing organic waste, particularly in rural areas with limited access to electricity and clean cooking fuel. The FDD is a closed, airtight system that uses anaerobic digestion to break down organic matter and produce biogas. FDD consists of two main components: a digester tank and a gas holder. The digester tank is where the organic waste is added, and the anaerobic digestion process occurs. The gas holder is a dome-shaped container that sits on top of the digester tank and stores the biogas produced during digestion. As the gas is created, it displaces the liquid in the digester tank and rises into the gas holder. The gas holder is connected to a piping system that allows the biogas to be used for various applications.

One of the primary advantages of the FDD is its simplicity. The straightforward design can be constructed using locally available bricks, concrete, and steel. It does not require complex machinery or sophisticated technology, making it an ideal solution for communities with limited resources and technical expertise. Additionally, the FDD can accept a wide range of organic waste materials, including animal manure, agricultural waste, and kitchen waste, making it a versatile solution for managing organic waste.

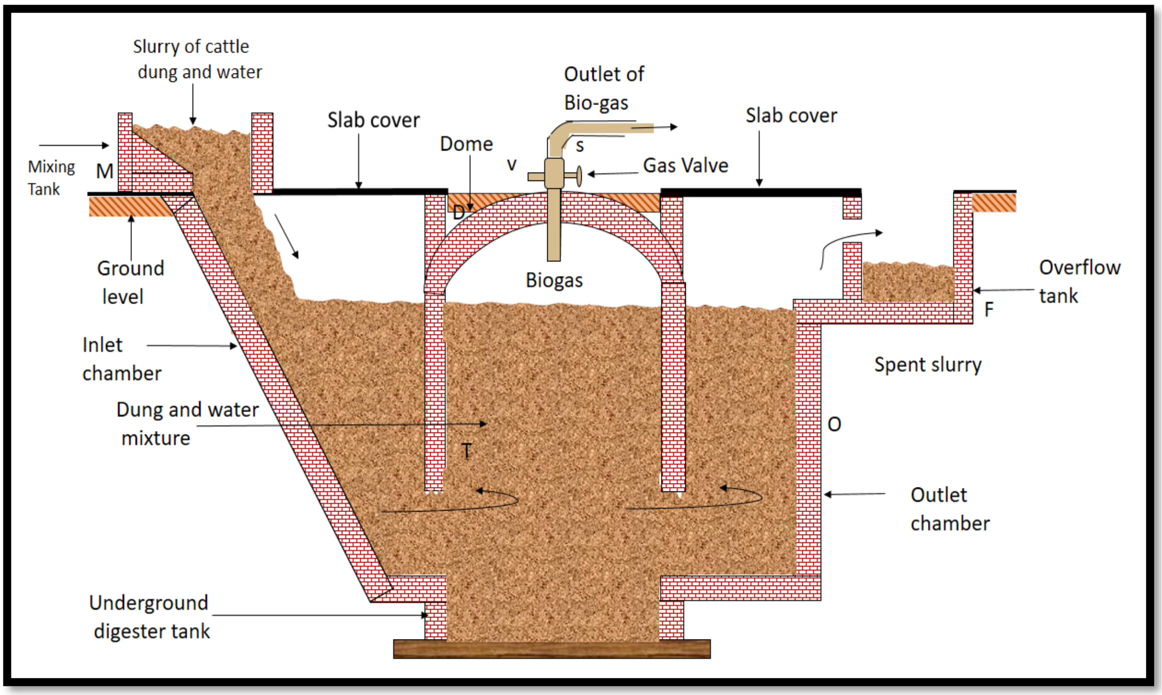


Figure 2. 3: Fixed Dome Digester

Another significant advantage of the FDD is its ability to produce a high-quality fertilizer as a byproduct. The digestion process breaks down the organic matter and makes a nutrient-rich liquid called digestate. This digestate can be used as a crop fertilizer, providing an additional source of income for farmers and promoting sustainable agriculture. Several studies have demonstrated the effectiveness of the FDD in various settings. In a study conducted in Nepal, FDDs were installed in 32 households, and the biogas produced was used for cooking and lighting. The study found that the FDDs significantly reduced the time and effort required to collect firewood and improved indoor air quality, reducing the risk of respiratory illnesses [98]. Another study conducted in India found that FDDs could be used to treat municipal solid waste, producing biogas and fertilizer while reducing the volume of waste sent to landfills [99].

2.1.4 Floating Drum Digester

A Floating Drum Digester (FDD) is a simple, low-cost, and efficient technology that converts organic waste into biogas. It is an anaerobic digester that utilizes the natural anaerobic digestion process to break down organic waste and produce biogas. The FDD is a popular technology in many parts of the world, especially in developing countries, due to its low cost and easy maintenance. The FDD consists of a floating drum or dome-shaped container made of a flexible material such as polyvinyl chloride (PVC) or high-density polyethylene (HDPE). The container is partially filled with water and organic waste, and the remaining space is filled with biogas. As the organic waste decomposes, it releases biogas, which rises to the top and displaces the water and waste mixture, causing the floating drum to rise. The FDD has several advantages over other types of anaerobic digesters.

First, it is a low-cost technology easily constructed using locally available materials. Second, it requires minimal maintenance and can be operated by small-scale farmers or households. Third, it produces a high-quality fertilizer that can be used to improve soil fertility and increase crop yields.

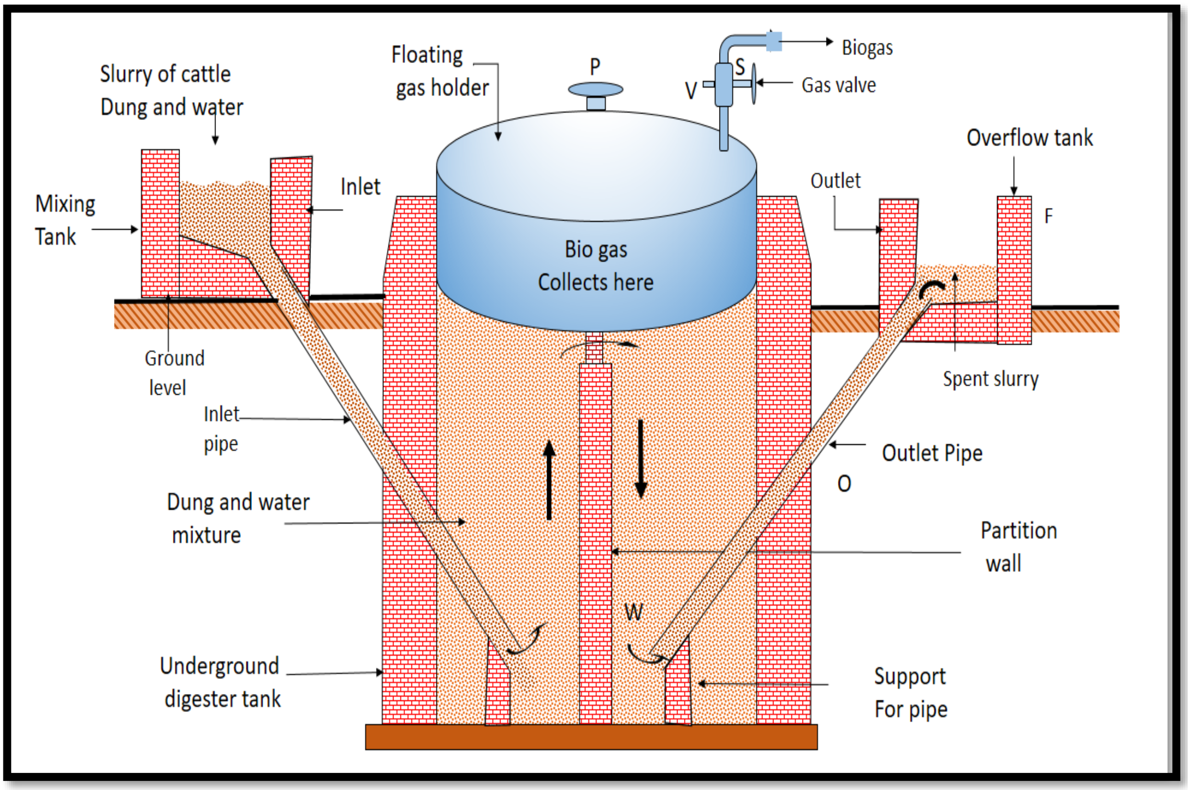


Figure 2. 4: Floating Drum Digester

Several studies have investigated the effectiveness of FDDs in producing biogas and reducing organic waste. A study [100] in Kenya found that FDDs effectively made biogas from cow dung and other organic wastes. The study showed that FDDs produced more biogas than traditional open-air digesters and had a shorter retention time. Another Greece study by [101] found that FDDs effectively treated olive mill wastewater and produced biogas. The study showed that FDDs had a high removal efficiency of organic matter and made a significant amount of biogas that could be used for energy production. In addition to its advantages, the FDD also has some limitations. One limitation is that it can only process a limited amount of organic waste at a time. Therefore, it may not be suitable for large-scale waste treatment applications. Another limitation is that the quality of the biogas produced may vary depending on the type and quality of the organic waste used.

2.1.5 Balloon Digester

A Balloon Digester is a simple and cost-effective technology used to generate biogas by the anaerobic digestion of organic waste. It is a biogas digester suitable for small-scale and household applications due to its low cost and ease of construction and maintenance.

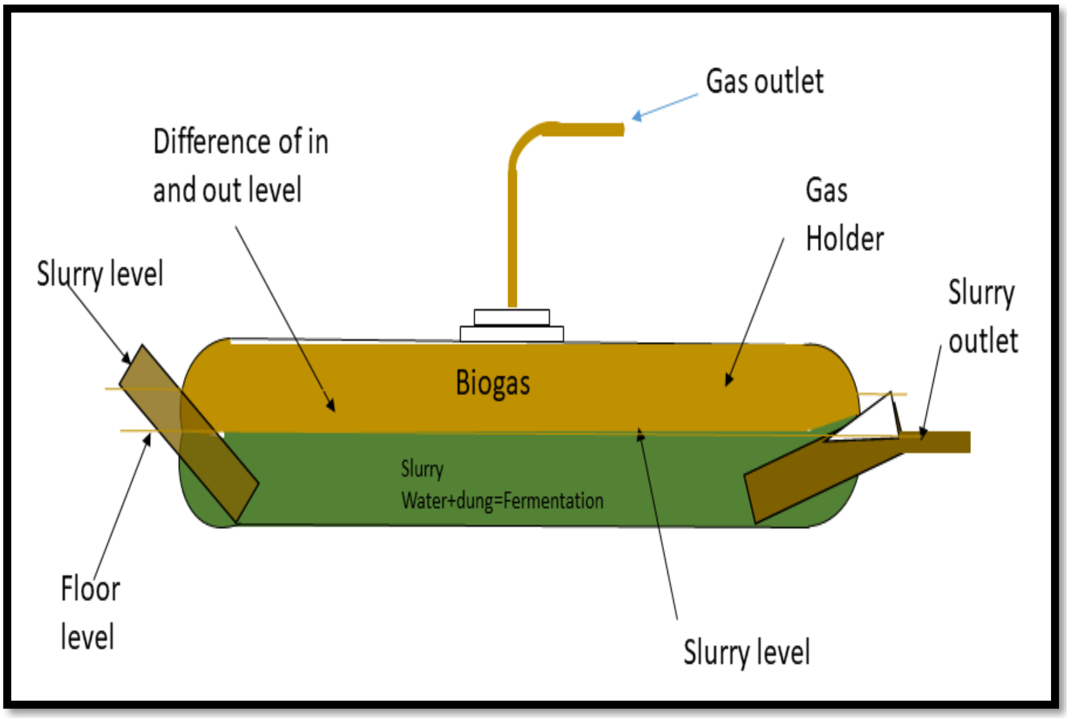


Figure 2. 5: Flexible Balloon Digester System

In this technology, the organic waste is mixed with water and stored in an airtight balloon-like structure where anaerobic microorganisms break down the organic matter and produce biogas. The balloon digester consists of a durable plastic bag, such as high-density polyethylene (HDPE), inflated with organic waste. The bag is sealed tightly to prevent air from entering or leaving the system. As the organic matter decomposes, it releases biogas that fills the balloon, causing it to expand. One of the main advantages of the balloon digester is its low cost and ease of construction. It can be made using locally available materials such as plastic bags, pipes, and valves. The system requires minimal maintenance and can be operated by households or small-scale farmers without specialized training.

Several studies have investigated the effectiveness of balloon digesters in producing biogas and treating organic waste. For instance, a study by [102] in Kenya found that the balloon digester could produce high-quality biogas from cow dung and kitchen waste. The study showed that the biogas production rate was relatively high and that the digester was easy to operate and maintain. Another study by [103] in India demonstrated that the balloon digester effectively treated food waste and produced biogas. The study showed that the digester had a high organic loading rate and made a significant amount of biogas that could be used for cooking and heating. One of the limitations of the balloon digester is its relatively small size, which limits the amount of organic waste that can be processed at a time. This makes it unsuitable for large-scale waste treatment applications. Additionally, the quality of the biogas produced may vary depending on the type and quality of the organic waste used.

2.1.6 Hybrid Reactors

Hybrid reactors are biogas plant that combines different technologies to enhance biogas production. These reactors are designed to maximize the efficiency of the biogas production process by incorporating various methods that complement each other. The hybrid reactor technology has gained significant attention recently due to its potential to increase biogas production and reduce greenhouse gas emissions. The hybrid reactor technology combines two or more anaerobic digestion processes to create a more efficient biogas production system. The most common combination is the mesophilic and thermophilic digestion processes. Mesophilic digestion occurs at temperatures between 20 and 45°C, while thermophilic digestion occurs at temperatures between 50 and 70°C.

The hybrid reactor technology combines these two processes to optimize biogas production. One type of hybrid reactor is the two-stage hybrid reactor, which consists of two separate reactors operating at different temperatures. The first reactor operates at mesophilic conditions, while the second operates at thermophilic conditions. The organic waste is first treated in the mesophilic reactor, where it is partially broken down. The partially treated waste is then transferred to the thermophilic reactor, which is digested to produce biogas. Another type of hybrid reactor is the multi-stage reactor, which consists of three or more reactors operating at different temperatures. Each reactor is optimized to enhance the production of specific microorganisms responsible for breaking down different types of organic waste.

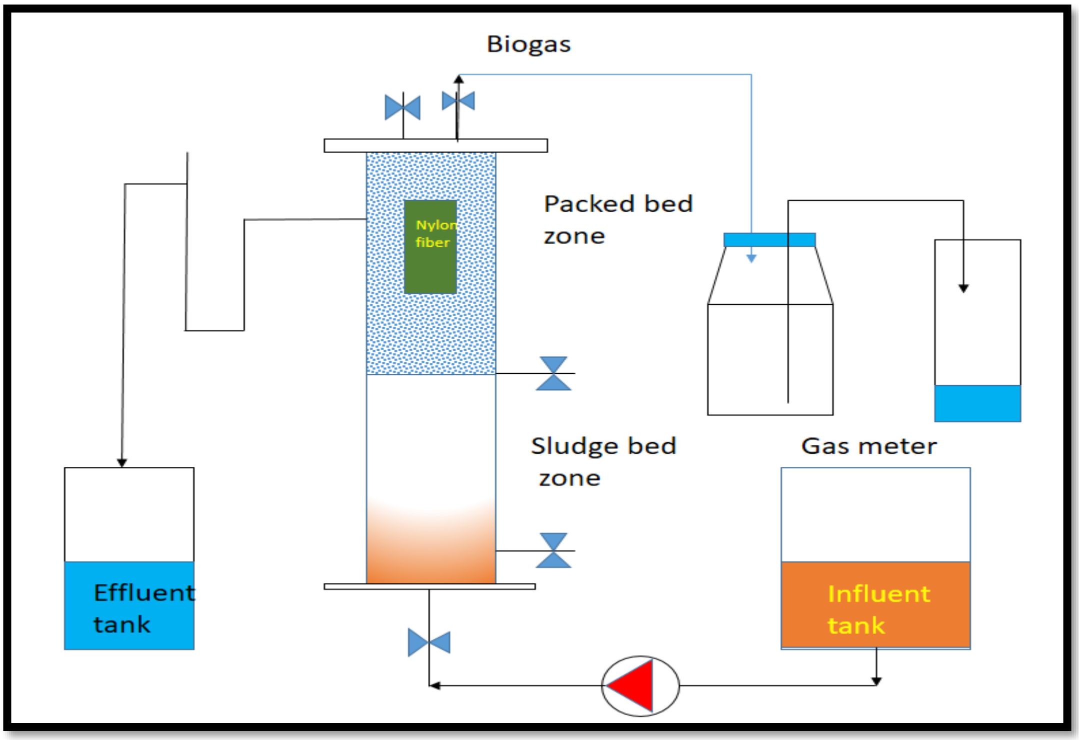


Figure 2. 6: Hybrid reactor

The multi-stage reactor technology has been shown to increase biogas production and reduce the retention time required for digestion. Hybrid reactors offer several advantages over traditional anaerobic digestion technologies. First, combining different processes in hybrid reactors can result in higher biogas yields and increased efficiency. Second, hybrid reactors can reduce the residence time required for digestion, thereby reducing the footprint of the biogas plant. Third, hybrid reactors can be optimized for different types of waste, including organic waste with high solid content, which can be challenging to digest in traditional anaerobic digesters.

Several studies have investigated the effectiveness of hybrid reactors in biogas production. A China study by [104] found that a two-stage hybrid reactor produced a higher biogas yield than a single-stage mesophilic reactor. The study showed that the two-stage reactor produced 34.6% more biogas than the single-stage reactor. Another study by [105] in China found that a multi-stage hybrid reactor had a higher biogas production rate and shorter retention time than a single-stage reactor. The study showed that the multi-stage reactor produced 49.5% more biogas than the single-stage reactor, reducing digestion's retention time by 50%. In addition to its advantages, the hybrid reactor technology has some limitations. One limitation is that it requires a higher capital investment than traditional anaerobic digestion technologies. Another limitation is that it may require more complex operation and maintenance procedures than conventional digesters. Therefore, hybrid reactors may not be suitable for small-scale biogas production applications.

2.1.7 Anaerobic Filter Reactor

Anaerobic digestion is a widely used process for treating organic waste material, which can produce biogas as a valuable end product. The Anaerobic Filter Reactor (AFR) is a commonly used anaerobic digestion technology. An AFR is a fixed-film reactor where microorganisms grow on the surface of a solid support media and degrade the organic matter in the wastewater. In this process, biogas is produced, mainly composed of methane and carbon dioxide. The AFR technology has several advantages over other anaerobic digestion technologies. Firstly, AFRs have a high biomass retention capacity and can handle high organic loading rates. Secondly, the design of AFRs is relatively simple, which results in low installation and operation costs. Thirdly, AFRs have a down hydraulic retention time, requiring less space than other anaerobic digestion technologies.

AFRs can be operated under different temperature regimes, including mesophilic (25-40°C) and thermophilic (50-60°C) conditions. In mesophilic states, the biogas yield is typically lower than in thermophilic conditions, but the process is more stable and less sensitive to variations in organic loading rates and temperatures. In thermophilic conditions, the biogas yield is higher, but the process is more susceptible to fluctuations in temperature and organic loading rates. AFRs can treat various organic waste materials, including sewage sludge, industrial wastewater, and agricultural waste. The efficiency of the process depends on the characteristics of the wastewater and the operating conditions. The organic matter in the wastewater is converted into biogas through a series of microbial reactions that occur in the AFR. The biogas can generate electricity or heat or be upgraded to natural gas quality and injected into the gas grid.

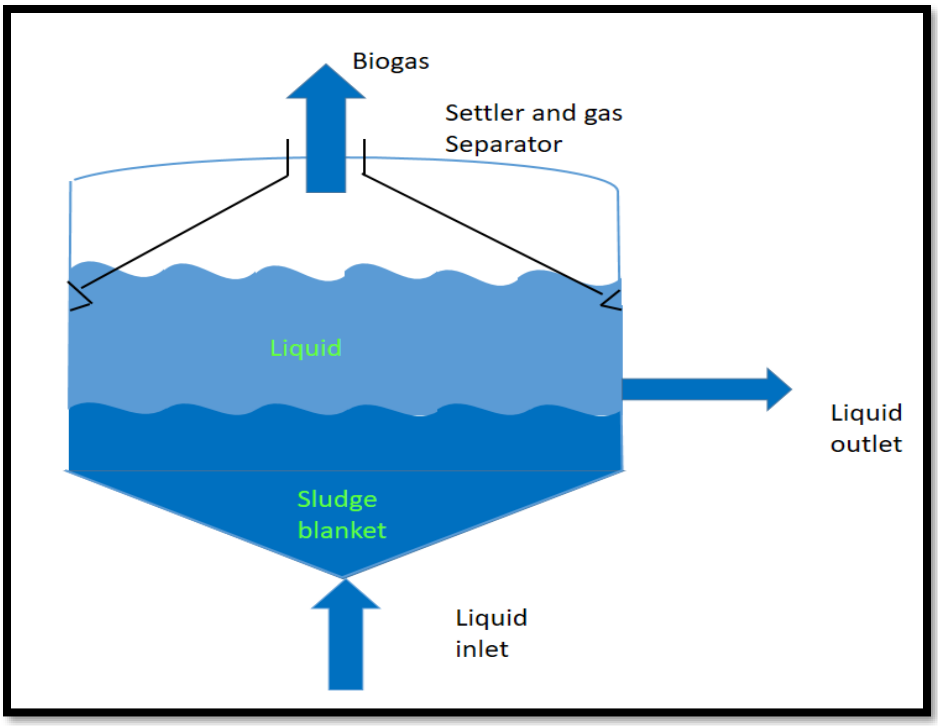


Figure 2. 7: Anaerobic Filter Reactor

Several studies have investigated the performance of AFRs in different applications. A study by [106] evaluated the performance of an AFR for the treatment of brewery wastewater. The study found that the AFR could remove more than 80% of the chemical oxygen demand (COD) and produce biogas with more than 65% methane content. Another study by [107] investigated using AFRs to treat food waste. The study found that the AFR could remove more than 90% of the COD and produce biogas with more than 60% methane content. AFRs have also been combined with other technologies to enhance the efficiency of the anaerobic digestion process. For example, a study by [108] investigated using an AFR combined with a UASB (Up-flow Anaerobic Sludge Blanket) reactor to treat swine wastewater. The study found that the AFR/UASB combination resulted in higher biogas production and better effluent quality than a single UASB reactor.

2.1.8 Horizontal Digester

Horizontal Digester-Biogas is a system of waste management that utilizes anaerobic digestion technology to convert organic waste into biogas. This technology is beneficial for managing organic waste from agriculture, food production, and municipal waste management. Horizontal Digester-Biogas is a simple, low-cost technology that has gained popularity recently due to its effectiveness in reducing waste, generating renewable energy, and improving soil health. Anaerobic digestion is a natural process when organic matter decomposes without oxygen. Bacteria break down organic waste into methane and carbon dioxide gases during this process. These gases can then be collected and used to produce renewable energy.

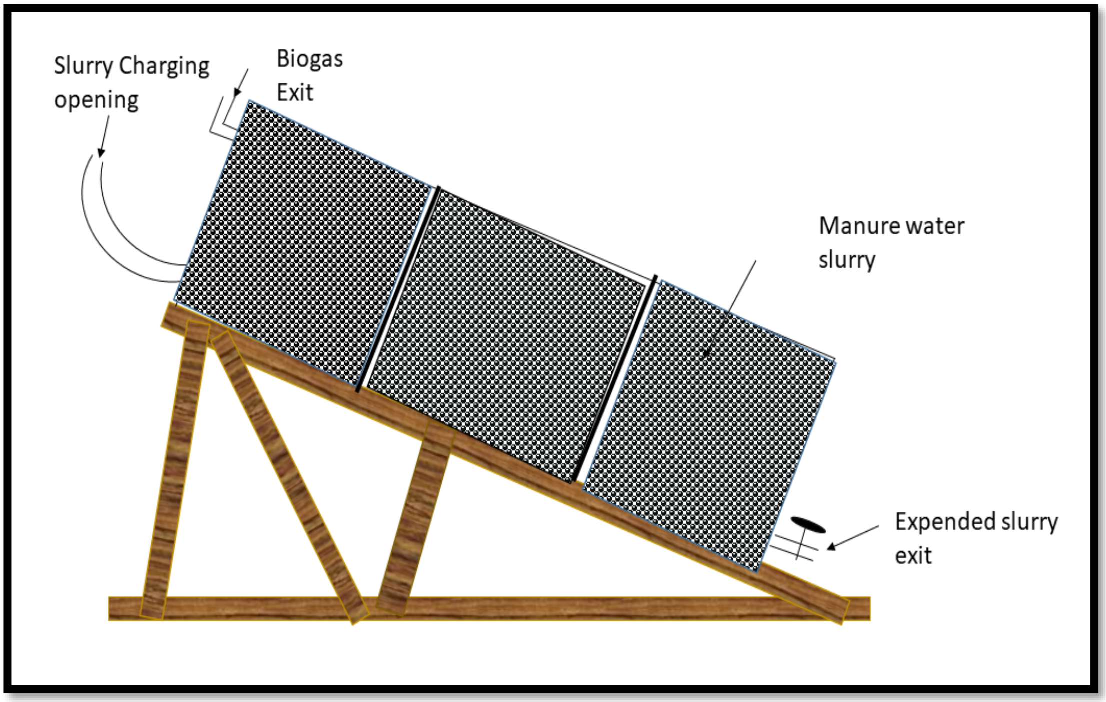


Figure 2. 8: Horizontal biogas reactor

The Horizontal Digester-Biogas system is a low-cost version of anaerobic digestion suitable for small-scale farms and communities. The Horizontal Digester-Biogas system consists of a shallow, rectangular tank made of concrete or plastic. The tank is usually 1-2 meters deep, 2-3 meters wide, and 5-10 meters long. Organic waste, such as animal manure, food waste, and crop residues, is mixed with water to create a slurry. The slurry is then fed into the digester tank through an inlet pipe. Once inside the tank, the slurry is heated to a temperature of around 35-40°C, which promotes the growth of bacteria that produce biogas. The biogas is collected through a pipe and stored in a separate container. The gas can be stored in a container and used as needed. In addition to producing renewable energy, the Horizontal Digester-Biogas system has several other benefits. For example, it can help reduce greenhouse gas emissions by diverting organic waste from landfills. It can also help improve soil health by producing nutrient-rich organic fertilizer.

Several studies have investigated the effectiveness of the Horizontal Digester-Biogas system. A study by [109] found that the system could generate biogas with a methane content of 62%. The study also found that the system effectively reduced organic waste and produced organic fertilizer. Another study by [110] found that the system could generate biogas with a methane content of 70%. The study also found that the system could reduce the pathogen load in organic waste. The Horizontal Digester-Biogas system has gained popularity in many parts of the world, particularly in developing countries. In India, for example, the government has launched several initiatives to promote adopting biogas technology, including the Horizontal Digester-Biogas system. The Indian Ministry of New and Renewable Energy has established several programs to provide financial support and technical assistance to farmers and communities interested in adopting biogas technology.

2.1.9 Vertical Digester

A vertical digester-biogas plant is a waste management system that uses anaerobic digestion technology to convert organic waste into biogas. Anaerobic digestion is natural when organic matter is broken down without oxygen. This process involves using microorganisms to break the organic matter into methane and carbon dioxide gases. These gases can then be collected and used to generate renewable energy. A vertical digester-biogas plant is similar to a horizontal digester-biogas plant but is designed to be more space-efficient. In a vertical digester-biogas plant, the digester tank is built upwards instead of outwards, which allows for a smaller footprint. This makes the technology particularly useful for urban areas where space is limited. The anaerobic digestion process in a vertical digester-biogas plant occurs in a cylindrical tank divided into two or three compartments. The first compartment is the feeding compartment, where the organic waste is added to the tank. The second compartment is the digestion compartment, where the anaerobic digestion occurs. The third compartment, if present, is the storage compartment, where the biogas is stored until it is used. The organic waste used in a vertical digester-biogas plant can come from various sources, including agricultural waste, food waste, and sewage sludge. The waste is crushed or shredded to increase its surface area and mixed with water to create a slurry. The slurry is then pumped into the feeding compartment of the digester tank.

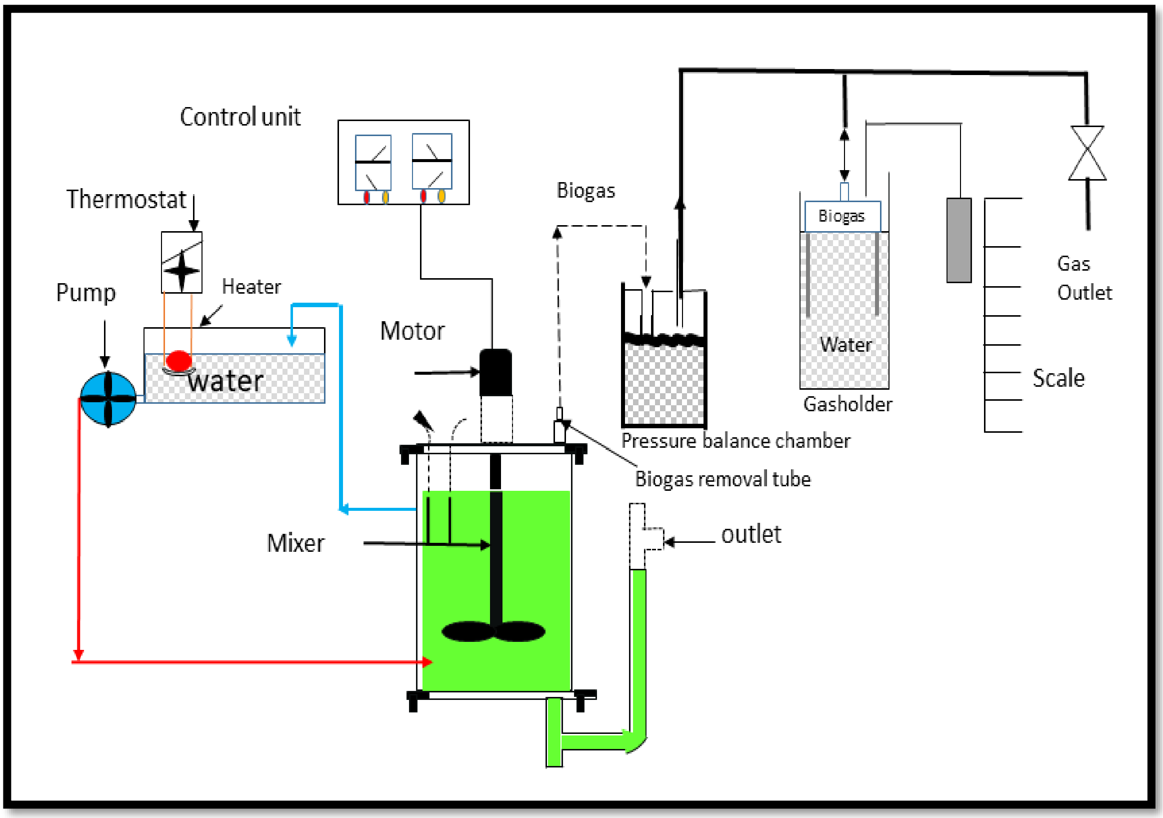


Figure 2. 9: Vertical Digester

The anaerobic digestion process in a vertical digester-biogas plant occurs in the digestion compartment. In this compartment, the slurry is heated to a temperature of around 35-40°C, which promotes the growth of bacteria that produce biogas. The bacteria break down the organic matter in the slurry and produce methane and carbon dioxide gases. These gases rise to the top of the digestion compartment and are collected through a pipe. The biogas produced in a vertical digester-biogas plant can be used for various purposes. The gas can be stored in a separate container and used as needed. In addition to producing renewable energy, the vertical digester-biogas plant has several other benefits. For example, it can help reduce greenhouse gas emissions by diverting organic waste from landfills. It can also help improve soil health by producing nutrient-rich organic fertilizer.

Several studies have investigated the effectiveness of the vertical digester-biogas plant. A study by [111] found that the vertical digester-biogas plant effectively converted sewage sludge into biogas. The study also found that the technology effectively reduced the pathogen load in the sewage sludge. Another study by [112] found that a vertical digester-biogas plant could generate biogas with a methane content of 72%. The study also found that the technology effectively reduced the volume of organic waste and produced organic fertilizer. The vertical digester-biogas plant has gained popularity in many parts of the world, particularly in China. The Chinese government has launched several initiatives to promote the adoption of biogas technology, including the vertical digester-biogas plant. The National Energy Administration of China has established several programs to provide financial support and technical assistance to farmers and communities interested in adopting biogas technology.

2.1.10 Multi-stage Digester

Multi-stage digesters are one type of biogas plant designed to optimize the anaerobic digestion process by breaking it down into several stages. This allows for greater efficiency and higher biogas production rates. The multi-stage digester consists of several interconnected tanks, each with its specific purpose. The first hydrolysis tank is where organic waste is introduced into the system. This tank contains water and microorganisms that break the waste into simpler organic compounds, such as sugars and amino acids. The organic matter is then transferred to the second tank, the acidogenesis tank, where acidogenic bacteria further break down the waste into volatile fatty acids (VFAs).

The multi-stage digester allows for greater control over the anaerobic digestion process by separating the different stages and optimizing the conditions in each tank for the specific microorganisms involved. For example, the hydrolysis tank requires a pH of around 7.0 and a temperature of 35-45°C, while the methanogenesis tank requires a pH of 7.2-7.4 and a temperature of 55-60°C. Several studies have investigated the effectiveness of multi-stage digesters in biogas production. For example, a study by [113] compared the performance of a single-stage digester and a multi-stage digester for treating food waste. The study found that the multi-stage digester produced significantly more biogas than the single-stage digester, with a 44% increase in biogas production.

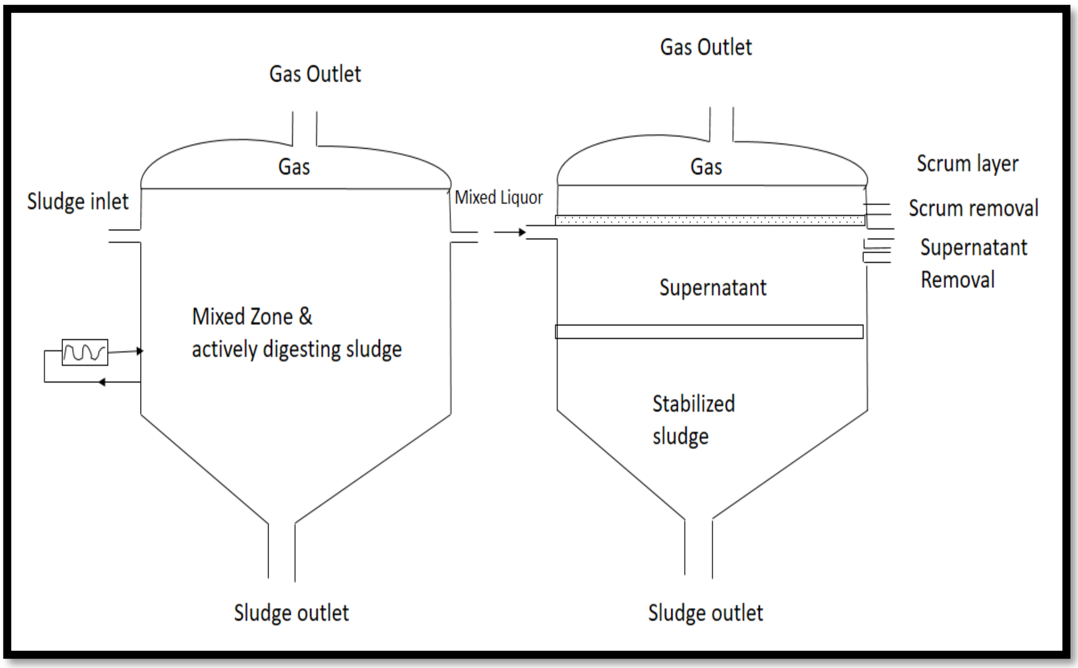


Figure 2. 10: Schematic diagram of multi-stage digester

Another study by [114] investigated using a four-stage digester to treat cow manure. The study found that the multi-stage digester produced a higher biogas yield and had a shorter hydraulic retention time than a conventional single-stage digester. Multi-stage digesters have several advantages over single-stage digesters. For example, it can handle a broader range of feedstocks and are more resistant to process fluctuations. It also has a higher tolerance to inhibitors, which certain types of waste can produce. In addition to their benefits for biogas production, multi-stage digesters have several environmental benefits. It can help reduce greenhouse gas emissions by diverting organic waste from landfills, where it would otherwise decompose and release methane into the atmosphere. It can also help reduce the use of fossil fuels by generating renewable energy.

The Comparative Analysis of Biogas Digesters comprehensive examines various biogas digester types. This Analysis encompasses crucial aspects such as operational conditions, advantages, disadvantages, and their respective levels of development. Understanding these factors is essential for making informed decisions in selecting and implementing biogas digester technologies. This comparative study is valuable resource for stakeholders in the biogas industry, offering insights into the strengths, weaknesses, and current status of these vital components in sustainable energy production. By evaluating these digester types side by side, this analysis facilitates the identification of the most suitable solutions for specific environmental and operational contexts.

Table 2. 1: Comparative Analysis of Biogas Digesters

Biogas Digester Type	Operating Conditions	Advantages	Disadvantages	Level of Development	References
Continuous Stirred Tank Reactor (CSTR)	Constant mixing of substrate.	Efficient for homogeneous substrates.	High energy requirements.	Well-established technology.	[94], [95]
Plug Flow Digester	Continuous flow of substrate.	Efficient for fibrous materials.	Sensitive to substrate variations.	Well-established technology.	[96], [97]
Fixed Dome Digester	Batch processing with a fixed dome.	Robust and simple design.	Slow digestion process.	Widely adopted in certain regions.	[98], [99]
Floating Drum Digester	Floating drum on the substrate.	Low construction cost.	Requires periodic maintenance.	Moderate development in some regions.	[100], [101]
Balloon Digester	Inflatable bag expands with gas.	Low cost and simple design.	Limited to small-scale applications.	Emerging technology in some areas.	[102], [103]
Hybrid Reactors	Combination of different digester types.	Combines advantages of various types.	Complex design and operation.	Limited application, research ongoing.	[104], [105]
Anaerobic Filter Reactor	Substrate flows through a filter medium.	Efficient for high solids content.	Prone to clogging.	Limited development, research ongoing.	[106], [107]
Horizontal Digester	Horizontal tank for anaerobic digestion.	Suitable for certain feedstock types.	Requires more space than vertical.	Limited application, research ongoing.	[109], [110]
Vertical Digester	Tall vertical tank for anaerobic digestion.	Efficient use of space.	May have mixing challenges.	Limited application, research ongoing.	[111], [112]
Multi-stage Digester	Series of digesters with different conditions.	Improved digestion efficiency.	Complex design and operation.	Limited application, research ongoing.	[113], [114]

2.2 Studies affecting parameters of biogas production

Biogas production is influenced by various parameters that impact the efficiency and yield of the process. Understanding and optimizing these parameters are essential for maximizing biogas production, improving energy generation, and promoting sustainable waste management practices.

2.2.1 Temperature

Temperature is a critical parameter that affects the biogas production process in anaerobic digesters. The efficiency and output of the process are significantly influenced by the temperature at which it is carried out. Studies have shown that temperature can impact various aspects of biogas production, including microbial activity, organic matter degradation, and gas composition. Temperature is a key factor in anaerobic digestion, which is the process that produces biogas. The anaerobic digestion process is carried out by microbial communities that require specific environmental conditions to thrive. The optimal temperature range for biogas production is typically between 35°C to 55°C, depending on the particular type of microorganisms in the reactor. Below this temperature range, the rate of microbial activity and biogas production slows down, while above this range, the microorganisms become less effective or may die off.

Several studies have investigated the impact of temperature on biogas production. A study [115] examined the effect of temperature on the anaerobic digestion of poultry litter. The study found that the optimal temperature for biogas production was 55°C, and biogas production was reduced at lower temperatures. This result is consistent with other studies that have reported that the optimal temperature range for biogas production is between 35°C to 55°C. Another study by [116] investigated the impact of temperature on the microbial community composition in anaerobic digesters. The study found that the microbial community composition was significantly influenced by temperature. Specifically, the relative abundance of different microbial groups changed with temperature, with some groups becoming more dominant at higher temperatures. This result suggests that microbial community composition is essential when optimizing biogas production at different temperatures.

In addition to microbial activity, the temperature can also affect the degradation of organic matter, which is a critical step in the anaerobic digestion process. A study by [117] investigated the effect of temperature on cow manure's degradation of organic matter. The study found that the rate of organic matter degradation increased with increasing temperature up to 50°C, after which the degradation rate decreased. This result suggests that the temperature at which the anaerobic digestion process is carried out can impact the efficiency of organic matter degradation. Furthermore, the temperature can also influence the biogas composition produced in anaerobic digestion.

A study [118] investigated the effect of temperature on the design of biogas produced from food waste. The study found that increasing the temperature from 35°C to 55°C produced more methane in the biogas. This result is consistent with other studies that have reported that higher temperatures result in higher methane content in biogas.

Temperature is a key parameter affecting biogas production; as reviewed by [119], the temperature range for biogas production is 20 to 60 degrees Celsius. This range can be further classified into three categories:

(a) The low-temperature range is suitable for psychrophilic bacteria and is less than 20 degrees Celsius.
(b) The medium-temperature range is suitable for mesophilic bacteria and ranges between 20 and 40 degrees Celsius.
(c) The high-temperature range is suitable for thermophilic bacteria and ranges from 40 to 60 degrees Celsius.

The highest rate of gas production and removal of CO_2 was achieved at 50 degrees Celsius.

2.2.2 pH

pH is a crucial parameter in biogas production processes and an essential factor that affects the activity of microorganisms responsible for converting organic matter to biogas. pH plays a critical role in determining the microbial diversity, metabolic pathways, and efficiency of the anaerobic digestion process. Studies have shown that pH affects various aspects of biogas production, including microbial activity, organic matter degradation, and gas composition. Anaerobic digestion is a complex process that involves multiple microorganisms, and each organism has a specific pH range that supports its growth and activity. The optimal pH range for most microorganisms involved in biogas production is between 6.5 and 8.5. However, particular microorganisms have unique pH ranges necessary for their activity. For instance, acidogenic bacteria require a pH range of 5.5-6.5, while methanogenic bacteria require a pH range of 6.5-8.5. Therefore, maintaining the appropriate pH level is critical to ensure the microbial community functions optimally.

Several studies have investigated the impact of pH on biogas production. [120] investigated the effect of pH on the microbial community structure in anaerobic digesters. The study found that pH significantly influenced the microbial community composition. Specifically, the relative abundance of different microbial groups changed with pH, with some groups becoming more dominant at higher or lower pH levels. This study suggests that pH is critical in regulating microbial diversity in anaerobic digestion systems. In addition to microbial diversity, pH can also affect the degradation of organic matter, which is a crucial step in biogas production. A study by [121] investigated the effect of pH on the degradation of cornstalks in anaerobic digesters. The study found that the optimal pH for cornstalk degradation was 7.5, and the degradation rate decreased at lower or higher pH levels. This result suggests that maintaining the appropriate pH level is critical to ensure efficient organic matter degradation.

Another study by [122] investigated the effect of different pH levels on biogas production. The pH levels tested were 4, 7, and 9. Biogas production is a complex process involving other microbial communities' activity, including methanogens. Methanogens are microorganisms that produce methane gas as a byproduct of their metabolism. The study found that the best pH value preferred by methanogens for biogas production is around 6 to 7. At a pH of 4, there was a significant decrease in biogas production. This is because the acidic environment created by the low pH inhibited the activity of methanogens. Similarly, at a pH of 9, the high alkalinity of the environment was not favorable for the growth and activity of methanogens, resulting in decreased biogas production.

The pH of the biogas production environment is a critical factor affecting microbial activity and biogas production. Maintaining an optimal pH range is crucial to ensure the microbial communities' efficient functioning in biogas production. This study highlights the importance of controlling pH levels in biogas production processes to maximize biogas yield. Furthermore, pH can also affect the biogas composition produced in anaerobic digestion. A study [123] investigated the effect of pH on biogas composition during the anaerobic digestion of food waste. The study found that increasing the pH from 6.5 to 7.5 resulted in a significant increase in the methane content of biogas. This result is consistent with other studies that have reported that higher pH levels result in higher methane content in biogas.

Moreover, pH can affect the buffering capacity of the anaerobic digestion system. The buffering capacity is the ability of the system to maintain a stable pH level despite fluctuations in acid or alkali concentrations. A study by [124] investigated the effect of pH on the buffering capacity of anaerobic digesters during the digestion of pig manure. The study found that the buffering capacity of the system decreased at pH levels outside the optimal range of 6.5-8.5. This result suggests that maintaining the appropriate pH level is critical to ensure the stability of the anaerobic digestion process.

2.2.3 Feedstock Composition

Biogas production is a complex process that involves the degradation of organic matter by microorganisms, producing methane-rich biogas. One of the critical factors that affect biogas production is feedstock composition. Feedstock composition refers to the chemical composition of the organic matter used as a substrate for biogas production. The chemical composition of the feedstock can significantly impact the microbial community structure, biogas yield, and quality of the produced biogas. The chemical composition of the feedstock can affect the degradation rate and efficiency of the anaerobic digestion process. The feedstock composition influences the nutrient availability and accessibility of the organic matter for microbial degradation. High nutrient content in the feedstock can support microbial growth, leading to faster degradation rates and higher biogas yields. However, too high a nutrient content can lead to acidification of the digester and a decrease in biogas yield. Moreover, inhibitory compounds in the feedstock can hinder microbial activity and decrease biogas yield.

Several studies have investigated the effect of feedstock composition on biogas production. [125] investigated the impact of various food waste and cow manure ratios on biogas production. The study found that the ratio of food waste to cow manure significantly impacted the methane yield and quality of the produced biogas. The study showed that increasing the proportion of food waste in the feedstock resulted in higher methane yield and higher methane content in the produced biogas.

Similarly, [126] investigated the effect of different organic waste blends on biogas production. The study found that the chemical composition of the feedstock significantly influenced the methane yield and quality of the produced biogas. The study also showed that combining organic wastes with complementary nutrient profiles resulted in higher methane yield than individual organic wastes. Furthermore, the effect of feedstock composition on biogas production has been studied in the context of co-digestion. Co-digestion involves using multiple feedstocks for biogas production, and it is a promising approach to enhance biogas yield and quality. [127] investigated the effect of co-digestion of food waste and grease trap waste on biogas production. The study found that co-digestion of the two feedstocks resulted in higher methane yield and better biogas quality than individual feedstocks. The chemical composition of the feedstock can also affect the microbial community structure in the digester. Microorganisms involved in biogas production have specific nutrient requirements, and changes in feedstock composition can lead to changes in the microbial community structure.

A study by [128] investigated the effect of different organic waste blends on microbial community structure during anaerobic digestion. The study found that the chemical composition of the feedstock significantly influenced the microbial community structure, with distinct microbial communities associated with different feedstock blends. [129] Suggests that a specific ratio of feed, cafeteria, vegetable, and fruit waste can improve organic waste utilization for sustainable agriculture in Bangladesh. The authors compare the effects of four ratios: 1:1:1, 1.5:0.5:1.0, 1.0:1.5:0.5, and 0.5:1.0:1.5. The first ratio, 1:1:1, involves equal proportions of each type of waste. The other ratios involve varying amounts of each waste type. According to the study, the 1:1:1 ratio provides better results than the different ratios. This could be due to the balanced composition of the wastes, which provides a more diverse nutrient profile for the soil. The equal ratio could also offer a more balanced microbial community, essential for soil health and nutrient cycling.

[130] Carried out a study to examine the effects of various ratios of food waste with vegetable waste in anaerobic digestion using chicken dung. The authors tested five different feedstock ratios using chicken dung in two separate digesters. Digester D3 had a ratio of 1:1, Digester D4 of 2:1, Digester D5 of 3:1, Digester D1 of 0:1, and Digester D2 of 0:1. The results showed that when the ratio of food waste to chicken dung was 1:1 (Digester D3), the maximum volume of biogas generation and the highest percentage of methane gas were created. The highest rate of methane gas was 72%, and the maximum volume of biogas produced was 18.83 kg. The authors suggest that the optimal ratio of carbon to nitrogen in the 1:1 ratio could have contributed to the increased biogas production and methane

percentage. The chicken dung used in the feedstock has a high nitrogen content, complementing the carbon-rich food and vegetable waste.

2.2.4 Carbon-Nitrogen Ratio (C-N Ratio)

Biogas production is an increasingly important area of research due to the need for sustainable and renewable energy sources. The C: N ratio, or the ratio of carbon to nitrogen in a substrate, is one parameter that can significantly affect biogas production. The C: N ratio is important because it determines nitrogen availability for microorganisms during anaerobic digestion. Microorganisms require a nitrogen source to synthesize proteins and perform other essential functions. If the C: N ratio is too high, nitrogen will be limited, and biogas production will be reduced. On the other hand, if the C: N ratio is too low, excess nitrogen may lead to the accumulation of ammonia, which can be toxic to microorganisms and further reduce biogas production.

Several studies have investigated the impact of the C: N ratio on biogas production. For example, a study by [131] found that a C: N ratio of 25:1 was optimal for biogas production from food waste, resulting in a methane yield of 259.9 mL/g VS (volatile solids). When the C: N ratio was increased to 30:1 or decreased to 20:1, methane yields decreased by 16.9% and 14.8%, respectively. The authors attributed the reduced methane yield at higher C: N ratios to nitrogen limitation, while the decreased yield at lower C: N ratios was likely due to ammonia toxicity. Another study by [132] investigated the impact of the C: N ratio on biogas production from dairy manure. The authors found that a C: N ratio of 20:1 was optimal for biogas production, with a methane yield of 289.1 mL/g VS. When the C: N ratio was increased to 25:1 or decreased to 15:1, methane yields decreased by 8.5% and 11.9%, respectively.

[133] Investigated the impact of the C: N ratio on biogas production from corn stover. The authors found that a C: N ratio of 30:1 was optimal for biogas production, with a methane yield of 306.5 mL/g VS. When the C: N ratio was increased to 40:1 or decreased to 20:1, methane yields decreased by 14.7% and 9.9%, respectively. In addition, several other studies have investigated the impact of the C: N ratio on biogas production from various substrates, including pig manure, chicken manure, and sewage sludge. While the optimal

C: N ratio may vary depending on the substrate, these studies consistently show that the C: N ratio is an essential parameter for maximizing biogas production.

The [134] study investigated the impact of different C: N ratios on anaerobic digestion. The study looked at C: N ratios ranging from 6.62 to 64.58 and measured each ratio's biogas production and methane yield. The results showed that biogas production and methane yield decreased as the C: N ratio increased. This is likely due to nitrogen limitation, as microorganisms require nitrogen for protein synthesis and other essential functions. The study also found that a C: N ratio of 20 to 30 was optimal for anaerobic digestion. This range is consistent with other studies investigating the impact of the C: N ratio on biogas production from various substrates. The optimal C: N ratio may vary depending on the substrate, but a range of 20 to 30 is generally considered ideal. Maintaining an optimal C: N ratio maximizes biogas production and ensures efficient anaerobic digestion. Biogas production can be significantly reduced if the C: N ratio deviates too much from the optimal range due to excess carbon or nitrogen. Therefore, monitoring and adjusting the substrate's C: N ratio is essential to ensure optimal biogas production.

2.2.5 Stirring

Stirring or mixing is an essential aspect of the biogas production process. To facilitate the anaerobic digestion process, it is necessary to ensure that the organic matter is adequately mixed with the microbial community. Stirring or mixing also helps to improve the mass transfer of nutrients and gases, thereby increasing the efficiency of biogas production.

Several studies have investigated the impact of stirring or mixing on biogas production. [135], Investigated the effect of mixing intensity on the anaerobic digestion of food waste. The study found that increasing the mixing intensity from 50 to 200 rpm significantly increased biogas production by 37%. The researchers attributed the increase in biogas production to improved mass transfer of nutrients and gases due to increased mixing intensity. Another study by [94] investigated the effect of stirring on biogas production during the anaerobic digestion of pig manure. The study found that stirring significantly improved biogas production by increasing substrate availability to the microbial community. The researchers also observed that stirring reduced the accumulation of volatile fatty acids, which can inhibit the activity of methanogenic bacteria, thereby improving the stability of the anaerobic digestion process.

Moreover, a study by [136] investigated the effect of stirring on the microbial community structure during the anaerobic digestion of cow manure. The study found that mixing significantly increased the abundance of specific microbial groups, such as Syntrophobacter, which are known to play a crucial role in the degradation of organic matter and the production of biogas. Additionally, [137] investigated the effect of mixing frequency on biogas production during the anaerobic digestion of chicken manure. The study found that increasing the mixing frequency from once to three times daily significantly increased biogas production by 33%. Furthermore, a study by [138] investigated the effect of stirring on biogas production during the anaerobic digestion of corn stover. The study found that mixing significantly increased biogas production by 23% by improving the degradation of organic matter and substrate availability to the microbial community.

The study by [139] investigated the effect of stirring on biogas production during the anaerobic digestion of cow dung and maize silage. The researchers mixed cow dung and maize silage in a 3:1 ratio and stirred the mixture at 100 rpm for 40 days. The study found that initiating significantly increased biogas production by 32% compared to the control group, where no stirring was applied. The researchers attributed the increase in biogas production to improved mass transfer of nutrients and gases due to increased stirring. The researchers suggested that stirring improved the accessibility of organic matter to the microbial community, thereby promoting the growth and activity of specific microbial groups.

2.2.6 Hydraulic retention time

One critical parameter affecting biogas production efficiency is hydraulic retention time (HRT) when wastewater or organic waste remains in the anaerobic digester.

Several studies have investigated the effect of HRT on biogas production. For example, in a study by [140], the researchers evaluated the impact of HRT on biogas production from food waste in a continuously stirred tank reactor (CSTR). It was found that the highest biogas yield was obtained at an HRT of 20 days, attributed to the optimal balance between the organic loading rate (OLR) and the hydraulic load rate (HLR). The researchers also noted that a longer HRT did not necessarily result in higher biogas production, as the OLR decreased with increasing HRT. Similarly, in a study by [141], the authors investigated the effect of HRT on biogas production from poultry manure using a batch anaerobic digester. It was found that the HRT significantly affected biogas yield, with the highest yield obtained at an HRT of 30 days. The researchers noted that longer HRTs resulted in higher biogas yields due to the higher degradation rate of the organic matter. Still, beyond a certain point, the yields decreased due to substrate accumulation and inhibition. Another study by [142] investigated the effect of HRT on the performance of a two-stage anaerobic digestion system to treat sewage sludge. The authors found that the optimal HRT for the first-stage acidogenic reactor was 3-4 days, while the optimal HRT for the second-stage methanogenesis reactor was 15-20 days. The researchers noted that shorter HRTs in the acidogenesis reactor resulted in higher volatile fatty acid (VFA) concentrations and lower pH values, negatively affecting the methanogenesis reactor's performance.

In contrast, a study by [143] evaluated the effect of short-term HRT shock loading on biogas production from food waste. It was found that a short-term HRT shock loading of 12 hours significantly increased biogas yield, as it induced transient acidification and facilitated the release of intracellular compounds. The researchers noted that this approach could be a promising strategy for enhancing biogas production from food waste.

2.2.7 Total solid content

Total solids (TS) content is a crucial parameter affecting biogas production. Several studies have investigated the effect of TS content on biogas production. For example, in a study by [144], the TS content of the feedstock was increased from 6% to 10%, resulting in a significant increase in biogas production of up to 30%. Similarly, [145] reported that increasing the TS content from 5% to 10% resulted in a 29% increase in biogas production. However, high TS content can also negatively affect biogas production. For example, [146] found that increasing the TS content from 10% to 20% resulted in a 16% decrease in biogas production. Similarly, [147] reported that high TS content (>20%) could lead to acidification and reduce biogas production. The optimal TS content for biogas production depends on several factors, such as the type of feedstock and the anaerobic digestion (AD) process.

Feedstocks with high lignocellulosic content, such as agricultural residues and energy crops, typically require a higher TS content to ensure efficient biogas production [148]. On the other hand, feedstocks with high organic matter content, such as sewage sludge and food waste, can achieve optimal biogas production at lower TS content [149]. Several techniques have been developed to optimize biogas production at different TS contents. Co-digestion of other feedstocks can improve the biodegradability of the feedstock and increase biogas production at high TS content [150]. Pre-treatment of the feedstock, such as thermal or mechanical treatment, can also improve biogas production at high TS content by increasing the surface area and accessibility of the substrate [151].

2.2.8 Volatile solids content

The feedstock's volatile solids (VS) content is a key parameter affecting biogas production. VS are the organic compounds that can be converted into biogas through anaerobic digestion (AD). Several studies have investigated the effect of VS content on biogas production. For example, [152] found that increasing the VS content of food waste from 20% to 30% resulted in a significant increase in biogas production of up to 45%. Similarly, [153] reported that increasing the VS content of cow dung from 14% to 18% resulted in a 23% increase in biogas production. However, high VS content can also negatively affect biogas production. For example, [154] found that increasing the VS content of kitchen waste from 24% to 33% decreased biogas production by 21%.

Similarly, [155] reported that high VS content could lead to acidification and inhibition of the AD process. The optimal VS content for biogas production depends on several factors, such as the feedstock type and the AD process. Feedstocks with high lignocellulosic content, such as agricultural residues and energy crops, typically require a higher VS content to ensure efficient biogas production [156]. On the other hand, feedstocks with high organic matter content, such as sewage sludge and food waste, can achieve optimal biogas production at lower VS content [152]. Several techniques have been developed to optimize biogas production at different VS contents. Co-digestion of other feedstocks can improve the biodegradability of the feedstock and increase biogas production at high VS content [157]. Pre-treatment of the feedstock, such as thermal or mechanical treatment, can also improve biogas production at high VS content by increasing the surface area and accessibility of the substrate [158].

2.2.9 Organic loading rate

The amount of organic matter introduced to the digester per unit of reactor volume added per unit of time is known as the organic loading rate. The rate of substrate deterioration, methane production, and process stability are all determined by the Organic loading rate (OLR).

Several studies have investigated the effect of OLR on biogas production. For example, [159] found that increasing the OLR of food waste from 2 to 4 g volatile solids (VS)/L/day resulted in a significant increase in biogas production of up to 68%. Similarly, [160] reported that increasing the OLR of cow manure from 2.5 to 5.0 kg chemical oxygen demand (COD)/m^3/day resulted in a 30% increase in biogas production. However, high OLR can also negatively affect biogas production. For example, (2018) found that increasing the OLR of food waste from 4 to 8 g VS/L/day decreased biogas production by 30%. Similarly, [161] reported that high OLR could lead to acidification and inhibition of the AD process. The optimal OLR for biogas production depends on several factors, such as the type of feedstock, the reactor design, and the AD process.

Feedstocks with high lignocellulosic content, such as agricultural residues and energy crops, typically require a lower OLR to ensure efficient biogas production [162]. On the other hand, feedstocks with high organic matter content, such as sewage sludge and food waste, can achieve optimal biogas production at higher OLR [160]. Several techniques have been developed to optimize biogas production at different OLRs. Continuously stirred tank reactors (CSTR) are the preferred design for handling high organic loading rate (OLR) feedstocks due to their ability to maintain stable anaerobic digestion (AD) conditions [163]. In contrast, fixed-bed reactors are preferred for low OLR feedstocks because it provides longer retention times and higher methane yield [164]. Additionally, several process control strategies, such as pH regulation and feedstock pre-treatment, can improve biogas production at different OLRs [165].

2.2.10 System design

Reactor size is an important design parameter that can influence biogas production efficiency. Larger reactors typically have higher biogas yields due to their greater capacity to process more significant amounts of substrate. A study by [166] demonstrated that increasing the reactor size from 30 to 50 m^3 resulted in a 20% increase in biogas production. However, enormous reactors can also decrease biogas yields due to incomplete mixing and inadequate contact between microorganisms and substrate.

Reactor shape is another design parameter that can impact biogas production efficiency. Studies have shown that the reactor's shape can influence the substrate's mixing and distribution, as well as the retention time of the substrate. A study by [167] compared the performance of a cylindrical reactor to a rectangular reactor and found that the rectangular reactor had a higher biogas yield due to improved mixing and shorter retention time. Reactor configuration is a critical design parameter that significantly impacts biogas production efficiency. Different configurations, such as single-stage, two-stage, or multi-stage, have been studied to determine their effects on biogas production. A study by [168] compared the performance of a single-stage and a two-stage reactor and found that the two-stage reactor had a higher biogas yield and shorter retention time. This was attributed to the ability of the two-stage system to maintain optimal pH and temperature conditions for the different microbial consortia involved in the anaerobic digestion process.

Co-digestion is another design parameter that can impact biogas production efficiency. Co-digestion involves using multiple feedstocks in a single reactor, which can enhance biogas production by improving nutrient balance and increasing organic loading rates. A study by [169] showed that co-digestion of organic waste and pig slurry resulted in a 24% increase in biogas production compared to the digestion of pig slurry alone. Pre-treatment methods are also an important design parameter impacting biogas production efficiency. Pre-treatment methods such as thermal, mechanical, or chemical treatments can increase substrate digestibility and improve biogas yields. A study by [170] showed that pre-treatment of corn stover with an alkali solution resulted in a 22% increase in biogas production compared to untreated corn stover.

2.2.11 Gas retention time

The Gas retention time (GRT) is an essential parameter in biogas production, as it influences the efficiency of the process. GRT is the time biogas spends in the reactor before it is collected and used. It is a critical parameter in the design and operation of biogas production systems because it determines the residence time of microorganisms in the reactor, the rate of organic matter decomposition, and the quality and quantity of biogas produced. Several studies have investigated the effects of GRT on biogas production, and the results have been summarized in the literature. In general, it has been found that longer GRTs are associated with higher methane yields and higher process stability. In comparison, shorter GRTs are associated with lower methane yields and increased process instability.

For example, a study by [171] found that increasing the GRT from 15 to 30 days in an anaerobic digester resulted in a significant increase in methane production from 0.25 to 0.34 m^3/kg VS (volatile solids) while reducing the GRT to 10 days resulted in a decrease in methane production to 0.20 m^3/kg VS. The authors also noted that longer GRTs improved the stability of the process by reducing the accumulation of organic acids and volatile fatty acids, which can inhibit methane production. Similarly, a study by [172] found that increasing the GRT from 10 to 20 days in an anaerobic digester resulted in an increase in methane yield from 0.29 to 0.40 m^3/kg COD (chemical oxygen demand) while reducing the GRT to 5 days resulted in a decrease in methane yield to 0.23 m^3/kg COD. The authors attributed these changes to the effects of GRT on the microbial population in the reactor, with longer GRTs allowing for the development of a more diverse and stable microbial community.

Other studies have reported similar trends, with longer GRTs generally associated with higher methane yields and improved process stability. However, it is essential to note that the optimal GRT for biogas production can vary depending on the specific conditions of the system, including the type of substrate, the temperature, and the hydraulic retention time (HRT).

2.2.12 Trace elements

Trace elements, also known as micronutrients, are essential for the growth and activity of microorganisms in anaerobic digestion. These elements, including iron, cobalt, nickel, zinc, manganese, and molybdenum, are required in small quantities. These elements are involved in various metabolic reactions and are needed to synthesize enzymes and co-factors involved in digestion [173]. While trace elements are essential, their concentration and availability can also affect biogas production. An excess or deficiency of certain elements can inhibit the activity of microorganisms and reduce biogas yield. For example, a lot of nickel or copper can lead to toxicity and inhibition of methanogenic microorganisms, reducing methane production [174]. Similarly, the deficiency of trace elements such as cobalt or molybdenum can limit the activity of methanogens, reducing biogas yield [175]. The feedstock's quality and quantity of trace elements can also influence biogas production. Using manure or other organic wastes as feedstock for biogas production can provide a source of trace elements. Still, the quality and quantity of these elements can vary depending on the origin and composition of the waste material. Therefore, it is essential to consider the trace element content of the feedstock when designing and operating biogas production systems [176].

Several studies have investigated the impact of trace elements on biogas production, and different approaches have been proposed to optimize the trace element supply to the microbial community. One method is to add trace elements as supplements to the biogas digester. However, the use of accessories can be expensive and may not be sustainable in the long term [177]. Another approach is to enhance the availability of trace elements by adjusting the pH, temperature, and retention time of the digestion process to promote the growth and activity of microorganisms that produce or consume the trace elements. This approach can help to optimize biogas production while reducing the need for expensive supplements [178]. Moreover, microorganisms adapted to specific trace element conditions have been proposed to maximize biogas production. For example, some microorganisms can tolerate high levels of heavy metals, which can be toxic to other microorganisms and enhance biogas yield in contaminated environments [179].

2.2.13 Inoculum

Inoculum, also known as seed material, plays a crucial role in biogas production. It serves as a source of microorganisms responsible for the anaerobic digestion of organic matter and biogas production. This review will explore the impact of inoculum on biogas production and the various studies conducted on this topic.

Several studies have investigated the impact of inoculum on biogas production. A study by [180] investigated the effect of inoculum on the anaerobic digestion of pig manure. The study found that using inoculum significantly increased biogas production by improving the activity of methanogenic bacteria. The researchers also observed that inoculum reduced the lag phase of the anaerobic digestion process, thereby enhancing the stability of the process. Moreover, a study by [181] investigated the effect of inoculum on biogas production during the anaerobic digestion of poultry waste. The study found that using inoculum significantly increased biogas production by promoting the growth and activity of methanogenic bacteria. The researchers also observed that inoculum reduced the lag phase of the anaerobic digestion process and improved the degradation of organic matter.

Furthermore, a study by [182] investigated the effect of inoculum on biogas production during the anaerobic digestion of food waste. The study found that using inoculum significantly increased biogas production by promoting the growth and activity of methanogenic bacteria. The researchers also observed that inoculum improved the stability of the anaerobic digestion process by reducing the accumulation of volatile fatty acids. In addition, a study by [183] investigated the effect of inoculum on biogas production during the anaerobic digestion of corn straw. The study found that using inoculum significantly increased biogas production by improving the degradation of organic matter and promoting the growth and activity of methanogenic bacteria. The researchers also observed that inoculum reduced the lag phase of the anaerobic digestion process, thereby improving the stability of the process.

Moreover, a study by [184] investigated the effect of inoculum on biogas production during the anaerobic digestion of pig manure and corn straw. The study found that using inoculum significantly increased biogas production by improving the degradation of organic matter and promoting the growth and activity of methanogenic bacteria. The researchers also observed that inoculum reduced the lag phase of the anaerobic digestion process, thereby improving the stability of the process.

2.3 Biogas used in IC engine

One of the most common ways to use biogas as a fuel is in internal combustion (IC) engines. Biogas can be used directly in engines or compressed to form CBG, which has a higher energy density and can be transported more efficiently. This literature review covers studies investigating biogas use in internal combustion (IC) engines. The studies explore the effects of biogas on engine performance, emissions, and efficiency at various operating conditions.

One study by [185] tested rice straw as an additive in a dual-fuel mode using biogas in an IC engine with a rated power of 4.4 kW at 1500 rpm. The study found that the engine's performance improved by using 20% and 40% rice straw additives, resulting in increased brake thermal efficiency (BTE) and power output. Another study by [186] investigated the effect of carbon dioxide dilution and compression ratio on a small biogas-fueled SI engine with a rated power of 4.41 kW at 3600 rpm. The study showed that increasing the compression ratio improves engine performance while increasing carbon dioxide dilution degrades it. The study found that the engine's brake power output and thermal efficiency improved when the compression ratio increased from 8.01:1 to 9.22:1.

[187] studied different biogas flow rates in a dual-fuel mode with a compression ratio range of 17:1 and a rated power of 4.86 kW. According to the study, at low biogas flow rates, the dual-fuel way of the CI engine had a higher BTE than the pure diesel mode. However, for all loads and engine speeds, the CI engine's specific fuel consumption when operating in dual-fuel mode was higher than in pure diesel mode. The study showed CO and HC emissions rose as the biogas flow rate increased. It is advised that the CI engine be operated in dual-fuel mode with a biogas flow rate of between 2 L/min and 4 L/min. The impact of injection timing and compression ratio on a dual-fuel mode engine's BTE and emission characteristics with a rated power of 4.86 kW and a compression ratio range of 17:1 was examined [188]. According to the analysis, the dual-fuel mode had the highest brake thermal efficiency, reaching 25.44%. At 29° BTDC, increasing the compression ratio to 18 produced the highest level of BTE. The study also discovered that advancing the injection timing from 26° BTDC to 32° BTDC lowered CO and HC emissions.

Another study by [189] investigated the effect of compression ratio on dual-fuel (diesel and biogas) engine performance. An IC engine with a rated power of 3.5 kW at 1500 rpm and a range of compression ratios from 12:1 to 18:1 was employed in the investigation. The study discovered that while the volumetric efficiency was unaffected by the methane fraction, the CO_2 content of the biogas did not significantly affect BTE. The study also found that, in the dual-fuel mode, exhaust gas temperature was marginally higher than in the diesel-only condition. [190] evaluated the performance of a constant-speed IC engine on compressed natural gas (CNG), methane-enriched biogas, and raw biogas. The engine had a rated power of 5.9 kW at 1500 rpm and used a compression ratio of 12.65:1 for all fuel types. The study found that the engine performance on methane-enriched biogas containing 95% methane was almost similar to CNG's, indicating that methane-enriched biogas is as good as natural gas. [191] compare the performance of a multicylinder engine using CBG and CNG at 50% maximum load and engine speeds ranging from 1500 to 3500 rpm. The study found that the engine running on CBG had higher thermal efficiency and reduced NOx and HC emissions compared to the engine running on CNG. The study concluded that CBG fuel could replace CNG in SI engines as an alternate fuel.

According to a study by [192], biogas has several advantages over fossil fuels regarding environmental impact and energy security. Biogas is a renewable and sustainable source of energy that reduces greenhouse gas emissions and helps to mitigate climate change. Biogas production also reduces the amount of organic waste that would otherwise end up in landfills or be burned, further reducing greenhouse gas emissions. The use of biogas in IC engines has been extensively studied over the past few decades. One of the earliest studies on biogas in IC engines was conducted by [193]. The study found that biogas can be used as a fuel for IC engines with only minor modifications to the engine. The study also found that the engine's performance was comparable to that of engines fueled by natural gas. Another study [194] compared the performance of diesel and biogas engines. The study found that the biogas engine had lower carbon monoxide, hydrocarbons, and nitrogen oxide emissions than the diesel engine. The study also found that the biogas engine had a higher thermal efficiency than the diesel engine.

In addition to the environmental benefits of using biogas in IC engines, there are also economic benefits. A study [195] found that using biogas in IC engines can be economically viable, especially in rural areas with a ready supply of organic waste. The study found that the cost of producing biogas was lower than that of producing diesel fuel, and using biogas in IC engines reduced the cost of electricity generation. CBG has a higher energy density than biogas and can be transported more efficiently. CBG can also be used in natural gas vehicles (NGVs) with only minor modifications to the engine. A study by [196] found that CBG can be used as a fuel for NGVs with similar performance and emissions characteristics to natural gas. Despite the advantages of using biogas and CBG in IC engines, several challenges must be addressed. One of the main challenges is the variability of biogas composition, which can affect engine performance and emissions. A study [197] found that biogas composition can vary depending on the feedstock and the conditions of the anaerobic digestion process. The study found that the methane content of biogas ranged from 50% to 70%, which can affect the fuel's energy density and the engine's performance.

A study by [198] investigated the performance and emissions of a CI engine fueled with biogas. The study found that the engine performance was similar to diesel fuels. Nitrogen oxides (NOx) and particulate matter (PM) were lower with biogas than diesel fuel emissions. However, the emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC) were higher with biogas. Another study [199] investigated the use of biogas-diesel dual fuel in a CI engine. The study found that the engine performance was similar to that of diesel fuel, and the emissions of NOx and PM were lower with biogas-diesel dual fuel than diesel fuel. However, the emissions of CO and UHC were higher with biogas-diesel dual fuel. Overall, the use of biogas in CI engines has shown promising results in terms of engine performance and emissions.

A study by [200] investigated the performance and emissions of a SI engine fueled with CBG. The study found that the engine performance was similar to that of gasoline fuel, and the CO, HC, and NOx emissions were significantly lower with CBG than gasoline fuel. A more recent study by [201] investigated the effect of CBG-H_2 blends on the performance and emissions of a SI engine. The study found that the engine performance improved with adding H_2 in CBG, and CO, HC, and NOx emissions were significantly reduced with CBG-H_2 blends compared to gasoline fuel. Using CBG as an alternative fuel in SI engines has shown promising engine performance and emissions results. The lower CO, HC, and NOx emissions make CBG more environmentally friendly than gasoline.

2.4 Research Gap

After a literature review, certain deficiencies or areas of insufficient research coverage have been identified, indicating gaps in existing research articles. These gaps suggest the need for further investigation and exploration to address unanswered questions or unexplored aspects within the subject area.

- ❖ Vegetables, fruits, and mixed cooked waste come out of every house. But the study has not discussed how all these three wastes are related to each other.
- ❖ Organic household waste, such as fruits, raw vegetables, and cooked waste are mixed to make biogas. But there has been limited research into biogas production

with various reactor temperature ranges, tumbling effects, and their different proportions.

- Compressed biogas use in IC engines is little reported.
- Numerous studies demonstrate biogas production using different kinds of organic waste and animal dung. More information is needed on how much CH_4 is made by individual household organic wastes.
- Multiple studies used animal waste, such as cow dung, to produce biogas. However, to find out whether cow dung can be used with other types of waste, such as fruit waste, raw kitchen waste, and cooked waste, as organic waste in biogas is not reported in detail.

2.5 Objectives of the research

The present study aims to analyze the waste management system on the DTU campus. Consistently more than1-ton organic waste is generated daily on the university campus from residential flats, hostels, and canteens. This study aims to develop a plant to produce biogas suitable for running an automotive ic engine.

1. To design and develop an experimental setup of a biogas plant
2. To study the effect of various process parameters, such as: -

- Different kinds of waste, like vegetables, fruits, and cooked waste to produce biogas at a small scale and analyze the composition of CH_4, CO_2, and H_2S with a biogas analyzer.
- Optimization of wastage to increases the production of CH_4 and simultaneously minimizes the release of CO_2.

3. To develop an experimental setup for a bi-fuel (petrol/ biogas) engine and to optimize its engine performance parameters using various engineering analysis tools.

CHAPTER 3

RESEARCH METHODOLOGY

Household organic waste can be a valuable resource if collected and appropriately utilized. In universities where large numbers of students and staff generate organic waste, effective collection and utilization can help reduce waste and contribute to sustainable practices. Collection of household organic waste on university campuses is crucial in minimizing the environmental impact of waste disposal. Biological garbage creates methane, a potent greenhouse gas that adds to climate change when dumped in landfills. Collecting organic waste helps reduce the amount of waste in landfills, thereby reducing methane emissions. Organic waste can be managed in different ways on university campuses. One standard method is the use of composting systems. Composting involves the decomposition of organic waste through the activity of microorganisms. This process produces nutrient-rich compost that can be used as a soil conditioner and fertilizer.

The utilization of household organic waste can provide several benefits on university campuses. One significant benefit is the production of compost, which can be used in landscaping, gardening, and agriculture. Compost can help improve soil quality, reduce the need for synthetic fertilizers, and promote healthy plant growth. In addition to composting, organic waste can be utilized through anaerobic digestion. The use of fossil fuels may be lessened, as a result, lowering greenhouse gas pollution. While collecting and utilizing household organic waste on university campuses can provide numerous benefits, some challenges must be addressed. One big problem is that people don't know or understand how important it is to handle organic waste. Many people are unaware of proper organic waste management's environmental and economic benefits and may not be motivated to participate in waste reduction initiatives. Another challenge is the lack of infrastructure and resources for organic waste management. Collecting and utilizing organic waste requires specialized equipment and facilities, which may not be available on all university campuses. It can make it challenging to implement effective organic waste management programs.

To address these challenges, universities can implement education and outreach programs to raise awareness about the importance of organic waste management. It can also invest in the necessary infrastructure and resources to facilitate organic waste collection and utilization. It can include the installation of composting and anaerobic digestion systems, as well as the training of staff and students on proper waste management practices. The research methodology for this project is a systematic approach that begins with collecting organic waste semi-segregated from Delhi technological university (DTU) campus. The waste is further segregated into three types, raw vegetable waste (RVW), fruit waste (FW), and mixed cooked waste (MCW). This step is essential as it allows for a more targeted analysis of the potential for biogas production from the segregated waste. After the waste has been segregated, a regression analysis is performed on the collected data to identify the most significant factors affecting biogas production.

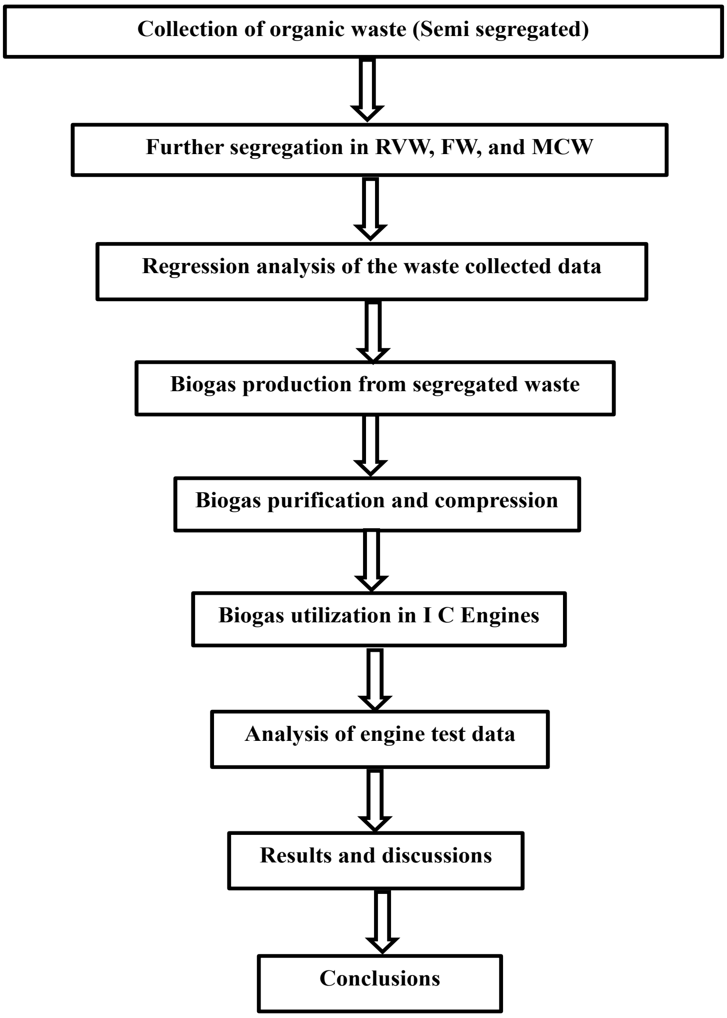


Figure 3.1: Research methodology

This analysis helps to determine the relationship between the different types of waste and their potential for biogas production. This step is essential for understanding the factors contributing to biogas production and identifying ways to optimize the process. Once the analysis is complete, the segregated waste is used to produce biogas through a series of steps, including purification and compression. This purified biogas is then utilized in IC engines to measure engine performance and obtain engine test data. The results and discussions section of the methodology presents the research project's findings. These findings include the amount of biogas produced, the efficiency of the biogas purification and compression processes, and the performance of the IC engines using biogas as fuel. Analyzing the results and discussions helps identify the potential of organic waste as a renewable energy source. It provides insights into the factors affecting biogas production from segregation.

Delhi Technological University (DTU), at latitude 28.7496°N and longitude 77.1174°E, was established in 1941 by the Government of India. The campus of DTU is spread over a vast area and houses various departments, research centers, laboratories, hostels, and sports facilities.

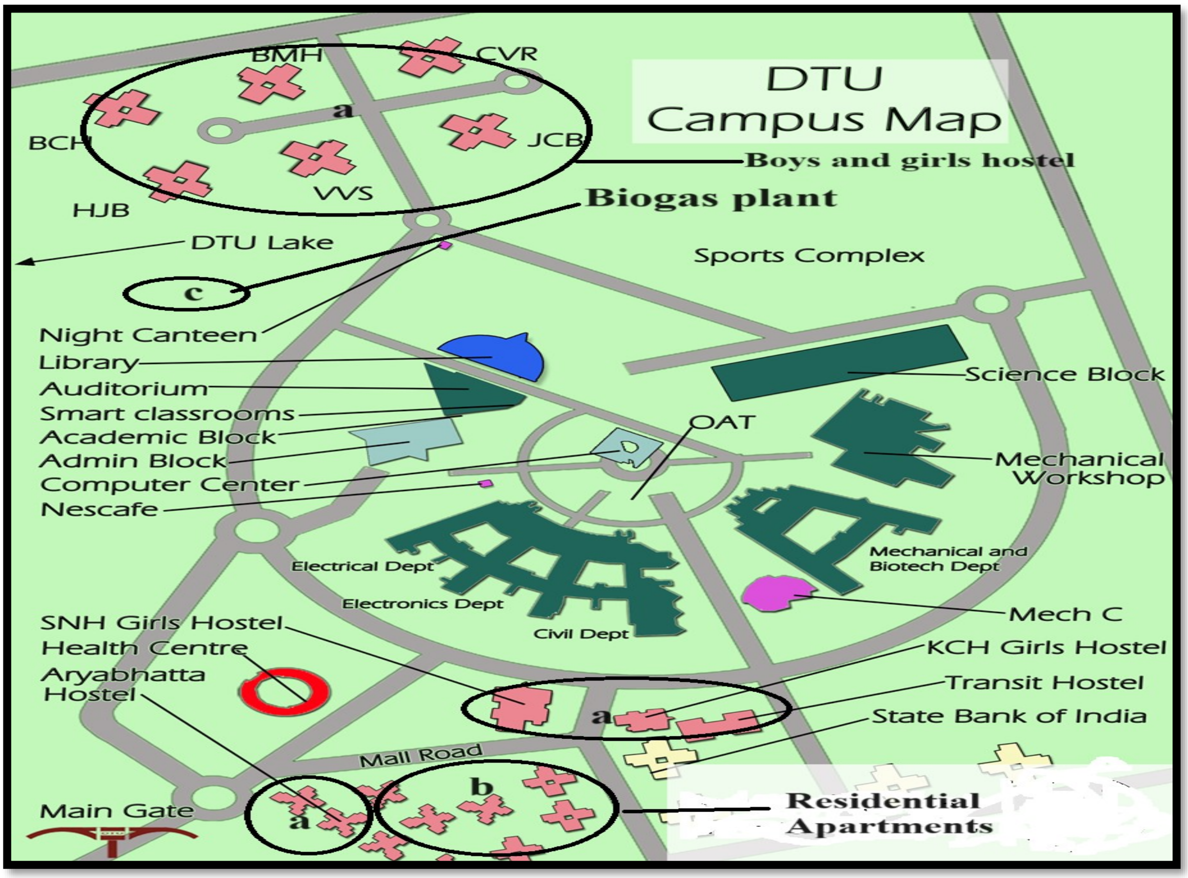


Figure 3.2: Location of (a) Boys and Girls hostel (b) Residential Apartments (c) Biogas plant in Delhi Technological University Campus [202]

This University has eight boys' hostels, six girls' hostels, and about 350 residential apartments for its employees [203]. University has 9045 students till 2018-19; undergraduate students 7170; postgraduates 898; doctoral students 395, and around 1000 - 1200 teaching and non-teaching staff [204]. DTU continues to uphold its legacy of providing quality education and producing professionals who contribute to the advancement of society through their knowledge and skills.

Figure 3.3: Dustbin distribution on the university campus

A comprehensive waste management plan was implemented on the university campus to initiate the zero organic waste processes. The first step was to distribute approximately 750 dustbins to all residential apartments and canteens on the campus. These dustbins had a capacity of 13 kg and were of two types: blue for dry waste and green for wet organic waste.

Separating waste at the source ensured that waste management could be done efficiently and effectively. Solid organic waste generated from residential apartments, canteens, and campuses through these dustbins was collected daily at one location. The collected waste was then transported to a central location where it was sorted and processed. The accumulated solid organic waste was separated into digestive organic waste and organic compost waste.

The digestive organic waste was introduced into a biogas digester, where biogas was produced. The biogas produced was then utilized as an energy source for the university campus. The organic compost waste was sent to a composting facility, which was processed and converted into organic compost. Composting is when microorganisms decompose organic waste into a nutrient-rich soil amendment.

The organic compost produced could be used as a soil conditioner in gardens and agricultural fields. This zero organic waste process helped reduce the university's carbon footprint and created a sustainable waste management system. Implementing this system was essential to promoting sustainable practices on the university campus. Separating waste at the source reduced the garbage transported to the landfill. The university reduced its dependence on fossil fuels and chemical fertilizers by converting organic waste into biogas and compost. Moreover, implementing this system helped educate the university's students and staff about waste management and sustainability. The university also organized awareness programs and workshops to create awareness about the zero organic waste process and encourage active community participation.

3.1 Sample collection and waste profile

Every day, many people, including students, employees, and visitors, enter the campus and eat in a mess, canteens, and cafeteria. In addition, thousands of students live in hostels; food is prepared four times a day in the mess and canteen. Moreover, more than three hundred flats are available where staff resides based on their grade pay. Most professors and higher officials live on the university campus with an average family of 4-5 members. Organic wastes such as tea powder, leftover food, fruit waste, vegetable waste, etc., are routinely used for biogas production; hence, it is called digestive organic wastes. Spinach sticks, cabbage, green leaves, dry leaves, orange peel, fibrous vegetables, fruits, etc., are used to make compost; hence it is called organic compost waste.

In the period between January 2020 to December 2020, a sample set (S1 to S24) consisting of 1620 waste bags was gathered. Consequently, an eight sample set eight-sample set was formed every four months. These bags contained various types of organic waste originating from households. The sample size of each sample set is studied by incrementing five garbage bags. As shown in Figure 3.4, more than 1000 kg of organic waste is generated daily from canteens, messes, and residential apartments. While weighing, ±10% accuracy has been taken for each household organic waste, shown in Table 3.1. Sample sets S1 to S8 were collected between January 2020 to April 2020.

Figure 3.4: Various types of household organic wastes are generated daily on the university campus

In this period, the total sample size was 220 waste bags, in which 90.94 kg of RVW, 32.67 kg of FW, and 25.74 kg MCW were found, as shown in Table 3.1(a). During this period, 36 types of organic waste were found as RVW, FW, and MCW in S1 to S8 sample sets.

Table 3.1: Sample details of various waste bags

Types of Household Organic Waste	**(a). S1 to S8, with a total sample size of 220 garbage bags collected between January 2020 and April 2020**							
	S1(10)	**S2(15)**	**S3(20)**	**S4(25)**	**S5(30)**	**S6(35)**	**S7(40)**	**S8(45)**
	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
Beetroot	-	-	0.53±0.053	-	-	-	-	-
Broccoli	-	-	-	-	-	-	1.95±0.195	-
Chard	0.26±0.026	-	-	-	-	-	-	-
Cauliflower	-	-	1.48±0.148	-	0.2±0.02	-	-	-
Zucchini.	-	-	-	-		-	1.15±0.115	-
Green fenugreek	0.46±0.046	1.73±0.173	-	1.35±0.125	1.62±0.162	-	-	0.8±0.08
Spinach	1.1 ± 0.11	1.3±0.13	1.35±0.135	2.38±0.212	1.42±0.142	3.46±0.346	1.05±0.105	1.25±0.125
Pumpkin	0.5±0.05	0.7±0.07	-	-	-	-	-	0.4±0.04
Onion	-	0.42±0.042	0.60±0.060		0.61±0.061	2.73±0.273	1.19±0.119	1.35±0.135
Potato	0.52±0.052	-	0.31±0.031	1.44±0.134	-	0.33±0.033	0.65±0.065	1.3±0.13
Carrot	-	0.21±0.021	0.25±0.025	1.12±0.102	1.53±.153	0.76±0.076	1.85±0.185	0.65±0.065
Ladyfinger	-	0.3±0.03	-	-	-	-	-	-
Green coriander	-	1.19±0.119	0.16±0.016	-	-	0.49±0.049	1.75±0.175	0.95±0.095
Cabbage	1.15±0.115	-	-	0.65±0.065	-	4.31±0.431	-	1.9±0.19
Radish	0.4±0.04	-	-	0.9±0.09	1.29±0.129	3.1±0.31	2.07±0.207	2.91±0.291
Tomatoes	0.16±0.016	-	0.78±0.078	0.3±0.02	-	0.2±0.02	-	0.45±0.045
Turnip	-	-	0.25±0.025	0.2±0.02	-	-	0.56±0.056	-
Capsicum	-	-	0.39±0.039	-	-	0.3±0.03	-	0.85±0.085
Bottle Gourd	-	-	0.15±0.015	0.21±0.021	-	-	-	1.75±0.175
Pea peel	-	-	-	1.96±0.196	5.53±0.553	1.72±0.172	4.12±0.412	2.98±0.298
Cucumber	-	-	0.3±0.03	-	-	-	-	-
Banana	0.7±0.07	0.45±0.045	0.83±0.083	0.7±0.07	0.2±0.02	2.34±0.234	2.36±0.236	2.5±0.25
Orange	_	0.53±0.053	0.54±0.054	0.4±0.04	-	-	-	-
Papaya	0.61±0.061	_	0.5±0.05	0.45±0.045	-	-	-	1.48±0.148
Apple	0.29±0.029	-	0.14±0.014	0.32±0.032	0.25±0.025	-	0.5±0.05	0.9±0.09
Pineapple	-	-	-	-	0.83±0.083	-	-	0.55±0.055
Pomegranate	-	-	-	-	-	1.58±0.158	0.7±0.07	2.17±0.217
Plum	-	-	0.7±0.07	-	-	0.37±0.037	-	0.3±0.03
Kumquats	-	0.57±0.057	-	-	-	-	-	0.55±0.055
Kiwi	0.25±0.025	-	-	-	-	-	0.76±0.076	-
Mango	-	-	-	-	-	-	4.43±0.443	1.25±0.125
Limes	-	-	0.4±0.04	0.20±0.020	0.27±0.027	-		

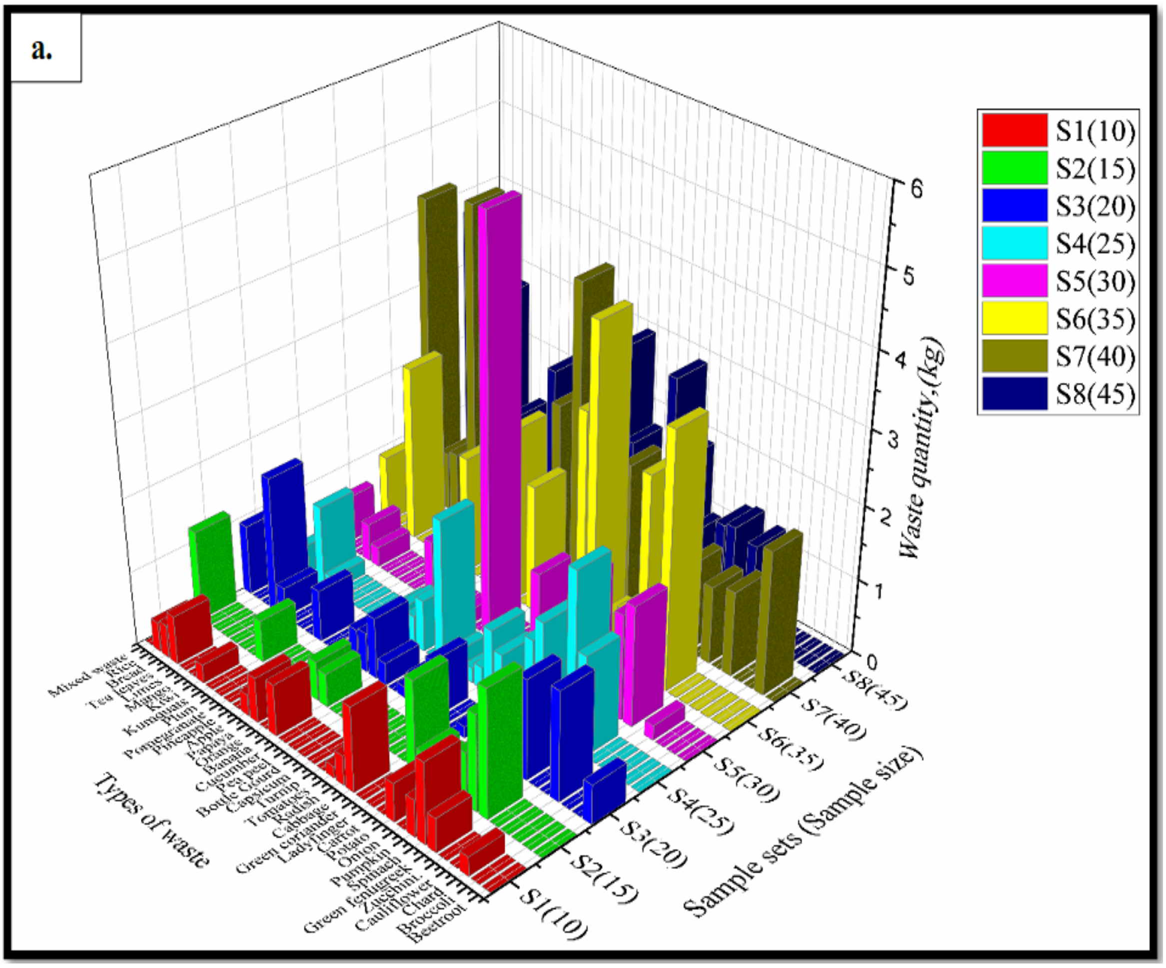
Tea leaves	0.66±0.066	-	1.85±0.185	1.11±0.111	0.52±0.052	2.39±0.239	0.86±0.086	2.8±0.28
Bread	0.45±0.045	-	-	-	-	-	0.8±0.08	0.5±0.05
Rice	0.4±0.04	-	-	0.4±0.04	-	-	0.55±0.055	0.6±0.06
Mixed waste	-	1.22±0.122	.95±0.095	-	0.63±0.063	0.92±0.092	4.20±0.420	3.73±0.373
Types of Household Organic Waste	**(b). S9 to S16, with a total sample size of 540 garbage bags collected between May 2020 to August 2020**							
	S9(50)	**S10(55)**	**S11(60)**	**S12(65)**	**S13(70)**	**S14(75)**	**S15(80)**	**S16(85)**
	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
Garlic	1.30±0.130	0.75±0.075	-	1.35±0.135	-	3.5±0.35	1.65±0.165	2.3±0.23
Asparagus	0.7±0.07	1.35±0.135	0.65±0.065	-	0.85±0.085	-	0.45±0.045	1.45±0.145
Chard	-	-	1.85±0.185	1.45±0.145	0.4±0.04	0.55±0.055	1.5±0.15	0.35±0.035
Cucumber	1.75±0.175	-	-	3.35±0.335	-	0.65±0.065	1.85±0.185	0.71±0.071
Chicory	0.68±0.068	-	1.55±0.155	1.75±0.175	0.5±0.05	-	2.7±0.27	0.95±0.095
Green bean	0.20±0.020	1.05±0.105	1.25±0.125	0.95±0.095	1.40±0.140	-	1.45±0.145	2.65±0.265
Broad bean	0.35±0.035	-	0.25±0.025	-	0.3±0.03	1.75±0.175	0.35±0.035	0.4±0.04
Lettuce	0.25±0.025	1.23±0.123	1.45±0.145	1.65±0.165	-	1.5±0.15	0.35±0.035	0.55±0.055
Tomato	0.5±0.05	3.5±0.35	2.25±0.225	-	1.50±0.150	-	0.55±0.055	0.6±0.06
Pea	1.95±0.195	-	-	2.75±0.275	1.70±0.170	1.65±0.165	2.15±0.215	1.5±0.15
Rhubarb	0.25±0.025	0.85±0.085	0.45±0.045	-	0.5±0.05	0.45±0.045	-	-
Radish	0.55±0.055	1.55±0.155	0.65±0.065	0.45±0.045	-	1.5±0.15	-	1.8±0.18
Celery	0.85±0.085	1.15±0.115	0.85±0.085	0.3±0.03	3.30±0.33	1.85±0.185	0.65±0.065	-
Courgette	1.15±0.115	-	1.45±0.145	1.85±0.185	-	2.7±0.27	1.1±0.11	-
Potatoes	3.05±0.305	2.47±0.247	1.25±0.125	2.7±0.27	2.60±0.260	1.45±0.145	1.2±0.12	4.5±0.45
Bottle gourd	2.67±0.267	-	0.25±0.025	0.3±0.03	-	0.35±0.035	-	1.65±0.165
Onion	2.25±0.225	-	0.23±0.023	0.4±0.04	1.9±0.19	0.35±0.035	3.5±0.35	0.45±0.045
Ladyfinger	0.85±0.085	0.5±0.05	0.27±0.027	0.55±0.055	-	0.50±0.050	0.5±0.05	1.5±0.15
Capsicum	-	0.35±0.035	-	2.65±0.265	0.35±0.035	2.65±0.265	0.4±0.04	1.60±0.160
Zucchini.	-	1.65±0.165	-	0.35±0.035	2.6±0.26	0.4±0.04	0.75±0.075	0.85±0.085
Arugula	-	0.85±0.085	2.70±0.270	-	2.85±0.285	-	0.7±0.07	-
Brinjal	-	2.15±0.215	1.65±0.165	0.65±0.065	0.8±0.08	0.65±0.065	1.4±0.14	-
Sem	-	1.35±0.135	3.5±0.35	-	0.45±0.045	1.7±0.17	1.55±0.155	1.5±0.15
Jackfruit	-	0.45±0.045	-	0.85±0.085	0.65±0.065	1.2±0.12	-	1.6±0.16
Watermelon	2.15±0.215	2.35±0.235	2.75±0.275	2.60±0.285	3.8±0.38	2.5±0.25	2.7±0.27	1.65±0.165
Banana	1.45±0.145	0.75±0.075	1.65±0.165	1.90±0.190	2.5±0.25	1.8±0.18	1.65±0.165	2.25±0.225
Mango	-	2.25±0.225	2.85±0.285	0.75±0.075	2.1±0.21	2.55±0.255	2.95±0.295	0.55±0.055

Limes	1.5±0.15	0.45±0.045	1.35±0.135	1.8±0.18	1.35±0.135	2.1±0.21	0.65±0.065	1.8±0.18
Pineapple	0.8±0.08	0.95±0.095	0.85±0.085	0.45±0.045	0.4±0.04	-	1.8±0.18	0.65±0.065
Apple	0.55±0.055	0.35±0.035	0.65±0.065	1.35±0.135	-	0.45±0.045	-	1.15±0.115
Pomegranate	0.7±0.07	-	-	1.15±0.115	0.6±0.06	-	1.4±0.14	1.6±0.16
Melon	1.7±0.17	3.05±0.305	0.65±0.065	1.25±0.125	2.55±0.255	1.85±0.185	0.85±0.085	1.45±0.145
Strawberries.	-	-	-	-	-	0.65±0.065	-	0.35±0.035
Papaya	0.4±0.04	0.35±0.035	0.55±0.055	0.25±0.035	1.35±0.135	0.55±0.055	0.55±0.055	-
Kiwi	-	-	-	-	-	0.4±0.04	0.6±0.06	-
Tea leaves	3.3±0.33	3.8±0.38	3.55±0.355	4.8±0.48	4.6±0.46	4.65±0.465	3.65±0.365	2.9±0.29
Bread	0.4±0.04	0.75±0.075	1.25±0.125	1.45±0.145	1.9±0.19	1.7±0.17	1.6±0.16	1.4±0.14
Rice	0.9±0.09	1.75±0.175	0.5±0.05	1.5±0.15	1.4±0.14	2.1±0.21	1.9±0.19	2.65±0.265
Mixed waste	4.55±0.455	3.05±0.305	4.85±0.485	3.5±0.35	4.6±0.46	5.1±0.51	5.3±0.53	5.5±0.55
Types of Household Organic Waste	**(c). S17 to S24, with a total sample size of 860 garbage bags collected between September 2020 to December 2020**							
	S17(90)	**S18(95)**	**S19(100)**	**S20(105)**	**S21(110)**	**S22(115)**	**S23(120)**	**S24(125)**
	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
Broccoli	0.4±0.04	0.3±0.03	0.4±0.04	-	0.45±0.045	1.45±0.145	1.22±0.122	-
Brussels sprouts	0.55±0.055	0.5±0.05	0.9±0.09	-	0.9±0.09	1.5±0.15	1.4±0.14	-
Cabbage	0.95±0.095	-	-	0.9±0.09	2.52±0.252	1.12±0.112	1.6±0.16	1.8±0.18
Cauliflower	0.6±0.06	1.9±0.19	1.1±0.11	0.45±0.045	1.9±0.19	0.5±0.05	0.90±0.09	1.4±0.14
Grapefruit	0.71±0.071	-	0.5±0.055	1.75±0.175	1.6±0.16	0.45±0.045	0.75±0.75	0.90±0.09
Kale	-	0.3±0.03	-	1.4±0.14	0.50±0.05	-	0.9±0.09	-
Leeks	-	-	0.9±0.09	-	0.75±0.75	0.4±0.04	0.35±0.035	0.75±0.75
Lemons	0.55±0.055	3.5±0.35	0.9±0.09	0.45±0.045	0.35±0.035	0.95±0.095	1.4±0.14	0.9±0.09
Parsnips	0.25±0.025	0.7±0.07	0.3±0.03	0.9±0.09	-	1.1±0.11	0.5±0.05	0.8±0.08
Rutabagas	-	0.6±0.06	-	1.14±0.114	1.8±0.18	1.9±0.19	1.85±0.185	0.6±0.06
Tangelos	0.35±0.035	0.95±0.095	-	0.9±0.09	1.4±0.14	1.8±0.18	0.45±0.045	0.8±0.08
Tangerines	0.85±0.085	0.6±0.06	1.5±0.15	1.6±0.16	0.83±0.083	0.55±0.055	1.35±0.135	1.43±0.143
Turnips	1.65±0.165	0.35±0.035	-	0.50±0.05	1.85±0.185	0.70±0.70	0.83±0.083	1.5±0.15
Beetroot	3.5±0.35	0.5±0.050	0.3±0.03	2.75±0.275	1.4±0.14	0.35±0.035	1.5±0.15	0.95±0.095
Carrots	-	-	-	-	1.35±0.135	1.5±0.15	1.4±0.14	0.85±0.085
Chicory	-	0.6±0.06	0.4±0.04	0.95±0.095	0.75±0.075	-	2.1±0.21	1.5±0.15
Potatoes	4.04±0.404	0.25±0.025	0.45±0.045	1.9±0.19	2.1±0.21	-	1.5±0.15	0.75±0.075
Morel Mushrooms	-	1.85±0.185	1.75±0.175	-	-	-	0.6±0.06	0.5±0.05
Parsnips	0.9±0.09	-	-	0.35±0.035	1.5±0.15	0.75±0.075	1.45±0.145	0.75±0.075
Rhubarb	-	-	-	-	0.5±0.05	1.8±0.18	0.8±0.08	2.15±0.215

Sorrel	0.35±0.035	2.85±0.0285	1.4±0.14	1.5±0.15	-	1.43±0.143	0.9±0.09	1.4±0.14
Spinach	-	-	2.25±0.225	1.35±0.135	-	0.8±0.08	1.5±0.15	1.6±0.16
Spring Greens	0.6±0.06	0.95±0.095	0.35±0.035	1.8±0.18	1.4±0.14	1.75±0.175	0.75±0.075	1.4±0.14
Spring Onions	1.5±0.15	1.6±0.16	0.95±0.095	1.25±0.125	-	1.14±0.114	1.4±0.14	1.35±0.135
Watercress	2.35±0.235	0.45±0.045	-	1.4±0.14	-	1.35±0.135	-	0.9±0.09
Green fenugreek	-	-	0.45±0.045	.8±0.08	1.5±0.15	0.5±0.05	0.55±0.055	0.7±0.07
Pumpkin	1.35±0.135	-	0.9±0.09	1.45±0.145	1.45±0.145	1.4±0.14	-	1.52±0.152
Onion	0.45±0.045	1.25±0.125	1.35±0.135	1.5±0.15	1.5±0.15	1.8±0.18	0.4±0.04	1.45±0.0145
Ladyfinger	0.9±0.09	-	-	-	0.6±0.06	-	-	0.55±0.055
Green coriander	-	-	1.9±0.019	0.9±0.09	-	0.6±0.06	0.8±0.08	0.55±0.055
Radish	-	0.9±0.09	1.5±0.15	0.8±0.08	-	-	-	1.4±0.14
Tomatoes	1.45±0.145	1.6±0.16	1.35±0.135	0.3±0.03	0.9±0.09	1.6±0.16	1.45±0.0145	0.8±0.08
Capsicum	1.6±0.16	1.35±0.135	1.8±0.18	-	0.8±0.08	-	-	0.4±0.04
Bottle Gourd	1.8±0.18	1.7±0.17	1.25±0.125	1.48±0.0148	1.45±0.0145	-	0.55±0.055	1.5±0.15
Pea peel	-	-	-	-	0.8±0.08	2.26±0.226	1.4±0.14	1.41±0.141
Banana	3.25±0.325	1.65±0.165	2.5±0.25	1.25±0.125	1.7±0.17	1.65±0.165	0.9±0.09	1.95±0.195
Apple	2.8±0.28	1.25±0.125	1.45±0.145	1.65±0.165	1.5±0.15	0.65±0.065	0.5±0.05	0.35±0.035
Limes	2.6±0.26	1.45±0.145	2.±0.20	2.75±0.275	1.45±0.145	1.3±0.13	2.55±0.255	1.5±0.15
Pineapple	2.5±0.25	2.75±0.275	0.65±0.065	1.45±0.145	2.5±0.25	1.5±0.15	1.75±0.175	3.05±0.305
Plum	0.65±0.065	0.35±0.035	0.5±0.05	-	0.65±0.065	1.45±0.145	1.15±0.115	1.65±0.165
Pomegranate	0.5±0.05	1.1±0.11	1.25±0.125	1.5±0.15	1.65±0.165	1.75±0.175	1.3±0.13	1.7±0.17
Sugarcane	-	-	-	0.5±0.05	1.3±0.13	1.15±0.115	1.65±0.165	1.3±0.13
Orange	1.65±0.165	2.5±0.25	2.75±0.275	2.5±0.25	1.55±0.155	1.7±0.17	1.5±0.15	2.25±0.225
Papaya	1.25±0.125	2.1±0.21	1.65±0.165	0.65±0.065	1.45±0.145	2.55±0.255	1.45±0.145	1.25±0.125
Carobs	0.35±0.035	-	0.65±0.065	-	0.35±0.035	0.5±0.05	1.5±0.15	1.65±0.165
Kiwi	-	0.5±0.05	-	1.15±0.115	1.5±0.15	0.35±0.035	0.65±0.065	0.5±0.05
Persimmon,	1.45±0.145	-	-	0.35±0.035	-	1.5±0.15	-	0.7±0.07
Pear	0.55±0.055	0.65±0.065	0.5±0.05	-	1.15±0.115	0.5±0.05	1.7±0.17	0.65±0.065
Raspberries.	-	-	-	0.5±0.05	-	-	0.35±0.035	0.5±0.05
Blackberries.	-	0.55±0.055	0.35±0.035	1.3±0.13	0.5±0.05	-	0.7±0.07	0.6±0.06
Grapes	-	-	1.1±0.11	-	0.5±0.05	-	0.5±0.05	0.9±0.09
Tea leaves	3.5±0.35	3.8±0.38	3.4±0.34	4.5±0.45	4.1±0.41	4.33±0.433	4.83±0.483	5.41±0.541
Bread	2.15±0.215	2.25±0.225	2.05±0.205	2.55±0.255	2.95±0.295	3.95±0.395	3.4±0.34	3.42±0.342
Rice	2.5±0.25	2.9±0.29	2.6±0.26	3.3±0.33	3.7±0.37	4.5±0.45	4.22±0.422	3.2±0.32
Mixed waste	5.4±0.54	6.5±0.65	6.2±0.62	5.5±0.55	5.52±0.552	6.72±0.672	6.5±0.65	7.5±0.75

Many cabbage, mango, and cooked mixed waste content were received in S6, S7, and S8 sample sets. Sample sets S9 to S16 were collected between May to August 2020. The smallest sample size was 50 garbage bags, S9, and the largest sample size was 85 garbage bag collections, which belonged to S16.

S1, S2, and S3 were collected in January with sample sizes of 10, 15, and 20 garbage bags. In total, 45 sample sizes, 16.95 kg of RVW, 6.51 kg of FW, and 5.53 kg of MCW were obtained, and the highest waste content among these samples: cabbage, green fenugreek, and tea leaves, as shown in Figure 3.5(a) and Table 3.1(a). Total sample sizes of S4 and S5 in February were 55 garbage bags in which RVW, FW, and MCW were obtained to be 22.71 kg, 3.42 kg, and 2.86 kg, respectively the maximum amount of spinach and pea peel waste was observed in these samples. Similarly, the S6, S7, and S8 have been interpreted in the order of March and April with 35, 40, and 45 sample sizes. The total sample size was 120 garbage bags, and RVW, FW, and MCW were obtained to be 51.28 kg, 22.74 kg, and 17.35 kg, respectively.



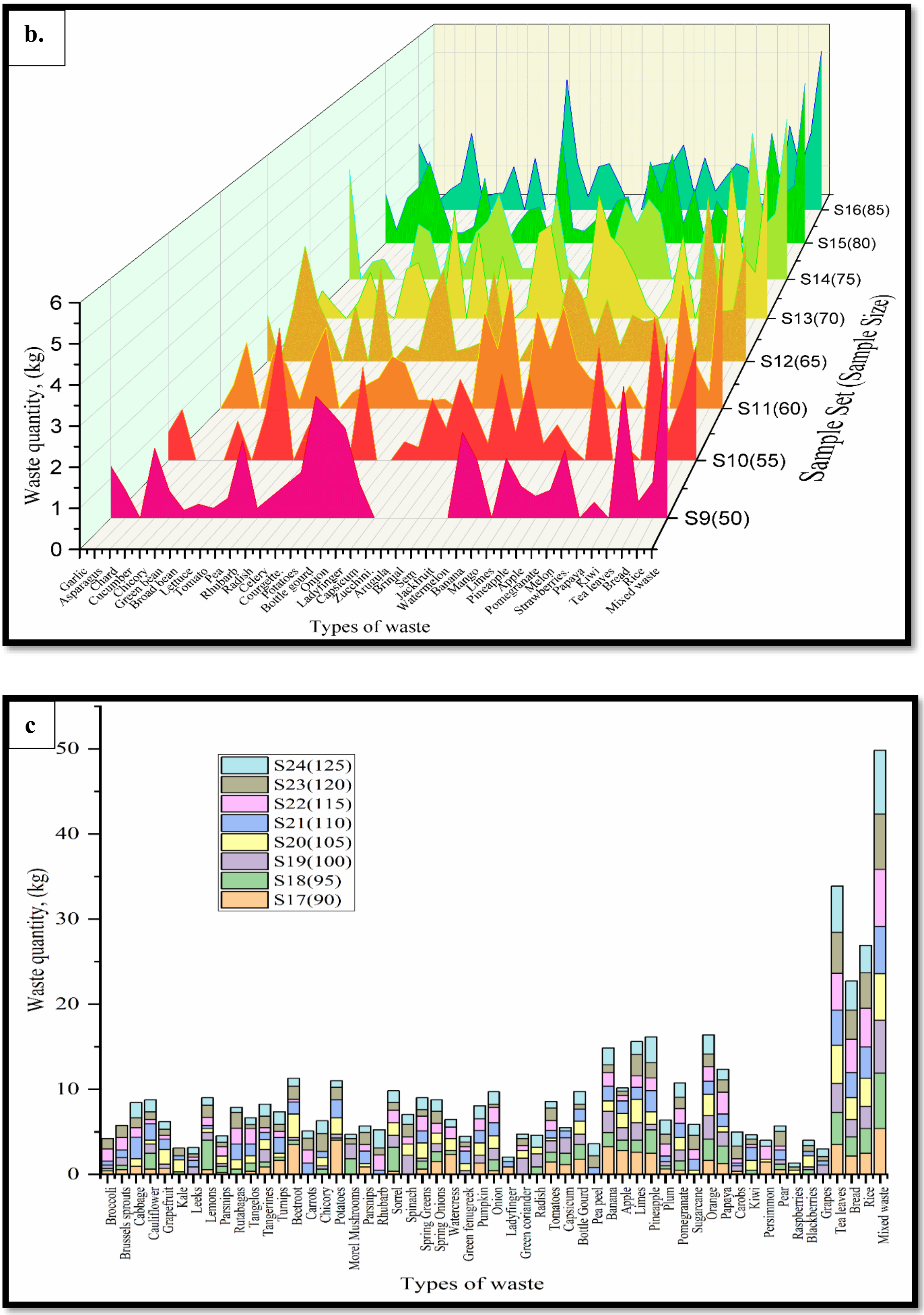


Figure 3.5: Quantity (kg) of different types of household organic waste collected in garbage bags (a) Sample set S1 to S8 (b) S9 to S16 and (c) S17 to S24

Thus, the total sample size in this period was 540 garbage bags containing 186.96 kg of RVW, 94.65 kg of FW, and 90.85 kg of MCW was found. During this time, 39 types of organic waste were found as RVW, FW, and MCW in S9 to S16. Collections of S9 and S10 taken in May, with sample sizes of 50 and 55, respectively, with a total sample size of 105, yielded 40.5 kg of RVW, 19.75 kg of FW, and 18.5 kg of MCW, with the highest number of mixed debris, potato, and tomato waste were found. S11 and S12 were taken in June with sample sizes of 60 and 65. Out of 125 sample sizes, 46.8 kg of RVW, 22.8 kg of FW, and 21.4 kg of MCW were found. Table 3.1(b) and Figure 3.5(b) show that the highest number of mixed debris, tea leaves, watermelon, mango, and cucumber waste were found in these samples. S13 and S14 were reviewed in July, with 145 sample sizes containing 48 kg of RVW, 27.5 kg of FW, and 26.05 kg of MCW, respectively, and the highest amount of waste, mixed waste in these samples, tea leaves, watermelon, and garlic were found.

Similarly, S15 and S16 were reviewed in August, with a total sample size of 165 waste bags containing 51.66 kg of RVW, 24.6 kg of FW, 24.9 kg of MCW, and the most mixed waste, tea leaves, waste of onion, mango, and potato was found. Sample sets S17 to S24 were studied from September 2020 to December 2020, with the smallest sample size being 90 and the largest sample size being 125 garbage bags. The total sample size in this period was 860 waste bags, of which 240.63 kg of RVW, 136.25 kg of FW, and 133.35 kg of MCW were found. During this, 55 types of organic wastes were found in RVW, FW, and MCW. S17 and S18 have 90 and 95 waste bags collected in September, with a total sample size of 185 consisting of 53.2 kg of RVW, 32.4 kg of FW, and 29 kg of MCW. Other mixed scraps, potato, banana, tea leaf, and lemon waste, were highest in these samples, shown in Table 3.1(c) and Figure 3.5(c).

Similarly, S19 and S20 were studied in October, with a total sample size of 205 waste bags containing 55.32 kg of RVW, 30.9 kg of FW, and 30.1 kg of MCW. In which mixed waste, orange, rice, beet, and lime were found to have the highest waste material. Collections S21 and S22 were taken in November with sample sizes of 110 and 115 with a total sample size of 225, yielding 64.3 kg of RVW, 34.3 kg of FW, and 35.77 kg of MCW. Other wastes, including tea leaves, rice, bread, pineapple, and orange, were the highest waste in these samples. S23 and S24 were collected in December with a total sample size of 245 bags containing 67. 81 kg of RVW, 38.65 kg of FW, and 38.48 kg of MCW yielded the highest waste amounts of mixed waste, tea leaves, rice, bread, limes, and oranges.

Table 3.2: Quantities of Raw Vegetable Waste (RVW), Fruit Waste (FW), and Mixed Cooked Waste (MCW) Collected During the Study

Months	Sample set (Sample size)	RVW, kg	FW, kg	MCW, kg
January	S1 (10)	4.55	1.85	1.51
January	S2 (15)	5.85	1.55	1.22
January	S3 (20)	6.55	3.11	2.8
February	S4 (25)	10.51	1.87	1.71
February	S5 (30)	12.2	1.55	1.15
March	S6 (35)	17.4	4.29	3.31
March	S7 (40)	16.34	8.75	6.41
April	S8 (45)	17.54	9.7	7.63
May	S9 (50)	19.3	9.25	9.15
May	S10 (55)	21.2	10.5	9.35
June	S11 (60)	22.5	11.3	10.15
June	S12 (65)	24.3	11.5	11.25
July	S13 (70)	22.65	14.65	12.5
July	S14 (75)	25.35	12.85	13.55
August	S15 (80)	24.75	13.15	12.45
August	S16 (85)	26.91	11.45	12.45
September	S17 (90)	27.65	17.55	13.55
September	S18 (95)	25.55	14.85	15.45
October	S19 (100)	24.85	15.35	14.25
October	S20 (105)	30.47	15.55	15.85
November	S21 (110)	32.85	17.75	16.27
November	S22 (115)	31.45	16.55	19.5
December	S23 (120)	32.55	18.15	18.95
December	S24 (125)	35.26	20.5	19.53

There were mainly three types of waste in each sample, RVW, FW, and MCW. In every model, total vegetable waste from RVW, complete fruit waste from FW, and entire mixed waste from MCW to shown in Table 3.2. Mixed waste means organic waste, which is very difficult to segregate, and all types of cooked waste are placed in the MCW category. Due to the reduced sample size, S1, S2, and S3 were studied in a month, and in April, due to the COVID-19 pandemic, only one sample set could be collected. About two models have been gathered and analyzed in the rest of every month. The outcome of this case study is that the household waste collected in one year was found in all the sample sizes, mainly fruits, raw vegetables, and mixed cooked waste. Organic waste in the form of RVW, FW, and MCW was collected during the study at 518.53 kg, 263.57 kg, and 249.94 kg, respectively.

3.2 Regression analysis

Sample sizes in most of the houses were primarily raw vegetable waste (RVW), fruit waste (FW), and mixed cooked waste (MCW). It means that these three wastes depend on each other. So, the inter-relationship of the three wastes was evaluated by the regression method. First, let's determine the relationship between RVW and FW by the single variable regression method at a 95% confidence level.

Regression line FW on RVW,

$$FW - \overline{FW} = \frac{Cov(RVW,FW)\ (RVW - \overline{RVW})}{\sigma_{RVW}^2} \tag{1}$$

Where $Cov = \ Coefficient\ of\ variation$;

$$Cov(RVW, FW) = \frac{1}{n}\sum RVW \times FW - \overline{RVW \times} \overline{FW}$$

(2)

The standard deviation of RVW (σ_{RVW})

$$\sigma_{RVW} = \sqrt{\frac{1}{n}\sum RVW^2 - (\overline{RVW}\ )^2} \tag{3}$$

Mean of vegetable waste, $\overline{\text{RVW}} = \frac{\sum \text{RVW}}{\text{n}}$; Mean of fruit waste, $\overline{\text{FW}} = \frac{\sum \text{FW}}{\text{n}}$;

Where $\text{n} = \text{no. of observations.}$

Using equations (1), (2), and (3), find out whether Regression line FW on RVW is

$$\text{FW} = 0.6375\text{RVW} - 2.792 \tag{4}$$

The standard error for FW (FW*)

$$\text{FW*} = \sqrt{\frac{\sum(FW - \widehat{FW})^2}{n-2}}\ , \tag{5}$$

Coefficient of determination (R^2) for FW-

$$R^2 = \frac{\sum(\widehat{FW} - \overline{FW})^2}{\sum(FW - \overline{FW})^2}\ , \tag{6}$$

Where FW is the actual value, $\widehat{\text{FW}}$ is an estimated value, and $\overline{\text{FW}}$ is the mean value.

Regression line RVW on FW

$$RVW - \overline{RVW} = \frac{Cov(RVW,FW)\ (FW-\overline{FW})}{\sigma_{FW}^2} \tag{7}$$

The standard deviation of FW (σ_{FW})

$$\sigma_{FW} = \sqrt{\frac{1}{n}\sum FW^2 - (\overline{FW}\,)^2} \tag{8}$$

Using equations (2), (7), and (8), find out the Regression line RVW on FW is

$$\mathrm{RVW} = 1.4159\mathrm{FW} + 6.0559 \tag{9}$$

The standard error for RVW (RVW*)

$$\mathrm{RVW}^* = \sqrt{\frac{\sum(RVW - \widehat{RVW})^2}{n-2}}, \tag{10}$$

Coefficient of determination (R^2) for RVW-

$$R^2 = \frac{\sum(\widehat{RVW} - \overline{RVW}\,)^2}{\sum(RVW - \overline{RVW}\,)^2} \tag{11}$$

Where $\widehat{\mathrm{RVW}}$ is an estimated value, RVW is the actual value, and $\overline{\mathrm{RVW}}$ is the mean value.

Similarly, the regression method has calculated the waste (RVW, MCW) and (FW, MCW) seen in Table 3.3).

3.3. Results of regression analysis

Households across the board incorporate vegetables, cooked dishes, and fruits into their daily meals, resulting in waste of this nature being prevalent in virtually every household sample. This indicates that when a family consumes fewer vegetables and cooked food, there is an uptick in the consumption of fruits and other food items. Consequently, this leads to an increase in the volume of fruit and mixed waste. Conversely, if a family consumes fewer fruits and opts for more vegetables and other food items, the quantity of vegetables and mixed waste escalates. Mixed waste refers to refuse that cannot be effectively sorted or separated. This category encompasses various organic waste types, including cooked rice, bread, used tea, cooked vegetables, and lentils, all belonging to distinct waste categories. Consequently, household-generated waste categories such as RVW (Raw Vegetable Waste), FW (Fruit Waste), and MCW (Mixed Category Waste) experience fluctuations in their daily production, contingent on consumption patterns.

Through regression analysis, specifically examining the relationships between RVW and FW, RVW and MCW, and FW and MCW, insights into the interplay between these waste categories were garnered. A comprehensive summary of the analytical findings is presented in Table 3.3, shedding light on the intricate dynamics of daily RVW, FW, and MCW waste generation within households. This analysis underscores the critical influence of consumption patterns on waste production, illuminating potential avenues for more effective waste management strategies.

Table 3.3: The result summary output of the regression statistics

(a) Relation between RVW and FW waste	**SUMMARY OUTPUT**									
	Regression statistics						**Coefficients**	**Standard Error**	**t Stat**	**P-value**
When FW on RVW, FW = 0.6375RVW-2.792	**Multiple R**	**R Square**	**Adjusted R Square**	**Standard Error**	**Observations**	**Intercept**	-2.7920	1.0378	2.6901	0.0133
	0.95	0.9026	0.8982	1.8811	24	(RVW)	0.6375	0.0446	14.285	1.31E-12
When RVW on FW, RVW=1.4159FW+6.059	0.95	0.9026	0.8982	2.8035	24	Intercept	6.0558	1.2297	4.9243	6.33E-05
						(FW)	1.4159	0.0991	14.285	1.31E-12
(b) Relation between RVW and MCW waste	**SUMMARY OUTPUT**									
	Regression statistics						**Coefficients**	**Standard Error**	**t Stat**	**P-value**
When RVW on MCW, RVW=1.3955MCW +7.722	**Multiple R**	**R Square**	**Adjusted R Square**	**Standard Error**	**Observations**	**Intercept**	7.0722	1.0772	6.5650	1.32E-06
	0.9571	0.9161	0.9123	2.6018	24	(MCW)	1.3955	0.0899	15.5066	2.51E-13
When MCW on RVW, MCW = 0.6565RVW - 3.77	0.9571	0.9161	0.9123	1.7845	24	Intercept	-3.77	0.9845	-3.8290	0.00091
						(RVW)	0.6565	0.0423	15.5066	2.51E-13
(c) Relation between FW and MCW waste	**SUMMARY OUTPUT**									
	Regression statistics						**Coefficients**	**Standard Error**	**t Stat**	**P-value**
When FW on MCW, FW=0.9529MCW+ 1.0587	**Multiple R**	**R Square**	**Adjusted R Square**	**Standard Error**	**Observations**	**Intercept**	1.0587	0.5657	1.8712	0.0746
	0.9739	0.9486	0.9463	1.3665	24	(MCW)	0.9528	0.0472	20.1594	1.13E-15
When MCW on FW, MCW=0.9956FW-0.5139	0.9739	0.9486	0.9463	1.3968	24	Intercept	0.5192	0.6127	0.8474	0.4058
						(FW)	0.9955	0.0493	20.1594	1.13E-15

3.3.1 Raw vegetable waste (RVW) and Fruit waste (FW)

The given statement discusses the statistical analysis of a dataset comprising 24 sample sets. The investigation uses regression models, where one dependent variable is predicted based on the other independent variable. There are 24 sets of samples in the dataset, and all calculations are done with a 95% confidence level. Two regression models have been developed - one for predicting fruit waste (FW) based on raw vegetable waste (RVW) and the other for predicting RVW based on FW. The regression equation for the FW on the RVW model is FW = 0.6375RVW-2.792.

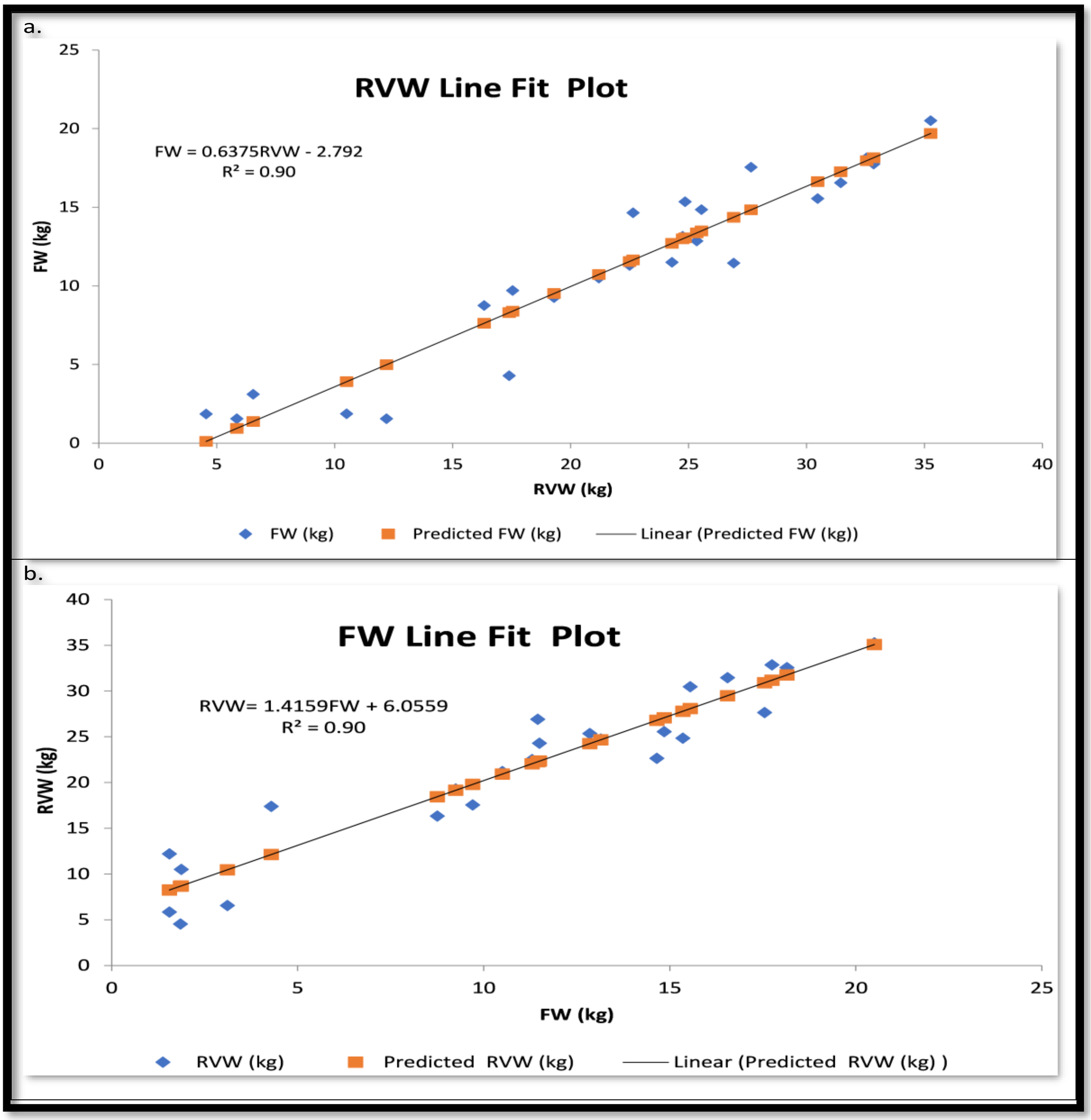


Figure 3.6: Graphical representation of the linear regression line (a) when FW on RVW (b) RVW on FW

The coefficient of determination (R^2), which measures how well the regression line fits the data, is approximately 0.9026, indicating that the model is about 90% accurate. The standard error, which measures the variability of the data around the regression line, is 1.8811. The p-value, which measures the statistical significance of the model, is approximately 1.31E-12. The p-value is much lower than the significance level of $\alpha=0.05$, which indicates that the model is highly significant. Similarly, the regression equation for the RVW on the FW model is RVW=1.4159FW+6.0559. The coefficient of determination (R^2) is 0.90, indicating that the model is highly accurate. The standard error is 2.8035, and the p-value is approximately 1.31E-12, indicating the model's high significance. In both models, predicted values of the dependent variable are shown on a straight line at different values of the independent variable, with the actual values of the dependent variable shown around the line.

3.3.2 Raw vegetable waste (RVW) and Mixed cooked waste (MCW)

The provided information offers a comprehensive statistical analysis of the intricate relationship between two key variables: raw vegetable waste (RVW) and mixed cooked waste (MCW). This examination commenced with applying regression analysis, which yielded two distinct regression lines, unveiling the mathematical connections between these waste categories. The first regression line is RVW = 1.3955MCW + 7.0722, while the second is MCW = 0.6565RVW - 3.77. These equations provide a structured understanding of how changes in one variable influence the other.

The analysis also included calculating key statistical indicators, including the coefficients of determination (R^2), standard errors, and p-values, which are crucial in assessing the reliability and significance of the regression lines. Both regression lines boasted remarkable R^2 values of 0.9161, signifying their capacity to elucidate approximately 91% of the variance observed in RVW and MCW. This high R^2 value highlights the robustness of the linear relationship between these variables. Furthermore, standard errors of 2.6018 for RVW and 1.7845 for MCW were calculated, providing insights into the accuracy and precision of the regression lines. The low standard errors suggest that these lines are reliable in explaining the variation in RVW and MCW. The significance of the regression lines was also scrutinized through the computation of p-values, which were notably small at 2.51E-

13. These values are far below the conventional significance level (α = 0.05), underscoring the high significance of both regression lines.

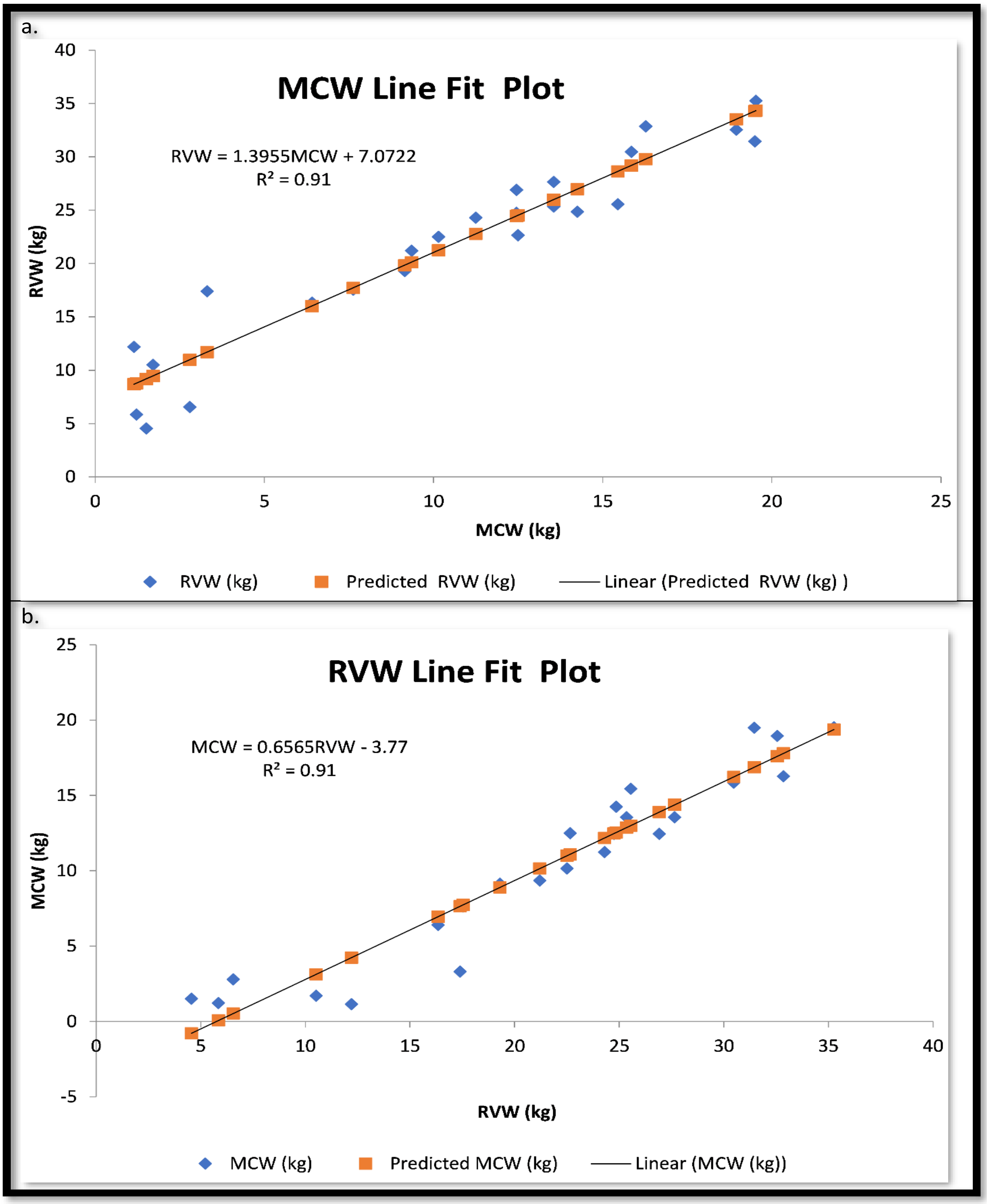


Figure 3.7: Graphical representation of the linear regression line (a) RVW on MCW (b) MCW on RVW

This implies that the observed relationship between RVW and MCW is not likely due to random chance but is a genuine and robust association. In Figure 3.7(a), the linear RVW line is traced across different MCW values, with the actual RVW values depicted around this line. Similarly, Figure 3.7(b) illustrates the linear MCW line across varying RVW values, with the actual MCW values surrounding this line. This meticulous statistical analysis collectively serves to underscore a strong, positive, and linear connection between RVW and MCW, backed by the high R^2 values and the exceedingly significant p-values. The regression lines and accompanying figures visually represent this substantial relationship, facilitating a clearer understanding of the waste dynamics under consideration.

3.3.3 Fruit waste (FW) and Mixed cooked waste (MCW)

This analysis centers around the relationship between fruit waste (FW) and mixed cooked waste (MCW), represented by two distinct regression models. The first regression model, FW=0.9529MCW+1.0587, signifies the connection between fruit waste and mixed cooked waste when the amount of fruit waste generated depends on the quantity of mixed cooked waste. Conversely, the second model, MCW=0.9956FW-0.5139, depicts the relationship when the generation of mixed cooked waste hinges on the amount of fruit waste. Table 3.3(c) serves as a crucial reference point for evaluating the accuracy and significance of these regression models.

The reported R^2, standard error, and p-value values for both models are particularly noteworthy. An R^2 value of 0.9486 indicates that these regression models can explain approximately 94.86% of the variance in fruit and mixed cooked waste. This high R^2 value underlines the models' effectiveness in capturing the relationship between FW and MCW. The standard error, measuring the average deviation of actual data points from the regression line, is reported as 1.3665. This suggests a relatively small degree of variability from the predicted values, indicating the models' accuracy in estimating waste quantities. The p-value, a crucial indicator of the statistical significance of the models, is exceptionally low at 1.13E-15.

This value, far below the common significance threshold of 0.05, confirms the high significance level in both conditions. It signifies that the observed relationships between FW and MCW are not due to random chance but are robust and reliable associations. Figure 3.8(a) displays the linear FW waste line against varying MCW values, showcasing how the actual FW values align around this line. Similarly, Figure 3.8(b) exhibits the linear MCW line against different FW values, illustrating how the actual MCW values cluster around this line.

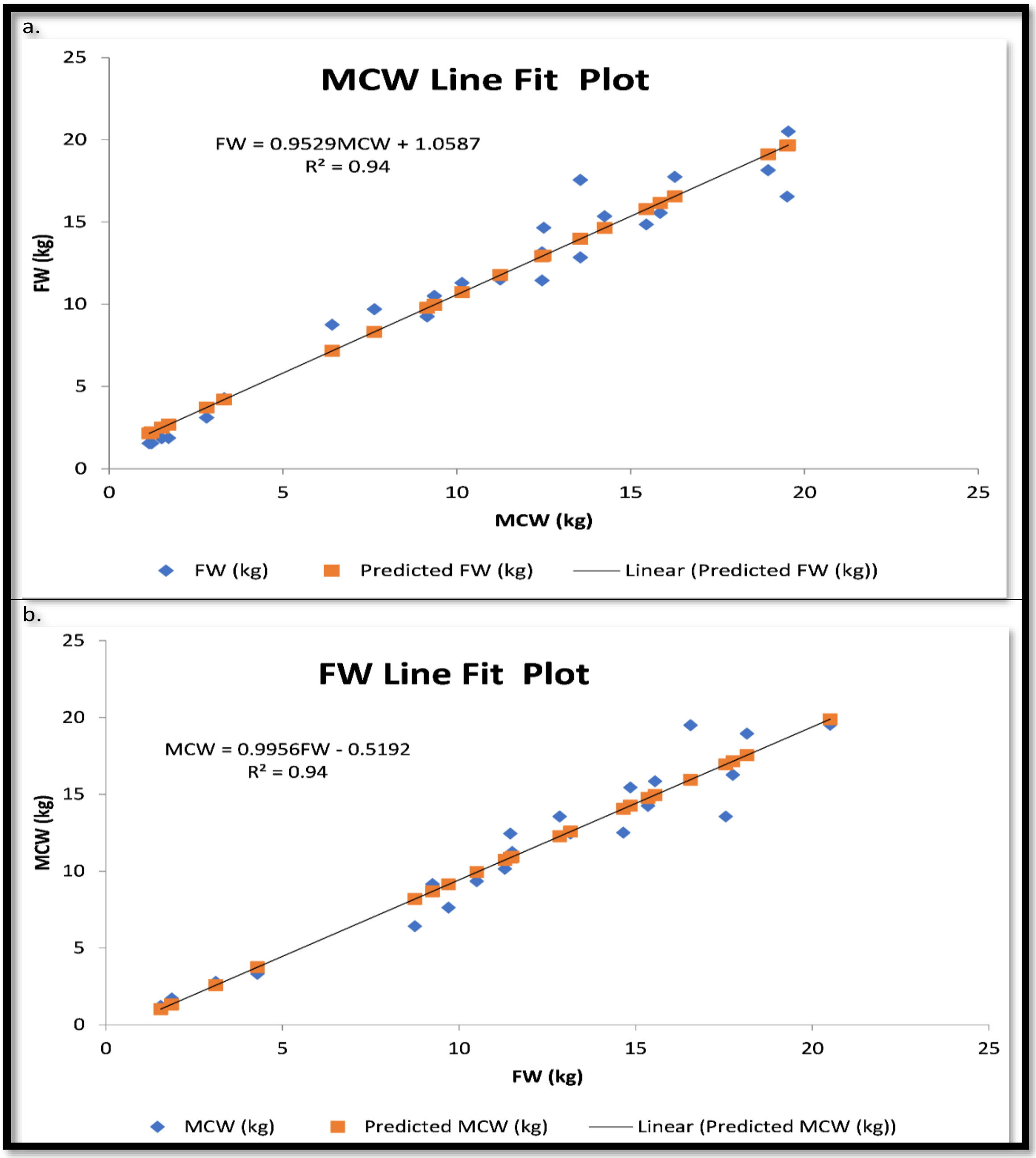


Figure 3.8: Graphical representation of the linear regression line (a) FW on MCW (b) MCW on FW

In conclusion, the regression model derived from the (FW, MCW) waste relationship is particularly significant due to its notably high R^2 value. This indicates that it provides the most accurate and reliable representation of the connection between fruit waste and mixed cooked waste.

3.4 Discussions

The study provides valuable insights into household waste composition, emphasizing the ubiquitous presence of vegetable, cooked food, and fruit waste in collected samples. It highlights an interesting trend where shifts in dietary habits directly influence waste generation patterns. Specifically, when one category of food is consumed less, there is a compensatory increase in the consumption of other food items, leading to variations in waste composition. This dynamic interplay underscores the importance of tailored waste management strategies that account for these fluctuations. The findings align with previous research, reinforcing the understanding that waste generation is intricately linked with dietary practices. The application of regression models has allowed for a quantitative understanding of these relationships. The models exhibit high accuracy, with coefficients of determination (R^2) ranging from 0.90 to 0.94, indicating a strong fit of the regression line to the data. The low p-values further affirm the statistical significance of the models.

Comparatively, the study's results are consistent with findings from other case studies. For instance, the research from the University of Benin Ugbowo campus illustrates a similar trend of significant organic waste production, leading to the generation of biogas and compost [205]. Likewise, the East Coast of Malaysia study emphasizes the importance of waste segregation practices among households, indicating a shared concern for effective waste management strategies [206]. Furthermore, the case study from Algiers City in Algeria highlights the influence of settlement size and waste management company characteristics on waste management practices, reinforcing the notion that contextual factors play a pivotal role in waste management efficiency [207].

The study's results align with previous research, providing valuable quantitative insights into the relationship between dietary habits and household waste composition. The high accuracy of the regression models underscores their utility in understanding and predicting waste generation patterns. These findings contribute to the broader discourse on effective waste management practices and highlight the need for context-specific strategies to address the complex dynamics of waste generation.

3.5 Conclusions

- The present study evaluates each collected sample set and the amount of RVW, FW, and MCW generated from 73 types of household waste on the DTU campus. Sample S1 to S24 sample sets with a total of 1620 sample sizes were collected throughout the study. A total of 518.53 kg RVW, 263.57 kg FW, and 249.94 kg of MCW were accumulated and segregated into digestive and compost wastes.
- The coefficient of determination (R^2) of these (RVW, FW), (RVW, MCW), and (FW, MCW) were observed to be 0.90, 0.91, and 0.94 with $p < 0.05$, and the standard error value lies between 1.3665 and 2.8035.

CHAPTER 4

EXPERIMENTAL INVESTIGATION ON BIOGAS PRODUCTION

The experiment aimed to investigate the effect of different factors on the anaerobic digestion process using ADs with a total capacity of 10 liters. The factors analyzed included other waste materials and proportions, temperature conditions, and the tumbling effect. The Taguchi method was used to design the experiment data, allowing for the simultaneous testing of multiple variables with fewer experiments. The experiment's results could provide valuable information on optimizing the anaerobic digestion process for the efficient production of biogas.

4.1 Equipment used during the experimental process

During the experiment process, various types of equipment are commonly used to gather data, conduct measurements, and analyze results. The choice of equipment depends on the nature of the experiment and the specific measurements or observations required.

4.1.1 Biogas digester

A biogas digester is a cylindrical container vital in anaerobic digestion, which involves decomposing organic materials without oxygen. This particular biogas digester has a height and diameter of 381 mm, providing a total capacity of 10 liters. It uses a mild steel (MS) sheet coated with a black surface. The black coating serves the vital purpose of maximizing heat absorption from the heating elements. The construction of this anaerobic digester is simple yet effective. It consists of thin MS sheets molded into a cylindrical shape, forming the walls of the digester. One end of the cylinder is fitted with a lid that can be sealed or opened to allow the addition of feedstock. An outlet valve is installed at the top of the cylinder to extract the biogas produced during digestion.

A thermocouple is installed inside the digester to monitor the temperature of the biogas creation process. The thermocouple acts as a sensor, measuring the temperature variations within the digester. This temperature information is displayed on a unit outside the digester, enabling the operator to observe and control the temperature range necessary for efficient anaerobic digestion. The mild steel (MS) sheet used in constructing the digester is specially coated with paint that enhances heat retention. This paint traps heat from the sun, facilitating the fermentation and conversion of organic waste inside the digester into biogas. Maintaining higher temperatures optimizes the digestion process, leading to increased biogas production.

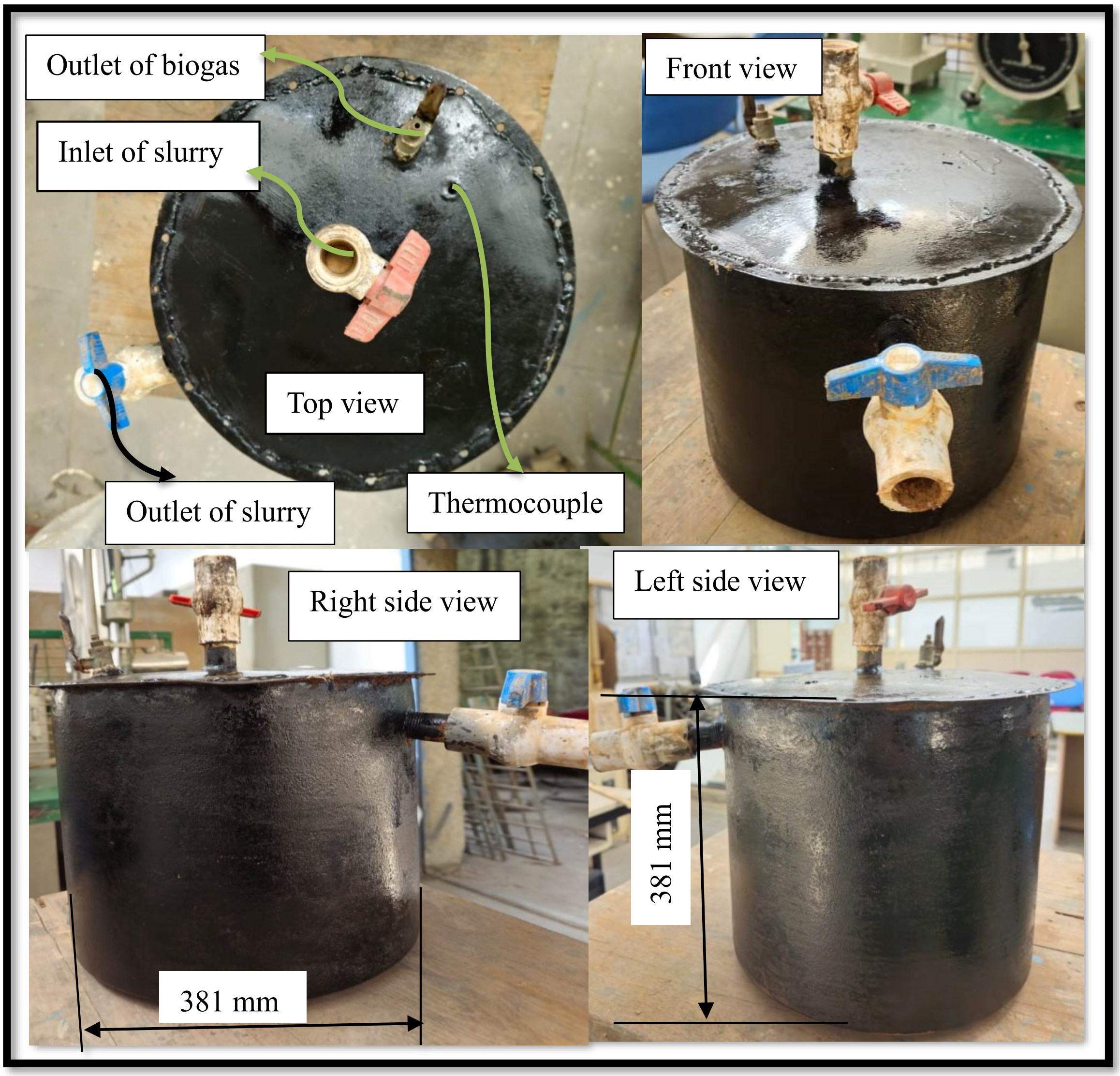


Figure 4. 1: Different view of biogas digester

The feedstock capacity of this anaerobic biogas digester is 7.5 liters. This means it can accommodate up to 7.5 liters of organic waste, sufficient to generate a decent amount of biogas daily. The feedstock, consisting of organic materials such as mixed cooked, vegetable, and fruit waste, undergoes the anaerobic digestion process inside the digester, producing biogas.

4.1.2 Heating container

The heating container is crucial in facilitating the anaerobic digestion process within a biogas digester. Designed to withstand the corrosive nature of the biogas produced during digestion, the container provides a controlled environment for the efficient decomposition of organic materials. A heating element is employed to supply heat to the biogas digester, which is connected to a power source and primarily heats the water. In this setup, three heating containers are utilized, and each container is constructed from stainless steel, measuring 1220 x 762 mm in size. The biogas digesters are placed inside these three containers, each accommodating three biogas digesters, resulting in nine digesters. The containers are designed to hold the digesters while ensuring efficient heat transfer securely.

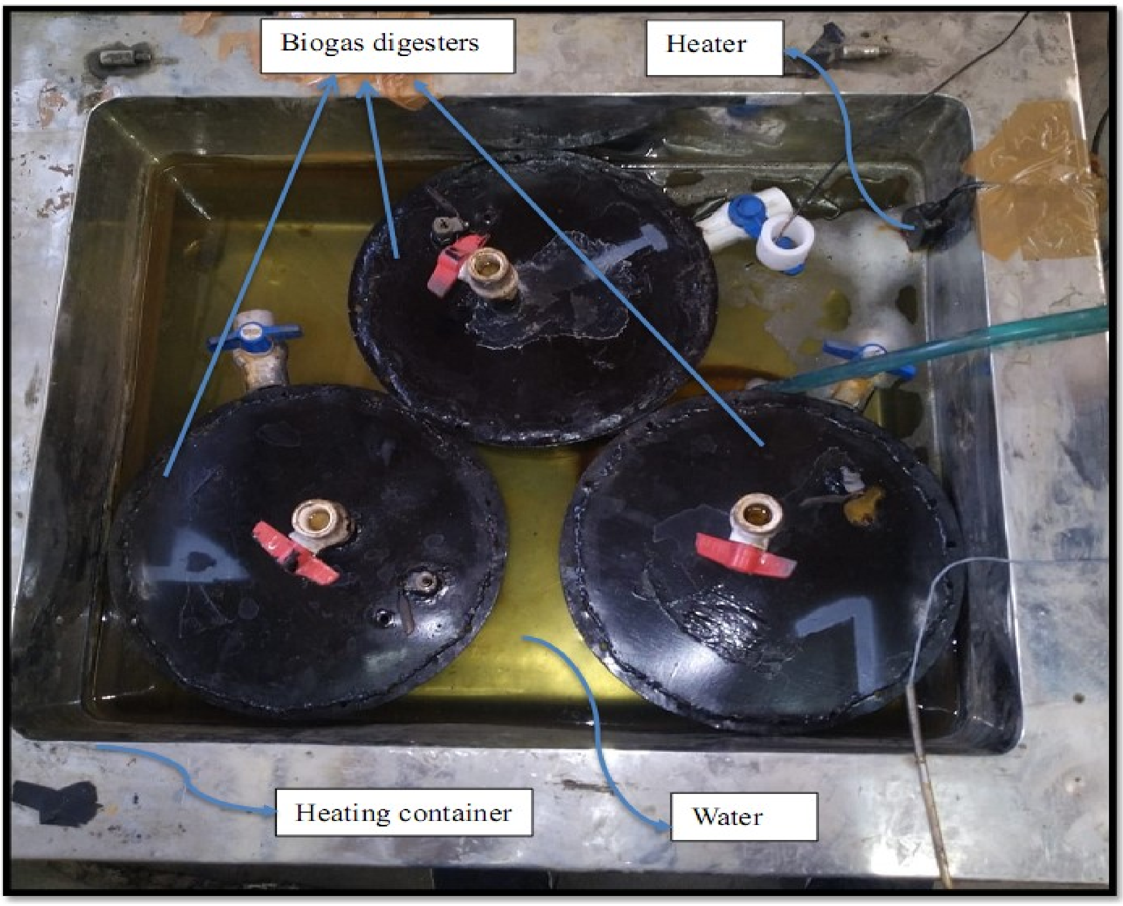


Figure 4.2: Biogas digesters and heating container

Water is the medium through which heat is transferred to the biogas digesters. The containers are filled with water, and the heating element heats this water. The heated water is circulated within the containers and transferred to the biogas digesters through convection. This heat, in turn, encourages the microorganisms responsible for anaerobic digestion to break down the organic material more effectively, leading to a higher biogas yield. Using three containers offers several advantages.

Firstly, it allows for efficient utilization of space and resources. The heating process can be more easily controlled and monitored by grouping the biogas digesters in containers. It ensures that the heat is evenly distributed among the digesters, promoting consistent and optimal digestion conditions. Moreover, using water as a heat transfer medium is highly effective and efficient. Water has excellent thermal properties and can efficiently carry and distribute heat. It also provides a scalable solution, as the heating system can be adjusted based on the size and requirements of the biogas digester. Using water as a heat transfer medium ensures that the digesters receive the heat for optimal performance. Combining a heating element, water, and containers for the biogas digesters constitutes a simple yet effective method for generating biogas.

The heating process enhances the efficiency of the anaerobic digestion process, resulting in a higher biogas yield. Using containers further improves the process's efficiency by facilitating heat distribution and control. This setup is particularly advantageous for generating renewable energy from organic waste materials, as it optimizes biogas production while utilizing space and resources efficiently. By harnessing the power of anaerobic digestion and employing effective heating techniques, the heating container system provides a sustainable solution for converting organic waste into valuable biogas.

4.1.3 Temperature control unit

The anaerobic digester is a vessel in which the digestion process occurs, and the temperature inside the digester is an essential parameter that needs to be carefully controlled. A temperature control unit (TCU) maintains the proper temperature inside the digester. The TCU consists of a thermocouple, which senses the temperature inside the digester, and a heater, which provides heat to the digester. The heater is controlled by a feedback loop that uses the temperature measured by the thermocouple to adjust the amount of heat supplied to the digester. It can sense the temperature of each anaerobic digester by installing a separate thermocouple in each one. This allows the TCU to maintain a different temperature in each digester, depending on the specific requirements of the feedstock and microorganisms involved. It can adjust the constant temperature of the digesters to ensure optimal digestion conditions.

Figure 4.3: Temperature control unit

The TCU also has an auto-cut heating power supply by heaters. This feature ensures that the heaters are turned off in case of a power failure or other malfunction. This prevents overheating of the digester, which can be dangerous and damage the equipment. The auto-cut heating power supply is typically implemented using a relay or a circuit breaker triggered by a power loss or a system fault. The TCU is a critical component of anaerobic digesters, ensuring the proper temperature is maintained inside the digester. The TCU can be programmed to adjust the temperature based on the specific requirements of each digester, and the auto-cut heating power supply feature ensures that the equipment is protected from overheating.

4.1.4 Tumbling setup

The tumbling effect involves the rotation of the digester at a specific speed to create a tumbling action that ensures that the organic materials are well-mixed. This can be achieved using different types of equipment, but in this case, a specially designed tumbling set is used. For small-scale biogas production, a tumbling set with a capacity of 10 liters is sufficient. This set is connected with a belt and tilted at a 30–45-degree angle in a horizontal position.

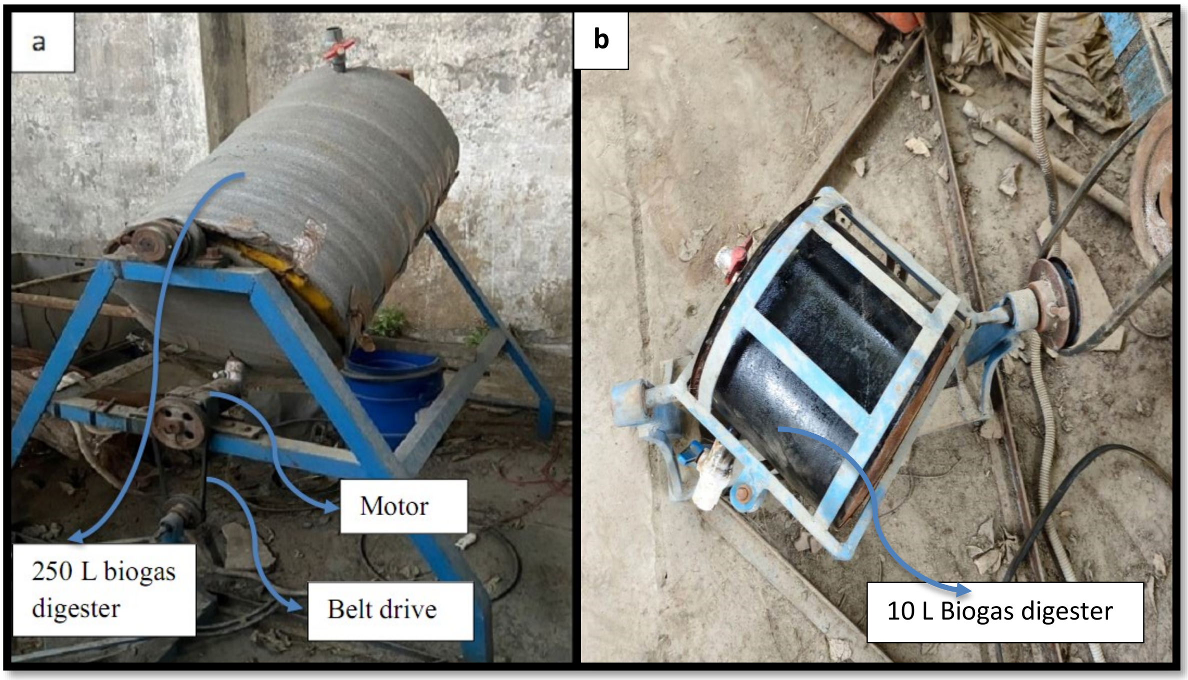


Figure 4.4: Tumbling setup for (a) Larger digester (250 L) (b) Smaller digester (10 L)

The belt helps to rotate the tumbling set at a speed of 15 rpm, creating a tumbling effect that mixes the organic materials. The tilt angle ensures that the organic materials are well mixed and do not settle at the bottom of the digester. The tumbling time for this set is typically 10 to 20 minutes after the feedstock has been added. For larger-scale biogas production, a more extensive tumbling set is required. This set is horizontally tilted at a 30–45-degree angle and connected with a belt, and it is rotated using a motor. The motor rotates the tumbling set at a speed that ensures the organic materials are well mixed but not too fast to cause any damage to the equipment.

The tumbling time for this set is typically longer than the small-scale set due to the larger volume of organic matter that needs to be mixed. It is essential for biogas production because it ensures that the organic materials are well mixed, which is necessary for the breakdown of the organic matter and biogas production. When the organic matter is not well varied, some areas of the digester may become anaerobic, forming dead zones. These dead zones can cause the production of toxic gases, which can be harmful to the environment and the biogas production process. The tumbling effect also helps to break down any large clumps of organic matter, making it easier for the bacteria to access the material and break it down into biogas. The tumbling action also helps to ensure that the bacteria are distributed evenly throughout the digester, which is essential for the efficient breakdown of the organic matter.

4.1.5 Biogas balloon

One way to store biogas for later use is by using a biogas balloon. These balloons come in various sizes, ranging from 0.005 to 5 cubic meters. The smaller sizes are typically used for household cooking, while the larger sizes are commonly used for heating and electricity generation in commercial and industrial settings.

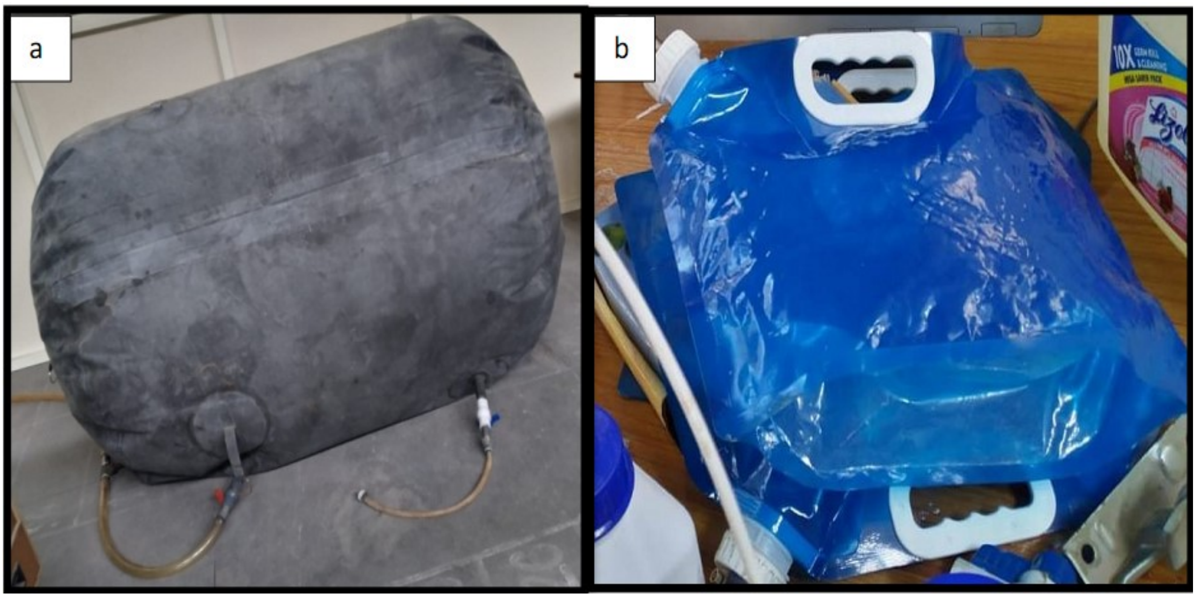


Figure 4.5: (a) Larger biogas balloon (5000 L) (b) Smaller biogas balloon (5 L)

It is made of a durable, airtight material such as polyvinyl chloride (PVC) and is designed to hold the biogas produced by anaerobic digestion. As the biogas is generated, it is transferred into the balloon, which is stored until needed. It is a cost-effective and environmentally friendly way to store biogas. Unlike traditional storage methods, which use expensive tanks or require pipelines, the biogas balloon can be easily installed and moved, making it a versatile option for small-scale biogas systems.

In addition to its versatility and cost-effectiveness, the biogas balloon has several other advantages. For example, because it is airtight, it helps prevent the release of greenhouse gases such as methane, which can significantly impact the environment. It also helps to reduce odors associated with the decomposition of organic material, making it a more pleasant and sanitary option. Another advantage of the biogas balloon is that it can be used in developing countries with limited access to traditional fuel sources. By harnessing the power of biogas, these communities can reduce their reliance on expensive and polluting conventional fuels such as kerosene, wood, and charcoal. The biogas balloon is an innovative and effective way to store biogas.

4.1.6 Biogas analyzer

The Biogas 5000 is a state-of-the-art biogas analyzer designed to provide accurate and reliable measurement of the composition and quality of biogas in different applications. It is a portable gas analyzer that can monitor biogas from various sources, including agricultural and municipal waste, landfills, and wastewater treatment plants. This versatile and easy-to-use analyzer provides critical data for process control, monitoring emissions, and regulatory requirements compliance. It is a handheld device that is compact and lightweight, making it easy to transport and use in the field. It features a clear and intuitive interface that allows the user to quickly and easily perform a wide range of measurements on biogas samples.

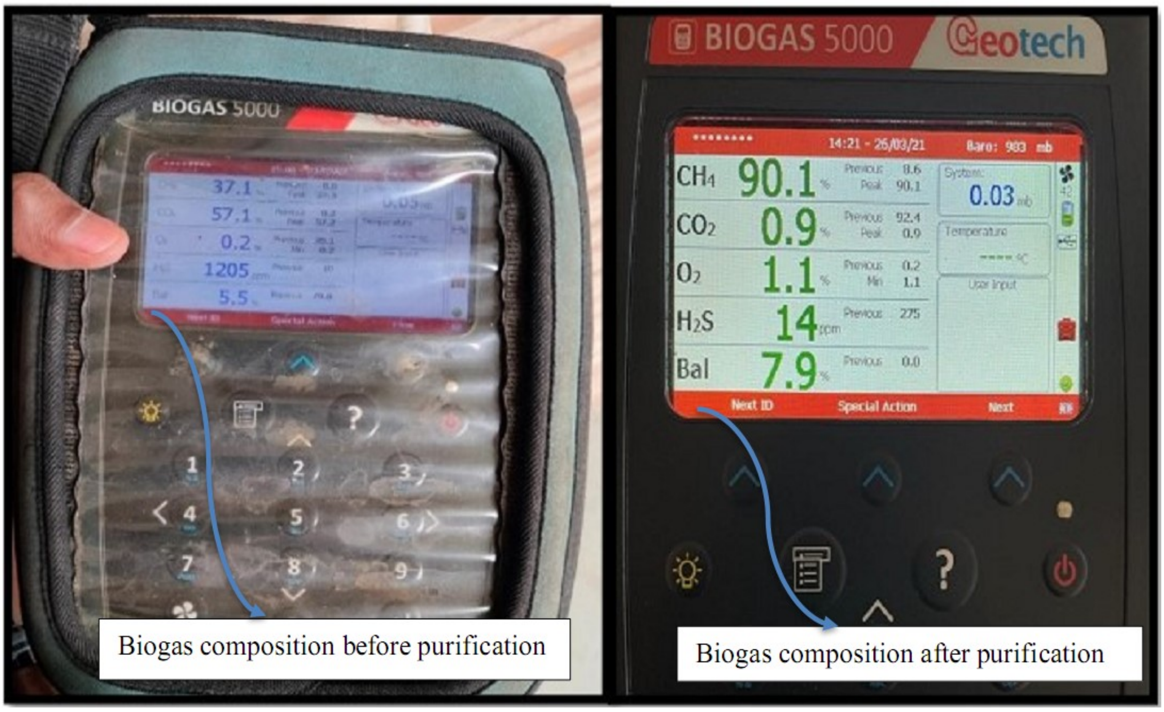


Figure 4.6: Portable biogas 5000 analyzer

The analyzer has various sensors, including a combustible gas sensor, an oxygen sensor, and a hydrogen sulfide sensor, which comprehensively analyzes the biogas composition. One of the key features of the Biogas 5000 analyzer is its ability to measure the methane content of biogas accurately. Methane is the primary constituent of biogas, and its concentration is a critical parameter determining biogas' quality and energy potential. The analyzer has an accuracy of +/- 0.5% for methane (CH_4) measurements in the range of 0-100% and +/- 0.2% for carbon dioxide (CO_2) measurements in the range of 0-100%. These specifications are based on a calibration using standard gases and operating conditions.

The analyzer uses a unique thermal conductivity sensor to measure the methane concentration and provides a real-time data display. This feature is essential for biogas production and utilization, allowing users to optimize the process and maximize energy efficiency. It is also designed to accurately measure other key parameters of biogas, including carbon dioxide, hydrogen sulfide, and oxygen. These parameters are essential for process control, monitoring emissions, and regulatory requirements compliance. The analyzer provides a comprehensive analysis of the biogas composition, which allows the user to detect any changes in the gas quality and adjust the process parameters accordingly. Another essential feature of the analyzer is its ability to store and download data. The analyzer has internal memory that can hold up to 500 readings and a USB port for data download to a computer or other device. This feature makes it easy to track the biogas production process's performance and generate reports for compliance with regulatory requirements.

4.1.7 Biogas compressor

Biogas compression is compressing the biogas to increase its pressure and density. Compressing biogas is an essential part of the biogas generation process as it enhances the efficiency and efficacy of the biogas system. The biogas compressor plays a vital role in biogas generation systems as it helps to compress the biogas from ambient pressure to the desired pressure for various applications. The desired pressure for a biogas system depends on the specific application. Generally, the pressure requirements can range from as low as 10-12 bars to as high as 200 bars. A lower pressure requirement can be suitable for small-scale biogas systems, whereas a higher one is ideal for large-scale industrial purposes. A

Compression of 10-12 bars would suffice for domestic use of biogas, where the pressure requirement is relatively low.

However, the pressure requirement would be higher if the biogas is used for industrial power generation. In such a case, a compression of up to 200 bar would be necessary to produce the desired power output. The biogas compression process involves different stages for achieving the desired pressure level. The compression process starts with the entrance of biogas into the compressor.

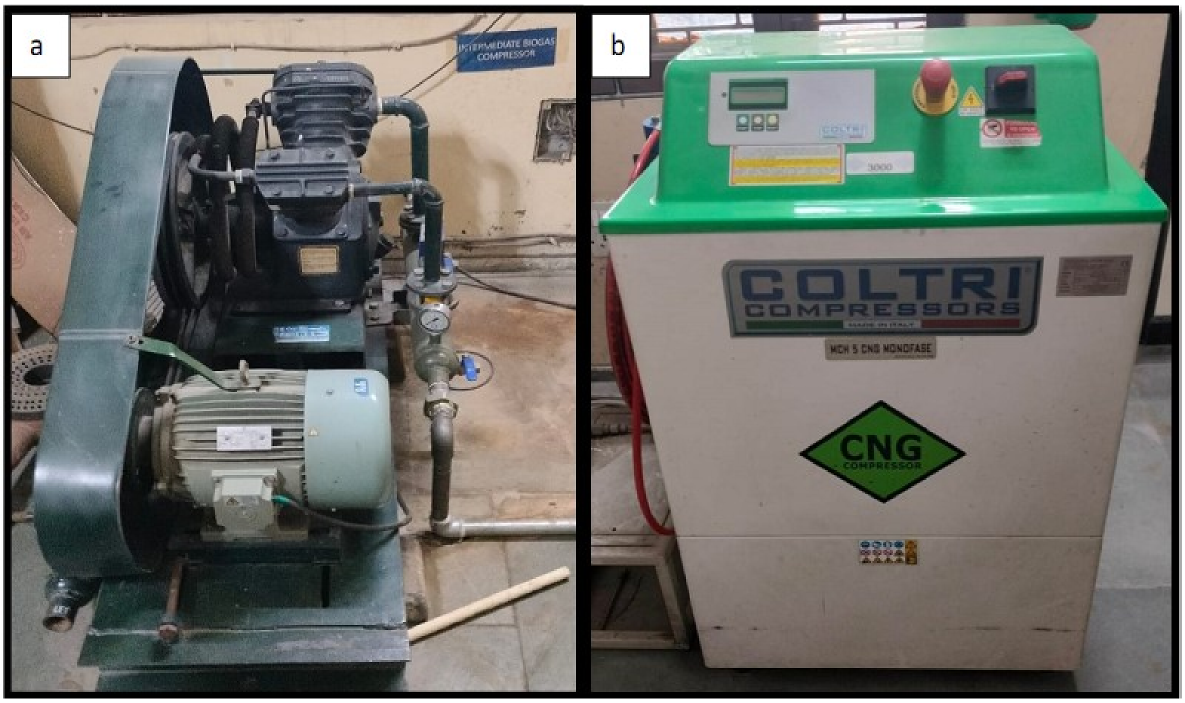


Figure 4.7: Biogas compressor (a) low compressor up to 10-12 bar (b) high compressor up to 200-250 bars

The compressor then compresses the biogas with the help of mechanical or electrical energy, which results in increased pressure and reduced biogas volume. These components include the compressor frame, valves, cylinder, crankshaft, and cooling system. The compressor's bracket provides a structure to hold the details together, and the valves direct biogas flow in and out of the cylinder. The cylinder is the central component of the compressor and is responsible for compressing the biogas. The crankshaft conveys mechanical energy to the cylinder, and the cooling system cools the compressed biogas and helps prevent overheating.

4.2 Experimental setup

The experimental setup described involves the fabrication and operation of small anaerobic digesters (ADs) made from mild steel sheets. These ADs have specific features, including a waste feed inlet, a biogas outlet, and a thermocouple mounted on the top surface. Nine such ADs were created, all with a volume of 10 liters. The process begins with preparing a slurry sample weighing 7.5 kg, consisting of 3.75 kg of cow dung and 3.75 liters of water. This slurry mixture is then poured into the biogas digester. Subsequently, increments of 0.75 kg of three different types of waste—FW (Fruit Waste), RVW (Raw Vegetable Waste), and MCW (Mixed Cooked Waste)—are added to the digester along with feed water after the methanogenic bacteria have formed.

The experimental design follows Taguchi analysis principles, with three biogas digesters placed in each container, totaling nine ADs distributed across three containers. Water is added to each container until it reaches the height of the digester. A heater is used to warm the water in the container, providing the necessary heat for the AD. An auto-cut system is employed through a temperature control panel to regulate the temperature inside the biogas digester. The digester's surface is coated in black to efficiently absorb heat from the surrounding water in the container while preventing rusting.

A feed waste inlet on the top surface of the biogas digester allows for periodic replenishing of the feed every five days. An outlet on the side surface ensures that as much feed waste is added as is removed during the top-up process. A thermocouple is installed on the surface to monitor the digester's temperature. A biogas balloon is also connected to the biogas inlet valve, allowing for the storage of generated biogas. The composition of the biogas is periodically analyzed using a biogas analyzer. Due to heat convection, there is a slight temperature variation of 2-3°C between the AD's temperature and the water temperature in the container. To address this, the water temperature in the container is auto-set to increase by 2 to 3°C to maintain the desired temperature within the digester.

A 200 W heater is employed for this purpose, and water is added daily to keep the container's water level. The setup also incorporates a tumbling mechanism connected via a belt to a 12V DC motor shaft, which operates at a speed of 15 revolutions per minute (rpm).

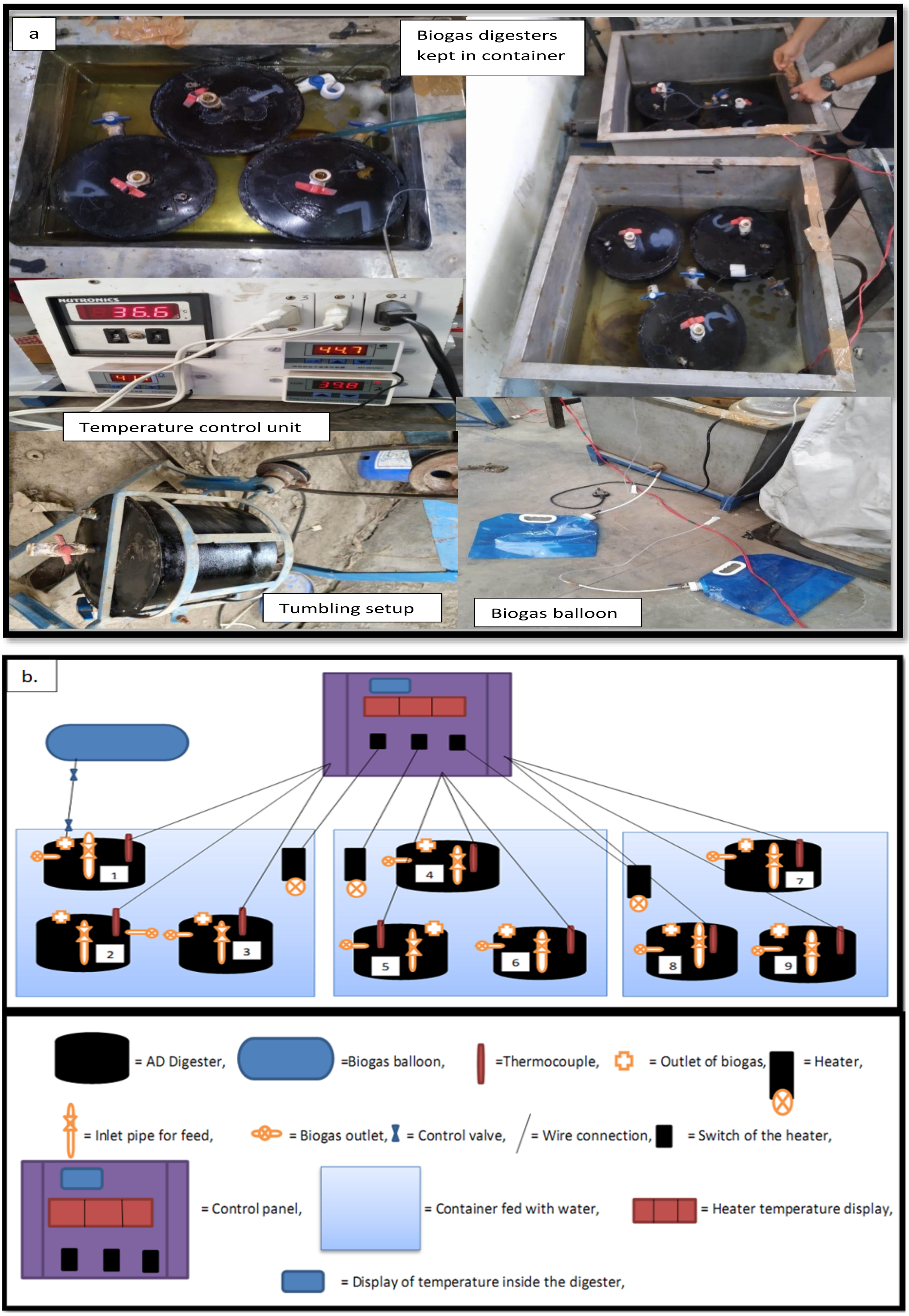


Figure 4.8: (a) Experimental setup of Anaerobic digester with TCU and tumbling setup (b) Schematic diagram of the experimental setup and its parts

This component likely plays a role in agitating the contents of the digester, aiding in the breakdown of waste materials and promoting efficient biogas production. In summary, this experimental setup involves carefully designing and operating small anaerobic digesters to generate biogas. The setup includes features to control temperature, facilitate waste feeding, collect biogas, and analyze its composition, ensuring a controlled and efficient process for biogas production.

4.3 Feed stocks

The feedstock for the experiment mainly consisted of fruit, raw vegetable, and mixed cooked waste. The fruit waste from the juice shop was collected inside the cafeteria. Most fruit wastes were banana, sweet lemon, mango, and sugarcane. Raw vegetables and cooked kitchen waste were collected from the University's dining hall. Their properties are summarized in Table 4.1. A crucible with a capacity of 50 ml was taken for Total solid (TS) calculation. First, the weight of the empty crucible was calculated using the weighing machine; then, a 20 ml sample was placed in a crucible and heated to 105°C in an oven.

Table 4.1: Characteristics of Substrates

Types of wastes	Total solid (TS) (%)	Volatile solid (VS) (%)	VS/TS (%)	pH
Fruit waste	27.5	25.3	92	5.9
Raw vegetable waste	10.55	9.25	87.67	5.7
Mixed cooked waste	12.15	10.45	86	6.5

Due to this, the sample moisture evaporates. After evaporation, the sample is cooled in a desiccator, and the final weight is recorded.

The initial weight of the empty crucible =W1 g (1)

Final weight of the crucible =W2 g (2)

Total solids present in the sample (%) = $\frac{Final\ weight(W2)}{Initial\ weight(W1)} \times 100$ (3)

A further processor has to be used to calculate VS. After cooling the sample in the desiccator, its weight was calculated. And again, that sample is kept in a muffle furnace at 600-degree temperature for 10 minutes, and the final weight (W3) is taken.

$$\text{Volatile content (\%)} = \frac{Initial\ weight(W1) - Final\ weight(W3)}{Initial\ weight(W1)} \times 100 \qquad (4)$$

4.4 Taguchi analysis

Taguchi analysis can be applied to optimize biogas production, a renewable energy source derived from organic waste. By utilizing this statistical method, various factors affecting biogas production, such as temperature, types of feedstocks, ratio, pH, and retention time, can be systematically studied. Taguchi analysis helps identify the optimal combination of factors and levels to maximize biogas yield while minimizing variations caused by uncontrollable factors. This approach enables efficient and cost-effective biogas production processes.

4.4.1 Without any tumbling

The study aimed to determine the most efficient feedstock values for the three inputs, namely ratio, feed, and temperature, to optimize CH_4 gas production. The results show that the feedstock was the primary factor affecting CH_4 gas production, while the feed ratio and temperature were secondary parameters. The study used Taguchi analysis, which is a statistical method for designing experiments to optimize the performance of a system or process. The optimal CH_4 gas production was obtained from fruit feedstock under non-tumbling effect conditions.

This finding is consistent with Taguchi's study on the non-tumbling effect. The method involves identifying the key parameters affecting the system's performance and determining the optimal values to achieve the desired output. The study analyzed the Signal to Noise ratio (SN ratio) and means of CH_4 gas production using a linear model analysis. The analysis results are presented in Table 4.2 and Table 4.3, respectively. The linear model analysis of SN ratios versus feed ratio, types of feed, and temperature aims to determine the combination of these factors that maximizes the signal-to-noise ratio, representing the desired outcome or quality of the biogas production process. The SN ratio can be defined based on the specific objectives of the experiment, such as maximizing biogas yield or minimizing variations in the gas composition. By analyzing the SN ratios, researchers can identify the optimal levels of each factor that lead to the desired outcome.

Table 4.2: Linear Model Analysis: SN ratios versus feed ratio, types of feed, temperature

Estimated Model Coefficients for SN ratios

Term	Coef	SE Coef	T	P
Constant	30.7926	0.4150	74.191	0.000
Ratio 1:1	-1.4646	0.5870	-2.495	0.130
Ratio1:1.5	-0.1905	0.5870	-0.324	0.776
Feed FW	2.4950	0.5870	4.251	0.049
Feed RVW	-0.9115	0.5870	-1.553	0.261
Temp. 35	1.6718	0.5870	2.848	0.104
Temp. 40	-0.8271	0.5870	-1.409	0.294

Analysis of Variance for SN Ratios

Source	DF	Seq SS	Adj MS	F	P
Ratio	2	14.762	7.381	4.76	0.174
Feed	2	28.689	14.344	9.25	0.098
Temp.	2	12.578	6.289	4.06	0.198
Residual Error	2	3.101	1.550		
Total	8	59.129			

Model Summary

S	R-Sq	R-Sq(adj)
1.2451	94.76%	79.02%

Response Table for Signal-to-Noise Ratios

Larger is better

Level	RATIO	FEED	TEMP.
1	29.33	33.29	32.46
2	30.60	29.88	29.97
3	32.45	29.21	29.95
Delta	3.12	4.08	2.52
Rank	2	1	3

Similarly, the linear model analysis of means versus feed ratio, types of feed, and temperature focus on the mean values of the response variable, which could be parameters like biogas production rate or methane content.

Table 4.3: Linear Model Analysis: Means versus feed ratio, types of feed, temperature

Estimated Model Coefficients for Means

Term	Coef	SE Coef	T	P
Constant	36.122	1.700	21.252	0.002
Ratio 1:1	-5.456	2.404	-2.270	0.151
Ratio1:1.5	-1.089	2.404	-0.453	0.695
Feed FW	10.111	2.404	4.206	0.048
Feed RVW	-4.656	2.404	-1.937	0.192
Temp. 35	6.111	2.404	2.542	0.126
Temp. 40	-3.222	2.404	-1.340	0.312

Analysis of Variance for Means

Source	DF	Seq SS	Adj MS	F	P
Ratio	2	221.34	110.67	4.26	0.190
Feed	2	461.02	230.51	8.87	0.101
Temp.	2	168.22	84.11	3.23	0.236
Residual Error	2	52.00	26.00		
Total	8	902.58			

Model Summary

S	R-Sq	R-Sq(adj)
5.099	94.24%	76.95%

Response Table for means

Larger is better

Level	RATIO	FEED	TEMP.
1	30.67	46.23	42.23
2	35.03	31.47	32.90
3	42.67	30.67	33.23
Delta	12.00	15.57	9.33
Rank	2	1	3

The tables show that the three inputs' most efficient FW feedstock values were significant at $p < 0.05$. The value of R^2, a measure of the model's goodness of fit, was found to be 94.76% in the SN ratio analysis and 94.24% in the means analysis.

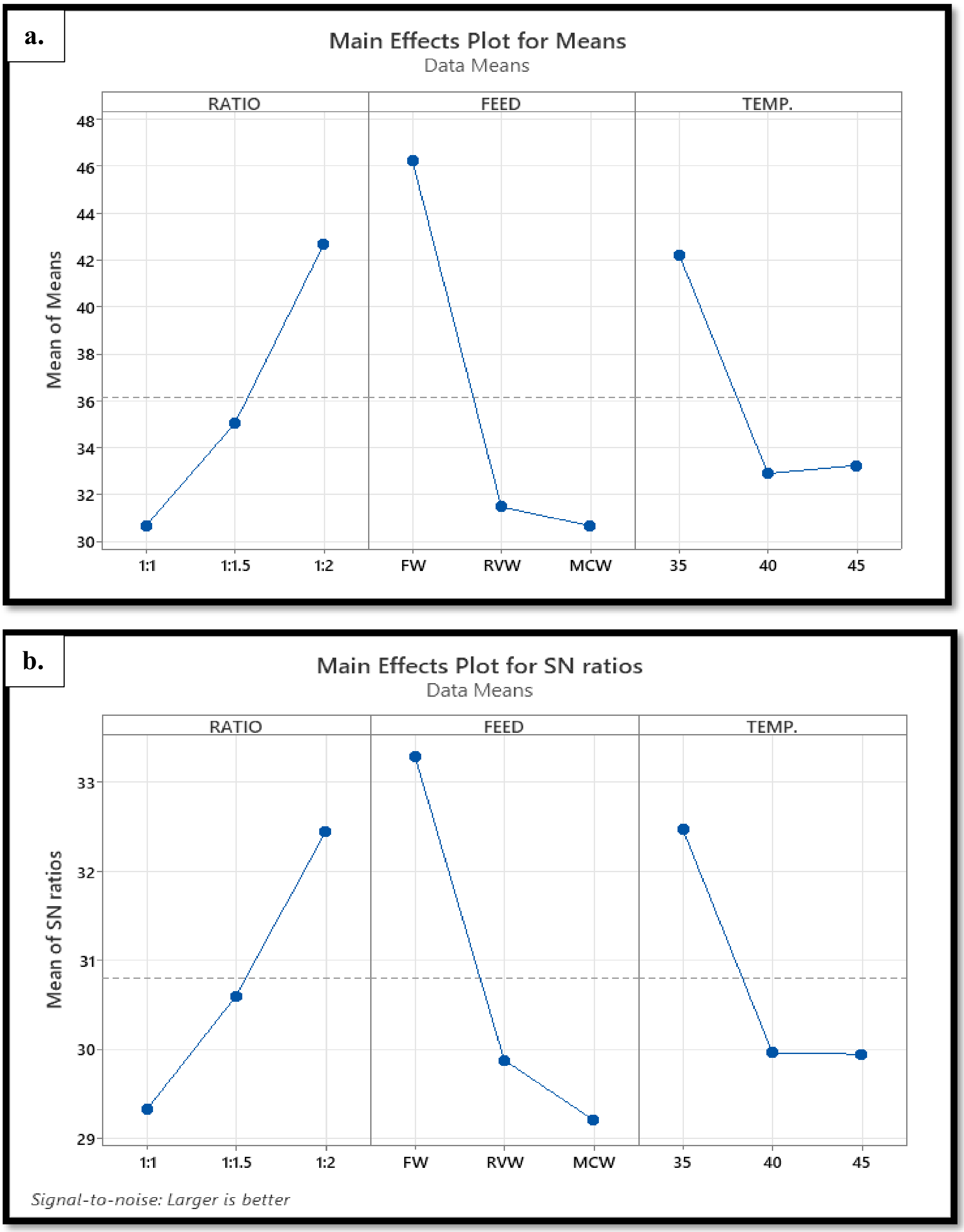


Figure 4.9: (a) Mean of means w.r.t feed ratio, types of feed and temperature (b) Mean of SN ratios w.r.t feed ratio, types of feed and temperature

This analysis aims to identify the factor levels that yield the highest mean values, indicating the optimal performance of the biogas production process. In both cases, Taguchi analysis employs statistical techniques to analyze the data collected from experimental trials with different factor combinations. The objective is to determine the most influential factors and their respective levels for achieving the desired outcome. Researchers can systematically explore the parameter space by applying Taguchi analysis, reducing experimental efforts, and cost-effectively optimizing the biogas production process.

This indicates that the DOE approach's experimental process produced more than 94% perfect results. The study also presented the results in Figure 4.9(a-b). The statistics show that in the mean of SN ratio and mean of means analysis, the optimal CH_4 value was obtained at FW feed and temperature of 35°C in level 1. In level 3, the best average CH_4 value was obtained at a ratio of 1:2.

4.4.2 Tumbling effect

The study aimed to determine the most influential parameters influencing CH_4 gas production: rotation time, feed types, and temperature. The study used Taguchi analysis, which is a statistical method for designing experiments to optimize the performance of a system or process. The technique involves identifying the key parameters affecting the system's performance and determining the optimal values to achieve the desired output. The results of the analysis are presented in Tables 4.4 and 4.5. The tables show that the tumbling time (rotation time) is less than $p < 0.05$, indicating that it is the most influential parameter in the production of CH_4 gas in the tumbling process.

The coefficient of determination (R^2) obtained in the Analysis of Variance for SN ratio and Analysis of Variance for Means was found to be 98.48% and 98.97%, respectively. This indicates that the result obtained from the DOE approach was up to 98% accurate. The study found that the optimum CH_4 output was achieved on the FW feed and rotation time of 10 minutes in level 1 and level 2. In level 3, the tumbling process was performed on the RVW feed. According to the rank of the tumbling effect, the most significant value was the rotation time, which had a position of 1, meaning that the tumbling process produced more CH_4. The second and third affecting parameters were found to be feedstock and temperature.

Table 4.4: Linear Model Analysis: SN ratios versus rotation time, types of feed, temperature

Estimated Model Coefficients for SN ratios

Term	Coef	SE Coef	T	P
Constant	35.7061	0.07328	487.275	0.000
Rot. Time 0	-1.0126	0.10363	-9.771	0.010
Rot. Time 10	0.7401	0.10363	7.142	0.019
Feed FW	0.1796	0.10363	1.733	0.225
Feed MCW	-0.5166	0.10363	-4.985	0.038
Temp 35	0.1303	0.10363	1.257	0.336
Temp 40	-0.1040	0.10363	-1.003	0.421

Analysis of Variance for SN Ratios

Source	DF	Seq SS	Adj MS	F	P
Rot. Time	2	4.94185	2.47092	51.13	0.019
Feed	2	1.23820	0.61910	12.81	0.072
Temp	2	0.08542	0.04271	0.88	0.531
Residual Error	2	0.09665	0.04833		
Total	8	6.36212			

Model Summary

S	R-Sq	R-Sq(adj)
0.2198	98.48%	93.92%

Response Table for Signal-to-Noise Ratios

Larger is better

Level	ROT. TIME	FEED	TEMP.
1	34.69	35.89	35.84
2	36.45	35.19	35.60
3	35.98	36.04	35.68
Delta	1.75	0.85	0.23
Rank	1	2	3

Table 4.5: Linear Model Analysis: Means versus rotation time, types of feed, temperature

Estimated Model Coefficients for Means

Term	Coef	SE Coef	T	P
Constant	61.2778	0.4138	148.084	0.000
Rot. Time 0	-6.9111	0.5852	-11.810	0.007
Rot. Time10	5.2222	0.5852	8.924	0.012
Feed FW	1.1889	0.5852	2.032	0.179
Feed MCW	-3.5444	0.5852	-6.057	0.026
Temp 35	0.8556	0.5852	1.462	0.281
Temp 40	-0.9444	0.5852	-1.614	0.248

Analysis of Variance for Means

Source	DF	Seq SS	Adj MS	F	P
Rot. Time	2	233.662	116.831	75.81	0.013
Feed	2	58.576	29.288	19.00	0.050
Temp.	2	4.896	2.448	1.59	0.386
Residual Error	2	3.082	1.541		
Total	8	300.216			

Model Summary

S	R-Sq	R-Sq(adj)
1.2414	98.97%	95.89%

Response Table for Means

Larger is better

Level	ROT. TIME	FEED	TEMP.
1	54.37	62.47	62.13
2	66.50	57.73	60.33
3	62.97	63.63	61.37
Delta	12.13	5.90	1.80
Rank	1	2	3

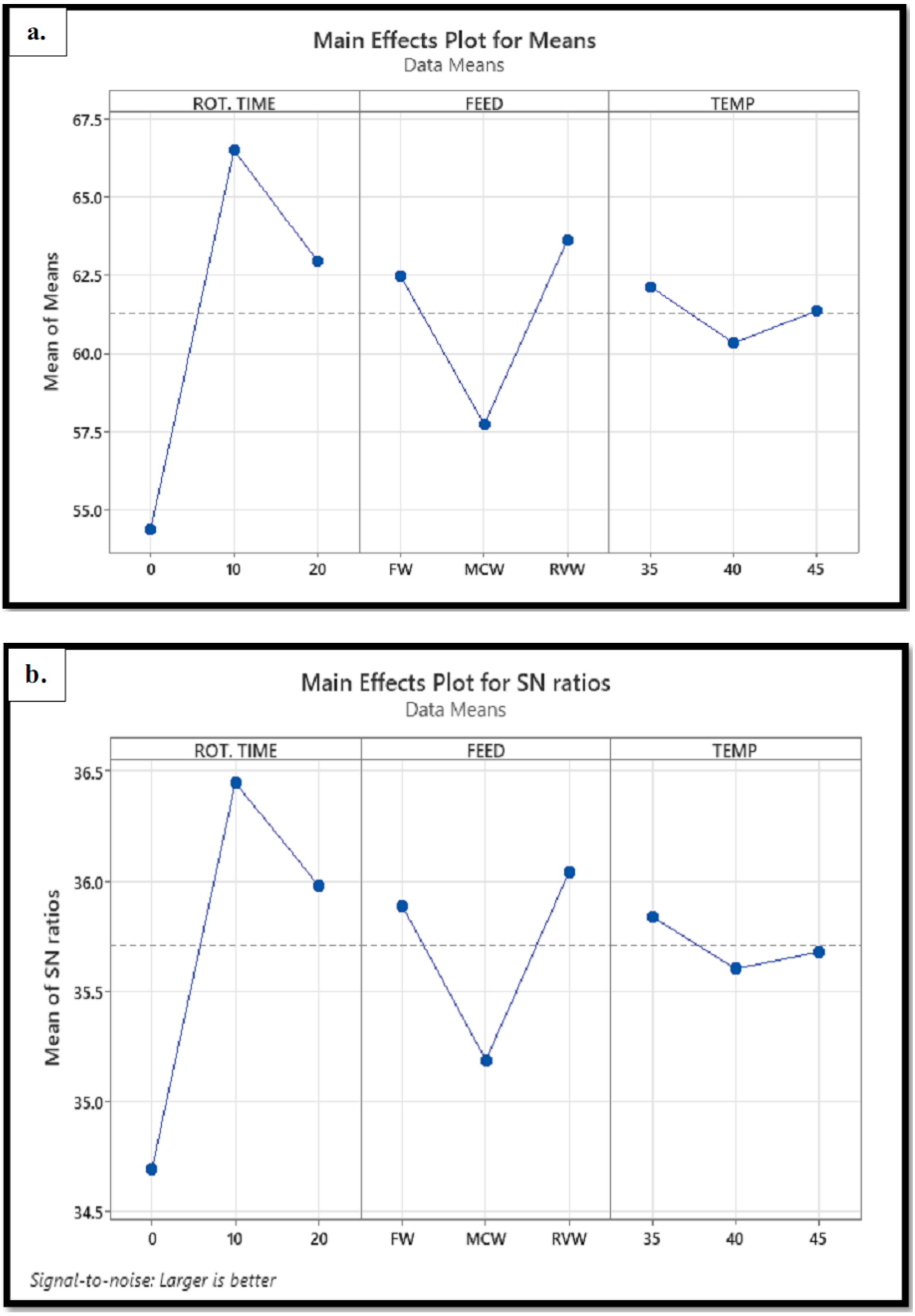


Figure 4.10: (a) Mean of means w.r.t rotation time, types of feed and temperature (b) Mean of SN ratios w.r.t rotation time, types of feed and temperature

The study also highlighted the importance of the tumbling effect on the production of CH_4 gas. The tumbling development refers to the effect of rotating the feedstock during the process, which enhances the mixing of the feedstock and increases the surface area available for the anaerobic digestion process. The study found that the tumbling effect significantly improved CH_4 gas production.

4.5 Analysis (Experimental investigation)

Table 4.6 exhibits that without the tumbling effect, ADs D1, D2, and D3 are placed together in a container whose temperature is maintained at 35 °C. In all three ADs, FW, RVW, and MCW are fed in the 1: 1, 1:1.5, and 1: 2. The feed counts have been kept in 1:1, 1:1.5, and 1:2 throughout the experiment. 1:1 means 0.375 kg of waste and 0.375 liters of water, 1:1.5 means 0.3 kg of waste and 0.45 liters of water, and 1:2 means 0.25 kg of waste and 0.5 liters of water have been used.

Similarly, ADs, D4, D5, and D6 are fed into container two at a temperature of 40°C and provided to MCW, FW, and RVW in 1:1, 1:1.5, and 1:2. ADs, D7, D8, and D9 were fed in container three at a temperature of 45 °C, and RVW, MCW, and FW were fed 1:1, 1:1.5, and 1:2. As can be seen in Table 4.7, D3, D9, and D2 are placed in container one at a temperature of 35 °C, and FW, MCW, and RVW are fed in the ratio of 1:1:5.

Table 4.6: Design of Experiment (DOE) of Set up one without tumbling effect

Anerobic Digester (AD) No.	Ratio	Types of feed	Temperature (°C)
D1	R1	F1	T1
D2	R2	F2	T1
D3	R3	F3	T1
D4	R1	F3	T2
D5	R2	F1	T2
D6	R3	F2	T2
D7	R1	F2	T3
D8	R2	F3	T3
D9	R3	F1	T3

Table 4.7: Design of Experiment (DOE) of Set up two with tumbling effect

Anerobic Digester (AD) No.	Temperature (°C)	Rotational time (Min.)	Types of feed
D3	T1	N1	F1
D9	T1	N2	F3
D2	T1	N3	F2
D7	T2	N2	F1
D1	T2	N3	F3
D6	T2	N1	F2
D5	T3	N3	F1
D4	T3	N1	F3
D8	T3	N2	F2

Note: Where T1=35°C, T2=40°C, T3=45°C and F1=FW, F2= RVW, F3=MCW, R1=1:1, R2=1:1.5, R3=1:2, N1=0 minute, N2 =10 minutes, N3=20 minutes and No. of anerobic digester = D1 to D9

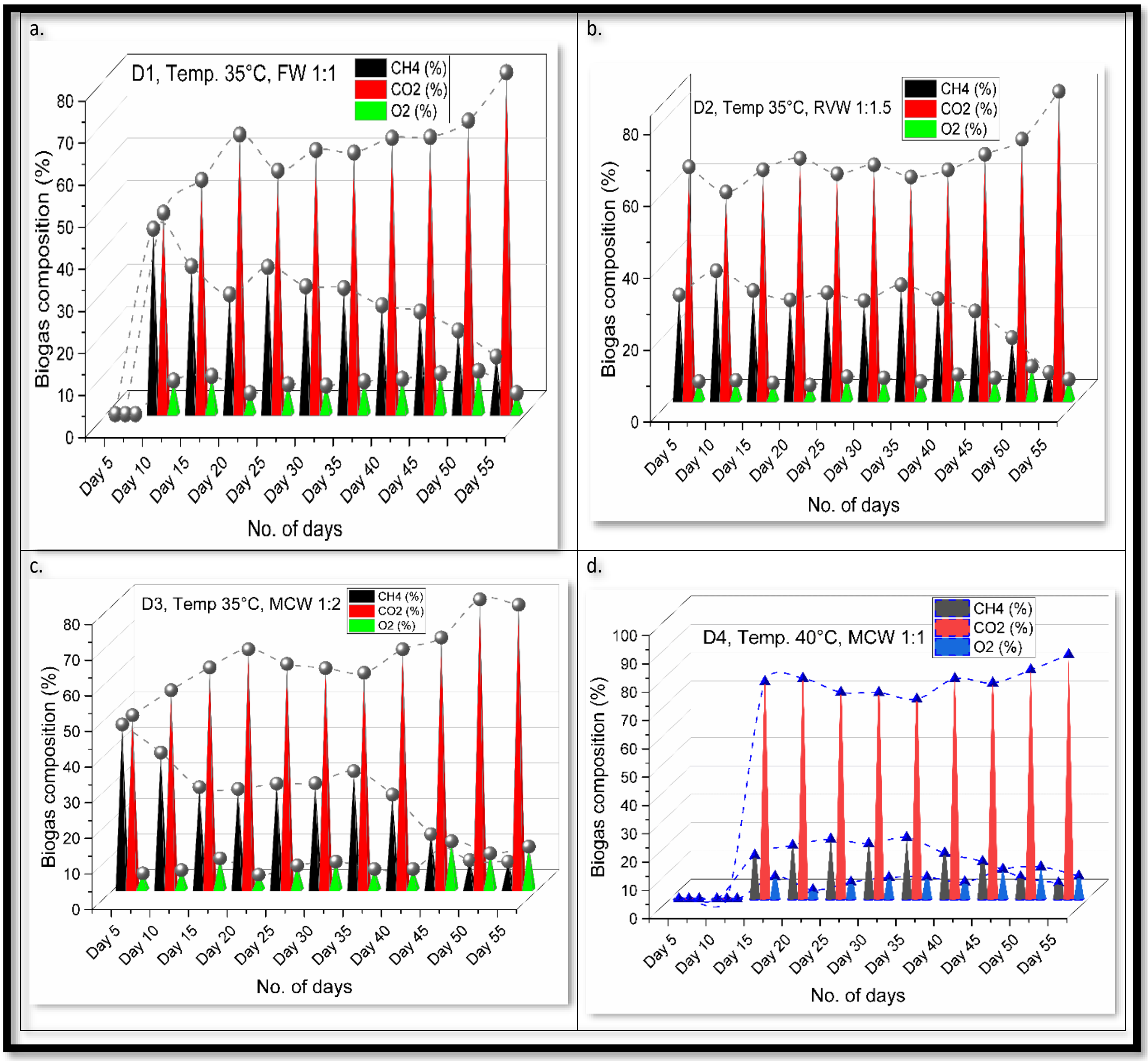
Each time after feeding, D3 is tumbled for zero minutes, D9 for 10 minutes, and D2 for 20 minutes. Each digester will have a 1:1.5 feed ratio, i.e., 0.3 kg of waste and 0.45 liters of water. This way, a total waste of 0.75 kg is fed into the digester. And tumbling for 0,10, and 20 minutes is done on the day the waste is treated in the top-up digester. Similarly, D7, D1, and D6 are maintained in container two at a temperature of 40 °C, followed by a 1:1.5 feed, and tumbled for 10, 20, and 0 minutes each time. D5, D4, and D8 are tumbled for 20, 0, and 10 minutes each by adding a 1:1.5 feed, maintained at 40°C in container three.

4.6 Experimental biogas production

Experimental biogas production can be achieved through two methods: without tumbling and with tumbling. Without tumbling, organic waste is stored in a sealed container for extended periods, relying on anaerobic bacteria to produce biogas. With tumbling, the waste is mechanically agitated to enhance digestion, resulting in faster gas production but requiring additional equipment and energy input.

4.6.1 Biogas Production without Tumbling

In container 1, the ADs (D1, D2, and D3) were maintained at 35 °C; among them, the fruit waste was added to D1 in a ratio of 1:1. During the initial days, no gas was generated; in this ratio, the four stages of biogas formation, hydrolysis, acidogenesis, acetogenesis, and methanogenesis, take time to complete. It explains why D1 did not release gas within five days of the experiment's beginning. Throughout the 55-day investigation, D1 obtained a maximum of 44.1%, a minimum of 13.7%, and an average of 26.1% methane, a maximum of 81.3%, and a minimum of 47.9% CO_2, a maximum of 10.1 % and a minimum of 5% O_2. As the amount of O_2 and CO_2 in a digester increases, the methane-producing bacteria die, reducing CH_4 gas formation. RVW in D2 was estimated to be 1:1.5; at this ratio, biogas mixtures were produced more rapidly than in D1.



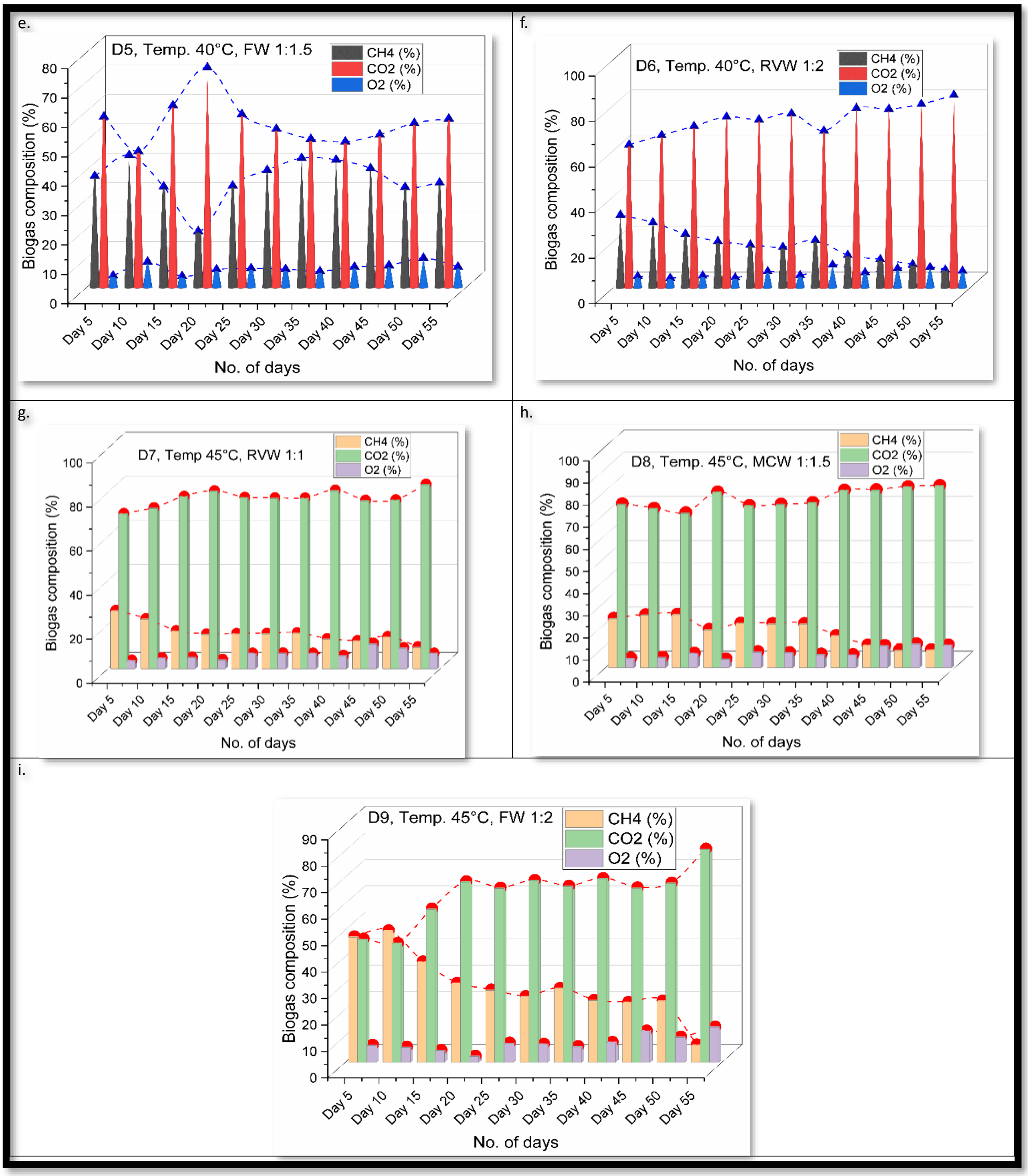


Figure 4.11: Composition of biogas at different temperatures and ratios of FW, RVW and MCW

The maximum, minimum, and average amount of CH_4 were determined to be 36.2%, 7.9%, and 26.7%, respectively; the maximum value of CO_2 was 86.1%, the minimum value was 58.1%, and the maximum value of O_2 was 9.6%, and the minimum value was 4.4 %. MCW in D3 was taken in the ratio of 1:2. The average amount of CH_4 in this digester was obtained at 26.68% throughout the experimental window.

Table 4.8: Biogas composition (CH_4, CO_2, O_2) obtained without tumbling effect

Anaerobic Digester (AD) No.	Ratio	Types of feed	Temperature (°C)	CH_4 (%) (Maximum, Minimum)	CO_2 (%) (Maximum, Minimum)	O_2 (%) (Maximum, Minimum)
D1	R1	F1	T1	(44.1, 13.7)	(81.3, 47.9)	(10.1, 5)
D2	R2	F2	T1	(36.2, 7.2)	(86.1, 58.1)	(9.6, 4.4)
D3	R3	F3	T1	(46.4, 7.9)	(81.5, 49)	(13.6, 4.2)
D4	R1	F3	T2	(21.7, 5.6)	(86.3, 70.6)	(11.3, 3.2)
D5	R2	F1	T2	(45, 19.1)	(74.8, 46.3)	(10, 3.8)
D6	R3	F2	T2	(32, 7.9)	(84.7, 62.9)	(10.1, 4.3)
D7	R1	F2	T3	(26.2, 9.7)	(83.5, 70.2)	(11.3, 3.6)
D8	R2	F3	T3	(23.9, 7.8)	(82.1, 69.8)	(10.6, 3.7)
D9	R3	F1	T3	(49.6, 6.4)	(80.4, 44.8)	(13.2, 2.2)

Maximum amounts of CH_4, CO_2, and O_2 were 46.4%, 81.5%, and 13.6%, respectively, while the minimum quantities were 7.9%, 49%, and 4.2%, respectively. This data demonstrates that when MCW is fed daily at a ratio of 1:2 and a temperature of 35°C in a biogas digester, CH_4 will be produced rapidly and in more significant quantities. The MCW was taken in a 1:1 ratio by maintaining the digester D4 at a 40°C temperature; no gas was produced for the first ten days. The maximum, minimum, and average quantities of CH_4 were obtained at 21.7%, 5.6%, and 12.67%. The maximum amounts of CO_2 and O_2 were 86.3% and 11.3%, and the minimum quantities were 70.6% and 3.2%. In D5, the FW was maintained at a ratio of 1:1.5, resulting in increased CH_4 production and a higher rate of gas production than in D4.

The maximum, minimum, and average amounts of CH_4 were achieved at 45%, 19.1%, and 37.12%, respectively. The maximum amounts of CO_2 and O_2 were obtained at 74.8% and 10%, while their minimum quantities were obtained at 46.3% and 3.8%. In D6, the RVW was placed at 1:2; In this ratio, the average amount of CH_4 gas obtained was 18.87%, which was better than that of D4 and less than that of D5.

The maximum amounts of CH_4, CO_2, and O_2 were 32%, 84.7%, and 10.1%, respectively, while the minimum quantities were 7.9%, 62.9%, and 4.3%. At 40 °C, the digester D5 with a feedstock FW and a ratio of 1:1.5 produces the fastest and highest amount of CH_4 gas. Digester D7 is maintained at 45°C with feedstock RVW in a 1:1 ratio. The biogas composition was formed quickly at this temperature, but the quantity was less. The maximum, minimum, and average amounts of CH_4 were achieved by 26.2%, 9.7%, and 16.23%, respectively. And the maximum quantities of CO_2 and O_2 were obtained at 83.5% and 11.3%, respectively, while the minimum amounts of 70.2% and 3.6% were obtained. At D8, the feedstock MCW was taken as 1:1.5, with an average value of CH_4 of 15.12% during the experiment. A maximum quantity of CH_4, CO_2, and O_2 was obtained at 23.9%, 82.1%, and 10.6%, respectively, while the minimum amount was 7.8%, 69.8%, and 3.7%, respectively.

The feedstock FW in D9 is taken as 1:2 and has better CH_4 gas than in D7 and D8. The maximum, minimum, and average amounts of CH_4 were obtained at 49.6%, 6.4%, and 29.02%. The maximum amount of CO_2 and O_2 was 80.4% and 13.2%, while the minimum was 44.8% and 2.2%. FW produces more CH_4 gas at various temperatures and ratios than other wastes such as RVW and MCW.

Outcome

- The maximum, minimum, and average values of CH_4 obtained at 35°C in FW (1:1) were 44.1%, 13.7%, and 26.1%. 45%, 19.1%, and 37.12% in FW (1:1.5) were obtained at 40 °C, and 49.6%, 6.4%, and 29.02% in FW (1:2) at 45 °C. The best average CH_4 gas is produced when the temperature inside the digester is maintained at 40°C and fed into the feed FW (1:1.5).
- In RVW (1:1.5), the maximum, minimum, and average values of CH_4 obtained at 35°C are 36.2%, 7.2%, and 26.7%. The RVW (1:2) at 40°C was 32%, 7.9%, and 18.87%. 26.2%, 9.7%, and 16.23% were obtained at RVW (1:1) at 45 °C. In the case of RVW, the best average production of CH_4 can be achieved when the feed rate is in the ratio of RVW (1:1.5), and the digester temperature is maintained at 35°C.

- In the case of MCW (1:2), the maximum, minimum, and average values of CH_4 at 35°C are found to be 46.4%, 7.9%, and 26.68%. 21.7%, 5.6%, and 12.67% were obtained on MCW (1:1) at 40 °C. 23.9%, 7.8%, and 15.12% were obtained on MCW

(1:1.5) at 45 °C. In the case of MCW, the best CH_4 gas can be produced by keeping the feed of MCW (1:2) at a temperature of 35°C digesters.

- In some digesters, biogas composition starts forming after 10-15 days. This happens because biogas production depends on the quality of feedstock, feed ratio, C/N, pH, and temperature.

- Setting a retention time of 10-20 days ensures the microorganisms can decompose the organic waste and produce biogas. Adding feedstock once a week provides a steady supply of organic waste and helps maintain a consistent biogas production rate. After the retention time, the biogas produced was measured and analyzed for composition. Each digester's experimental time to produce biogas was set to 55 days. It provided enough time for the microorganisms to digest the organic waste and produce biogas. The feedstock was stopped in each digester after 40-45 days, allowing for a stable and sustainable biogas production rate.

Temperature is a vital parameter that influences biogas production because it directly affects the activity of microorganisms responsible for digestion. The optimum temperature range for biogas production is between 35 to 45 degrees Celsius. At this temperature, the anaerobic bacteria that break down the organic matter in the feedstock are most active, resulting in a higher yield of biogas. However, if the temperature is too high or too low, the activity of the microorganisms slows down, and the biogas production rate decreases. Fruit waste, such as leftover fruits and peels, is a valuable feedstock for biogas production because it contains many easily digestible carbohydrates, such as sugars and starches. The high sugar content of fruit waste results in a high yield of biogas, which includes a high proportion of methane, the primary component of biomethane. The use of fruit waste as a feedstock has been found to increase the yield of biomethane by up to 40% compared to other feedstocks.

Raw vegetable waste, such as peels and trimmings, is another valuable feedstock for biogas production. Vegetables contain a high amount of cellulose and other complex carbohydrates that are more challenging to break down than the sugars found in fruit waste. However, using raw vegetable waste as a feedstock has resulted in a more balanced nutrient composition in the biogas digestate, the leftover material after digestion. The balanced nutrient composition of the digestate can make it an excellent fertilizer for plants and crops.

Mixed cooked waste, which includes food waste from households, restaurants, and commercial kitchens, is a feedstock that can be challenging to handle because of its variable composition and high fat and protein content. However, mixed cooked waste has been found to produce good biomethane composition due to its high calorific value and nutrient content. The anaerobic bacteria can break down mixed cooked waste's high fat and protein content during digestion, resulting in a high biomethane yield.

Discussions

Food waste is the primary source for the generation of biogas. Biogas production can be boosted by mixing food waste, kitchen garbage, and fruit waste in varying proportions and temperatures. Some studies support our results. “For 40 days, a digester with a capacity of 200 L was used to produce biogas. In this study, the components for the biogas process were combined in 5 different ratios of food waste with vegetable waste, using chicken dung in the following ways: 1: 1 (Digester D3), 2: 1 (Digester D4), 3: 1 (Digester D5), 1: 0 (Digester D1), and 0: 1 (Digester D2). The maximum amount of biogas, 18.83 kg, and the highest percentage of methane gas, 72%, was produced when the ratio of food waste to chicken dung was 1:1 (Digester D3)” [130]. “The production of biogas from grass (GR) combined with the co-substrate food waste (FW) was then assessed under anaerobic conditions (methane).

Five laboratory-scale reactors were set up with varying amounts of grass and food waste that had an 8% total solid concentration: R1 (100% FW, 0% GR), R2 (75% FW, 25% GR), R3, (50% FW, 50% GR), R4 (25% FW, 75% GR), and R5 (0% FW, 100% GR). Twenty (20) days of digestion at room temperature (35 °C) were conducted. The R1, R2, R3, R4, and R5 produced 805, 840, 485, 243, and 418 mL of biogas. Only 805 mL of biogas was made from food waste, while 418 mL was produced from grass. Biogas from food waste only outperformed grass by 50%. However, 6% more biogas was produced by co-digestion (75% food waste, 25%) than by using solely food waste” [208]. “Three other food waste (FW) to bovine manure (BM) ratios: 0:1, 1:2, and 3:1 (corresponding to 0, 33, and 75% of food waste in the digester substrate, respectively) were tested in the laboratory experiment using batch feed systems. The continuous feed mechanism for the pilot-scale biodigester delivered a 1:2 FW: BM mixture. The treatment with the 1:2 FW: BM ratio had the largest cumulative biogas generation in the lab, producing 273 mL g-1 of volatile solids (VS)”

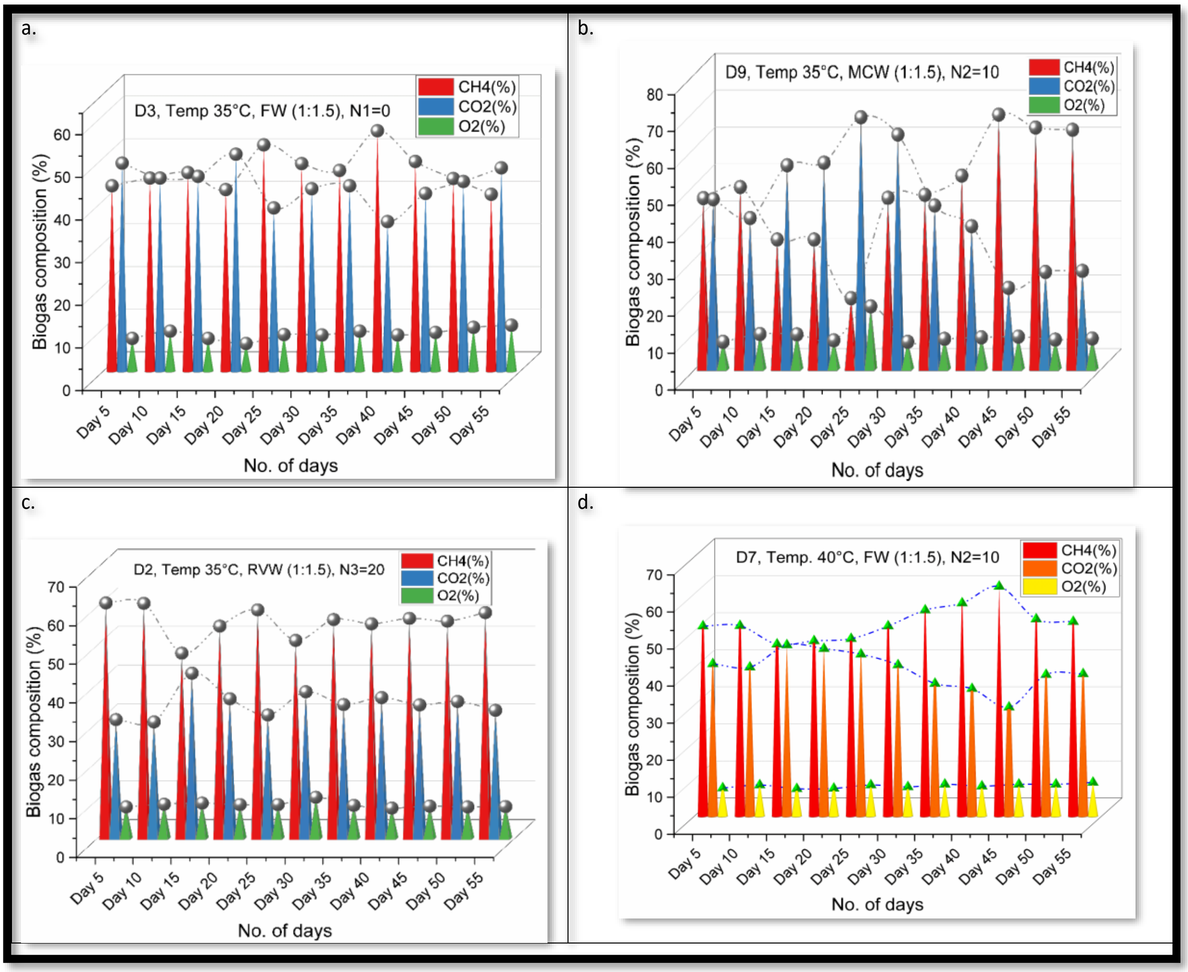
[209]. “The digester setups were tested for 24 days at room temperature (28 °C) and mesophilic temperature (37 °C) while being fed kitchen waste (KW) and poultry manure (PM) in ratios of 1:0 (D1), 1:1 (D2), 2:1 (D3), and 3:1 (D4) at a constant loading rate of 300 mg/L.

The production of CBG and the amount of methane in D2 above D1 increased by 16% and 74%, respectively, due to the co-digestion of KW and PM. At ambient temperature, the D3 with 66.7% KW and 33.3% PM produced the most CBG and methane (396 8 mL and 36%). All the digesters performed better in mesophilic conditions, although D3 had the greatest CBG (920±11 mL) and methane concentration (48%) levels”[210]. “This study examined the performance and microbial structure of two digesting processes—one including solely food waste and the other involving cow manure—at mesophilic (37°C) and thermophilic (55°C) temperatures. The mesophilic digester only fed food waste and showed maximum methane yield (480mL/g VS). Compared to the sum of the individual digestions of manure and food waste, the mesophilic co-digestion of food waste and manure produced 26% more methane”[211].

4.6.2 Biogas production with tumbling effect

As shown in Figure 4.12, in the tumbling effect, digesters D3, D9, and D2 were maintained at 35°C FW, MCW, and RVW, respectively. The rotation times for D3, D9, and D2 were kept at 0, 10, and 20 minutes, respectively. In D3, the maximum and minimum CH_4 in FW were obtained at 56.4% and 41.5%. The average amount of CH_4 during the entire experiment was 47.2%. The maximum amount of CO_2 and O_2 was 50.9% and 10.8%, and the minimum was 35.1% and 6.5%, respectively. A maximum and minimum amount of CH_4 gas in D9 is achieved by 69% and 19.3%. And the average amount of CH_4 is 45% throughout the experiment. The maximum CO_2 and O_2 were 68.3% and 17.1%, and the minimum values were up to 22.1% and 7.5%. In RVW in D2, the maximum CH_4 content is 61%, the minimum is 48% in 20 min rotations, and the average CH_4 content is 56.3% achieved throughout the experiment. During this period, the maximum quantity of CO_2 and O_2 was obtained at 42.8% and 10.7%, and the minimum amount at 30.2% and 7.9%. Digesters D7, D1, and D6 are maintained at 40-degree temperatures. The rotation time for FW in the D7 was kept at 10 minutes. The maximum amount of CH_4 was achieved by 62%, while the minimum amount was 46.4%, and the average amount of CH_4 during the whole duration of the experiment was 52.4%. The maximum values of CO_2 and O_2 were found to be 46.2% and 9.1%, respectively, while the minimum values were 29.4% and 7.4%. The rotation time of MCW in D1 was kept at 20 minutes. The maximum value of CH_4 was obtained at 62.5%, the minimum was 36.9%, and the average value was 50.9%. The maximum CO_2 and O_2 were obtained at 52.8% and 10.9%, while the minimum values were obtained at 27.8% and 9%.

The RVW's feed was inserted in the D6 digester, which was given a zero-minute rotation time. During the entire experiment period, the maximum value of CH_4 was obtained at 56.5%, the minimum was 32.5%, and the average value was 44.8%. The maximum CO_2 and O_2 were obtained at 57.8% and 19.6%, respectively, while the minimum values were 35% and 7.9%. In digester D7, the average CH_4 value was highest when FW was kept at a 40-degree temperature and rotation time of 10 minutes. The D5, D4, and D8 digesters are maintained at 45 degrees. D5 has FW, whose rotation time is 20 minutes; D4 has MCW, whose rotation time is 0 minutes; and D8 has RVW, whose rotation time is 10 minutes.



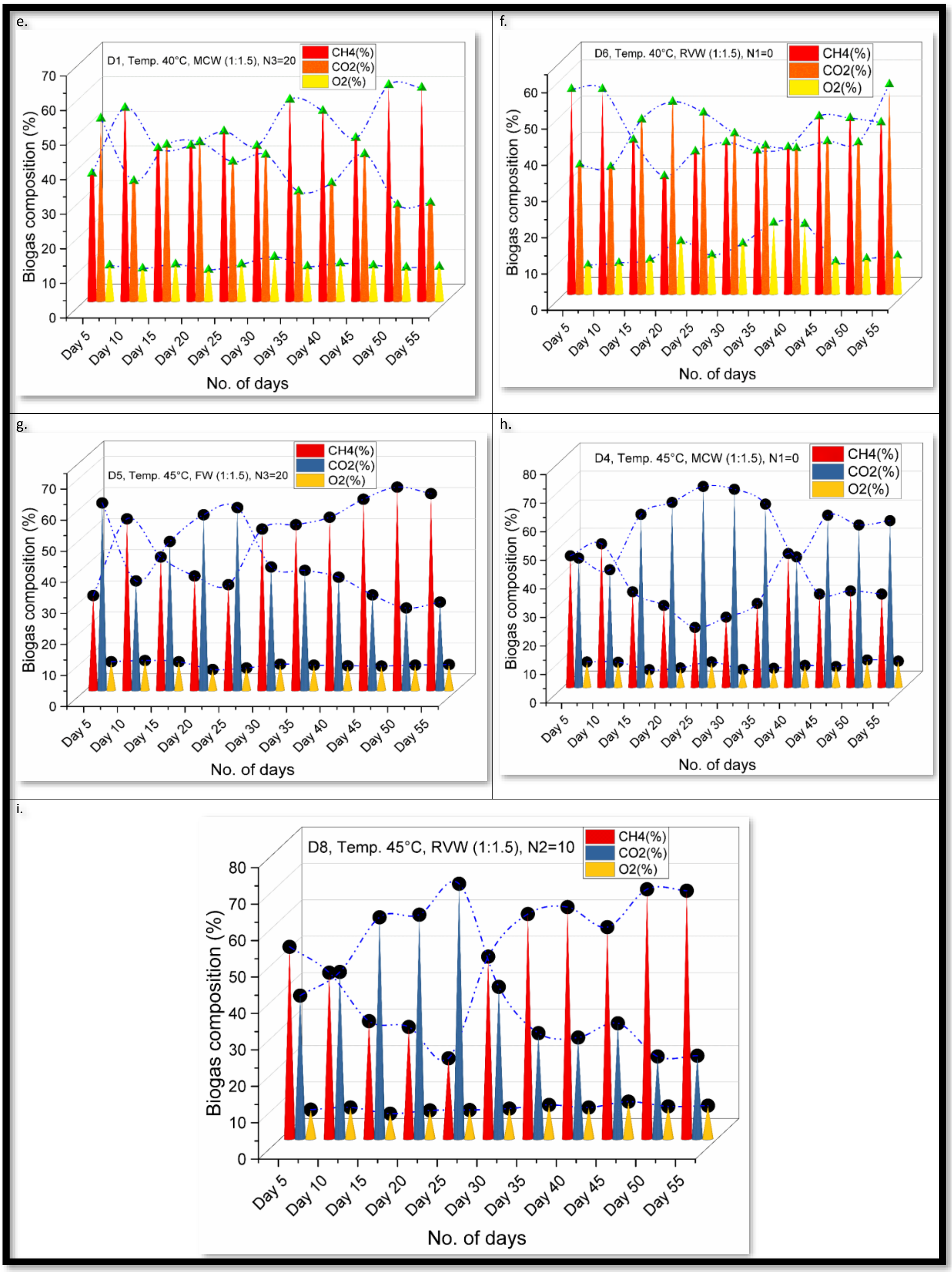


Figure 4.12: Composition of biogas with different periods of the tumbling effect

In D5, the maximum value of CH_4 was 65.4%, the minimum value was 30.5%, and the average value was 50.04% during the entire experiment. The maximum CO_2 and O_2 were

60.3% and 9.6%, while the minimum values were 26.5% and 6.7%. Maximum, minimum, and average values of CH_4 in D4 were obtained at 50.2%, 20.9%, and 34.4%. The highest and lowest values of CO_2 were found to be 70.3% and 41.1%, and the maximum and minimum values of O_2 were 9.5% and 6.1%. The maximum, minimum, and average values of CH_4 in D8 were obtained at 68.5%, 22.1%, and 50.3%, respectively.

Table 4.9: The biogas composition (CH_4, CO_2, O_2) is derived from the tumbling effect

Anaerobic Digester (AD) No.	Temperature (°C)	Rotation time (Min.)	Types of feed	CH_4 (%) (Maximum, Minimum)	CO_2 (%) (Maximum, Minimum)	O_2 (%) (Maximum, Minimum)
D3	T1	N1	F1	(56.4, 41.5)	(50.9, 35.1)	(10.8, 6.5)
D9	T1	N2	F3	(69, 19.3)	(68.3, 22.1)	(17.1, 7.5)
D2	T1	N3	F2	(61, 48)	(42.8, 30.2)	(10.7, 7.9)
D7	T2	N2	F1	(62, 46.4)	(46.2, 29.4)	(9.1, 7.4)
D1	T2	N3	F3	(62.5, 36.9)	(52.8, 27.8)	(10.9, 9)
D6	T2	N1	F2	(56.5, 32.5)	(57.8, 35)	(19.6, 7.9)
D5	T3	N3	F1	(65.4, 30.5)	(60.3, 26.5)	(9.6, 6.7)
D4	T3	N1	F3	(50.2, 20.9)	(70.3, 41.1)	(9.5, 6.1)
D8	T3	N2	F2	68.5, 22.1	(70, 22.6)	(10.2, 6.9)

The maximum CO_2 and O_2 were obtained at 70% and 10.2%, while the minimum values were 22.6% and 6.9%. Digester D2 with feed RVW and rotation time of 10 min was the maximum and average value of CH_4 obtained in this digester throughout the experiment. An anaerobic digester with enhanced agitation rates and tumbling can produce increased biogas. As a result, methane bacteria proliferate. During tumbling, the anaerobic digester is rotated as the feed from the stirrer to the digester is mixed using either a pump or a ratchet.

Outcome

- In D3 (35 °C), D7 (40 °C), and D5 (45 °C) digesters with FW (1:1.5) tumbling times of 0, 10, and 20 minutes, the maximum value of CH_4 was obtained as 56.4%, 62%, and 65.4%, respectively. D7 (40 °C) and D5 (45 °C) digesters achieved an average of 11% and 6% higher CH_4 gas generation as compared to D3 (35 °C) without tumbling.

- D4 (45 °C), D9 (35 °C), and D1 (40 °C) digesters of MCW (1:1.5) with tumbling times of 0, 10, and 20 minutes obtained the maximum value of CH_4 as 50.2%, 69%, and 62.5%, respectively. D9 (35 °C) and D1 (40 °C) digesters achieved an average of 31.1 % and 47.9 % higher CH_4 gas generation than D4 (45 °C) digesters.
- In case RVW (1:1.5), D6 (40 °C), D2 (35 °C), and D8 (45 °C) digesters with tumbling times of 0, 10, and 20 minutes obtained the maximum value of CH4 as 56.5%, 61%, and 68.5%, respectively. D2 (35 °C) and D8 (45 °C) digesters achieved an average of 25.7 % and 12.2 % higher CH_4 gas generation than D6 (40 °C) digesters.

The tumbling effect, also known as agitation or rotation of the digester, is a technique that can significantly enhance the efficiency of biogas production. This technique involves rotating the digester for a certain period after adding the feedstock, resulting in increased biogas production and shorter production times than non-tumbling systems. The tumbling effect improves biogas production by ensuring that the feedstock is evenly distributed and mixed with the microbial population in the digester. The rotation of the digester facilitates the mixing process by increasing the surface area of the feedstock exposed to the microbes, resulting in improved digestion rates and increased biogas production. The tumbling effect also helps to prevent the formation of scum and floating layers on the surface of the digester, which can inhibit digestion and reduce biogas production. It also helps reduce the retention time required for biogas production, resulting in shorter production times than non-tumbling systems. This means that more biogas can be produced in a shorter time, increasing the overall efficiency and productivity of the biogas production system.

The tumbling effect can also improve the quality and composition of the biogas. The enhanced mixing and digestion rates facilitated by the tumbling impact can result in a more homogeneous biogas composition with higher methane content. Methane is the primary component of biogas and is the most valuable product of the biogas production process. The tumbling effect can result in a biogas composition with a methane content of up to 70%, compared to 40-50% in non-tumbling systems. Another advantage of the tumbling effect is that it can reduce the residual organic material in the digestate, which is the leftover material after digestion. The residual organic material can be used as a valuable fertilizer for plants and crops, and reducing its amount can improve the efficiency and sustainability of the biogas production system.

Discussions

The stirrer study corresponds to our tumbling effect. “The impeller mixer in use is of the Rushton variety and rotates at speeds ranging from 50 to 300 rpm. The procedure is carried out in a bioreactor with a diameter of 125 mm and a height of 165 mm, with a substrate volume of 2000 ml, at 37 °C. It was discovered that the mixer speed significantly impacted the biogas production rate; at a speed of 200 rpm, methane, and carbon dioxide are produced at the highest rates” [212]. “In a 0.15 m^3 laboratory digester operating at 30°C, the study assessed the impact of stirring intervals on the production of biogas from a mixture of cow dung and maize silage (at a mixed ratio of 3:1). With no stirring as the control, SIEMENS LOGO PLC and ATV12HU15M2 Drive automatically controlled stirring at 100 rpm for 3 minutes at intervals of 1 hour, 2 hours, 6 hours, and 12 hours.

The stirring intervals significantly impacted the production of biogas ($P < 0.05$), increasing it by 3.11% and 1.48% at 6 hours and 12.7% and 1.75 percent at 12 hours, respectively [139]. “The study contains four stirring times (15 min/hr, 15 min/2 hr, 15 min/3 hr, and 15 min/4 hr), which translate to 6, 3, and 1.5 hr/day, respectively, and three stirring rates (30, 45, and 60 rpm). The obtained findings demonstrated that the stirring speed of 60 rpm was given the high energy production values (9.379 $MJ/m^3/day$) and energy consumption in the moving process (3.430 $MJ/m^3/day$). Net energy acquired (8.448 $MJ/m^3/day$) for the biogas production rate (0.423 $m^3/m^3/day$)” [213].

4.7 Upgradation of biogas for use in IC engine

Utilizing biogas in Internal combustion (IC) engines involves processing steps. It is then purified to remove impurities such as H_2S, CO_2, and moisture. Finally, purified biogas can be utilized as a fuel source in IC engines, offering a sustainable and renewable energy option with reduced emissions.

4.7.1 Water scrubbing technology

Water scrubbing is a commonly used technology for upgrading biogas to a higher methane concentration. Biogas is a renewable energy source generated by the anaerobic digestion of organic materials such as agricultural waste, municipal solid waste, sewage sludge, and food waste. However, the biogas produced from anaerobic digestion typically contains impurities such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), and other trace gases. These impurities reduce the energy content of the biogas and can cause corrosion and damage to equipment. Therefore, upgrading biogas is necessary to increase its energy content and reduce impurities. Water scrubbing is a standard method for upgrading biogas that is based on the principle of absorption. Biogas is passed through a liquid that selectively absorbs CO_2 and other impurities, allowing methane (CH_4) to pass through. Water is commonly used as the scrubbing liquid in this process, and it is typically used in a counter-current flow arrangement where the biogas flows in one direction.

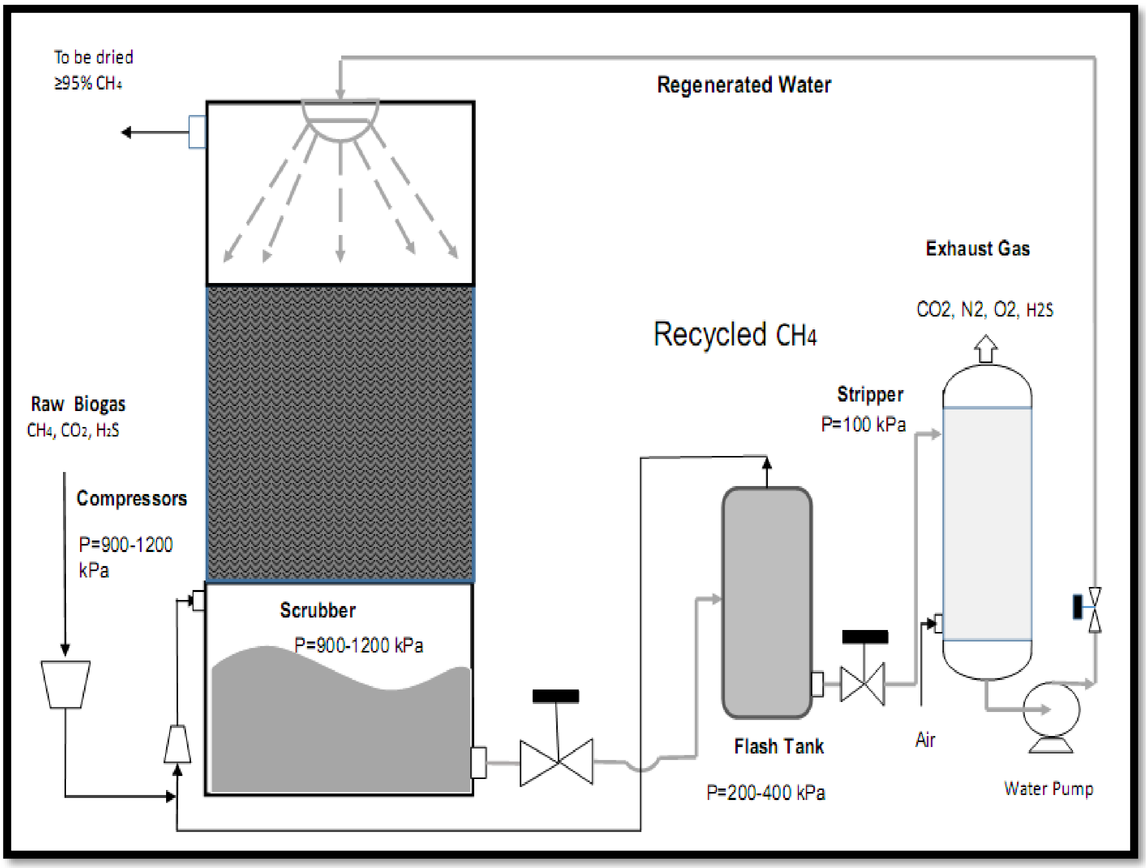


Figure 4.13: Biogas Cleaning and Upgrading Technology

In contrast, the water flows in the opposite direction. As the biogas flows through the water, CO_2 and other impurities are absorbed by the water, leaving behind a higher concentration of methane. The water scrubbing process is typically conducted in three stages: absorption, desorption, and purification. In the absorption stage, biogas is passed through a water scrubber, which absorbs CO_2 and other impurities. The water then flows into a separate tank where it is heated to release the absorbed gases in the desorption stage. The purified biogas is then collected and passed through a gas purifier to remove any remaining impurities before being used for energy generation.

Water scrubbing is a cost-effective and reliable method for upgrading biogas to a higher methane concentration. The technology is simple, easy to operate, and requires no chemicals or additional energy inputs. However, the efficiency of the water scrubbing process depends on several factors, such as the quality of the biogas, the flow rate of the gas and liquid, and the temperature and pressure of the system. Additionally, the water used in the scrubbing process must be periodically replaced or treated to prevent fouling and corrosion.

4.7.2 Purification of H_2S and CO_2 from raw biogas

The purification process of biogas involves the removal of impurities such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S). This process can be achieved through a series of steps, starting with the compression of raw biogas to increase its pressure to around 10-12 bars. The compressed biogas is then directed into a scrubber column, facilitating contact between the biogas and water. The scrubber column contains packing material, including iron oxide pellets and SS-304 pall rings. These materials are strategically arranged within the column, with each section comprising 50% of the packing. This arrangement ensures efficient contact between the raw biogas and water while preventing rusting of the scrubber.

The iron oxide pellets serve the purpose of removing hydrogen sulfide (H_2S) from the biogas. Hydrogen sulfide is a highly toxic and corrosive gas that needs to be eliminated to make biogas suitable for use. The pall rings, on the other hand, are responsible for removing carbon dioxide (CO_2), which is another impurity present in biogas. In the next step of the purification process, high-pressure water is sprayed into the scrubber column using a honeycomb pad and a 10-bar pump. The honeycomb pad ensures that the water is evenly distributed across the packing material. As the water sprays into the column, it comes into contact with the biogas, dissolving and absorbing the CO_2 and H_2S impurities.

The water, along with the dissolved impurities, is then drained out through an outlet. This continuous spraying and draining process helps increase the concentration of methane (CH_4) gas in the biogas. The removal of impurities continues until the desired purity level is achieved, producing pure biogas. Finally, the purified biogas is collected in a balloon or storage container for subsequent use as a fuel source. The entire purification process ensures the biogas is free from harmful impurities, making it a clean and environmentally friendly alternative to traditional fossil fuels.

4.7.3 Biogas compression

After the purification process, the pure biogas is stored in a balloon before compression. A high-pressure compressor compresses the biogas, typically at 200 to 250 bars. This compression process significantly increases the density and energy content of the biogas, making it more suitable for various applications. Once the pure biogas has been compressed, it is filled into bottles or cylinders, ready for use in a spark-ignition (SI) engine. The SI engine, known as a spark-ignition internal combustion engine, relies on a spark to ignite the fuel-air mixture and generate power. Compressed pure biogas as a fuel in the SI engine can effectively drive various mechanical systems, such as vehicles, generators, and other power-generating devices.

The purification of biogas brings several advantages to the overall biogas system. Firstly, it enhances the efficiency of the entire system. By removing impurities such as CO_2 and H_2S, fuel quality is improved. Impurities can decrease the energy content of biogas and adversely affect the combustion process. Therefore, purifying the biogas optimizes its energy content, increasing the efficiency of the SI engine. This results in better performance and higher power output from the engine, providing more usable energy for different applications. Secondly, the purification process contributes to reducing the environmental impact of biogas. Biogas is considered a renewable energy source because it is produced from organic waste materials and has lower greenhouse gas emissions than fossil fuels.

However, biogas can still contain impurities that may have adverse environmental effects when burned. For instance, CO_2, a greenhouse gas, can contribute to global warming.

Figure 4.14: Large-scale biogas purification and utilization in SI engine

Hydrogen sulfide, on the other hand, is a toxic gas that can harm the environment and human health. By removing these impurities through the purification process, the ecological footprint of biogas can be minimized. With its reduced impurity levels, the purified biogas emits fewer pollutants and greenhouse gases when used as a fuel in the SI engine. This translates into a cleaner and more sustainable energy option, contributing to the overall goal of reducing emissions and mitigating climate change.

4.8 Conclusions

- The study suggests that optimizing feed types and using a tumbling effect can improve the biogas production process.
- The Taguchi method can optimize these factors and achieve better biogas production rates with less variability, leading to more consistent outcomes.
- Present results show the best average biomethane (CH_4) generation at 40°C in the case of FW (1:1.5) feed, at 35°C in the case of RVW (1:1.5), and at 35°C in the case of MCW (1:2) feed is received.
- The study found that the tumbling effect had a significant impact on CH_4 gas production, and in the case of MCW feed, it produced an average of 47.9% more CH4 than without the tumbling effect.
- The study also found that tumbling led to faster CH_4 gas production compared to without tumbling. This information can help refine the biogas production process and improve its efficiency in real-world applications.

CHAPTER 5

ENGINE PERFORMANCE ANALYSIS

This chapter investigates using compressed biogas, gasoline, ethanol, methanol, and methyl acetate blends in 4- stroke multiple-cylinder spark ignition (SI) engine. The objective is to evaluate engine performance, combustion analysis, and emission parameters associated with these fuel blends. The following parameters are examined: brake thermal efficiency (BTE), indicated thermal efficiency (ITE), brake-specific fuel consumption (BSFC), brake-specific energy consumption (BSEC), cylinder pressure, mass fraction burned, mean gas temperature, rate of pressure rise, and emissions of nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and carbon dioxide (CO_2).

5.1 Experimental setup

Table 5.1 provides detailed information about the specifications of the engine, specifically the Maruti Wagon R, four-stroke, four cylinders engine, and the experimental setup used to test its performance. This information is essential for understanding the engine's characteristics and analyzing the experiment's results. These specifications determine the engine's power, torque, and efficiency. The test rig consists of several components, including an engine mount, a fuel supply system, an air intake system, an exhaust system, a dynamometer, and various sensors and instrumentation. Each component plays a critical role in the experimental setup, and their design and installation are essential for obtaining accurate and reliable results.

The engine mount is the foundation of the test rig and provides a secure and stable platform for the engine. The mount should be designed to minimize vibration and allow easy access to the engine for maintenance and adjustments. The fuel supply system provides a controlled amount of fuel to the engine. It typically consists of a fuel tank, fuel lines, fuel pump, and fuel injectors. The fuel system should be designed to deliver the correct fuel-air ratio for the engine under various operating conditions. The air intake system provides air to the engine, which is necessary for combustion. It typically consists of an air filter, air ducts, and an intake manifold. The intake system should be designed to deliver the correct amount of air to the engine under various operating conditions.

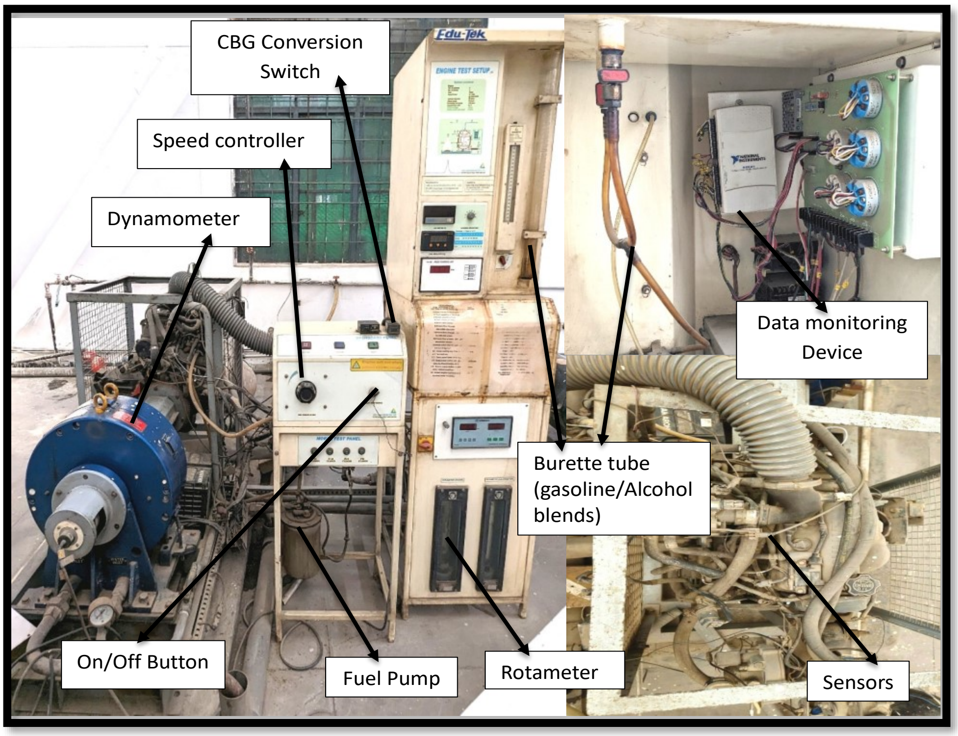


Figure 5.1: Experimental Set up of four-stroke multiple-cylinder SI engine

Table 5.1: Details of the experimental setup

Engine Specification	Details
Stroke Length	72.00 (mm)
Cylinder Bore	68.50 (mm)
Connecting Rod length	112.50 (mm)
Compression Ratio	9.2:1
Swept volume	265.34 (cc)
Engine type	Maruti Wagon R 4 stroke four cylinders
No. of cylinders	4
Maximum power output at 6200 rpm	47.70 kW
Cooling System	Water cooling close system
Orifice Diameter	40 mm
Dynamometer Arm Length	210 mm
Fuel Pipe diameter	33.90 mm
Number Of Cycles	10

The engine's cooling system is a water-cooled closed system, where a liquid coolant circulates through the engine to absorb and dissipate heat generated during engine operation. The cooling system is essential to prevent the engine from overheating and ensure longevity. The exhaust system removes the combustion products from the engine.

It typically consists of an exhaust manifold, pipes, and a muffler. The exhaust system should be designed to minimize backpressure and maximize the flow of exhaust gases. It typically consists of a load cell, torque transducer, and speed sensor. The dynamometer is designed to accurately measure the engine's power output under various operating conditions. The sensors and instrumentation measure different engine parameters, such as temperature, pressure, and exhaust emissions. It can include pressure transducers to measure cylinder pressure, thermocouples to measure exhaust gas temperature, and oxygen sensors to measure the air-fuel ratio. The sensors and instrumentation should be designed to provide accurate and reliable measurements under various operating conditions. The number of cycles refers to the number of times the engine completes one entire operation process during the experiment. In this particular scenario, the engine undergoes ten cycles, emphasizing the importance of the number of cycles for ensuring accuracy and consistency in the experimental results.

5.2 Details and properties of fuels used in the experiment

Table 5.2 lists several fuel properties for different types of fuels, including gasoline, ethanol blends, methanol blends, biodiesel, compressed natural gas, and hydrogen sulfide. Each of these fuels has different chemical compositions and properties, making them suitable for various applications. Density at 40°C measures how much mass-energy has per unit volume at a specific temperature. It is essential because it affects the amount of fuel that can be stored in a given volume, as well as the energy content of the fuel.

The density of the fuels listed in the table ranges from 721 kg/m^3 to 757 kg/m^3, with the CBG fuel having the lowest density of 0.90 kg/m^3. The higher the density, the more fuel can be stored in a given volume, but the lower the energy content. Lower heating value (LHV) measures the amount of energy that can be obtained from a unit of fuel when wholly burned. This property is essential because it determines the fuel efficiency and the amount of energy that can be generated.

Table 5.2: Fuels properties (Ethanol, Methanol, Methyl acetate, and CBG)

Fuel Properties	Unit	G100%	E10%	E20%	M10%	M20%	MA10%	MA20 %	CBG
Chemical formula	-	C_5-C_{12}	C_2H_5OH	C_2H_5OH	CH_3OH	CH_3OH	$C_3H_6O_2$	$C_3H_6O_2$	CH_4
Density at 40°C	kg/m^3	721	734	735	723	736	737	757	0.90
Lower heating value	MJ/kg	44	42.38	40.76	41.59	39.18	41.75	39.5	48.5
Flashpoint °C	-	26.3	30.5	29.8	28.2	27.5	21.5	18.1	-
Fire point °C	-	25.1	28.9	29.7	29.9	31.5	28.3	31.48	-
Methane (CH_4)	%	-	-	-	-	-	-	-	96.6
Hydrogen sulfide (H_2S)	%	-	-	-	-	-	-	-	0.0 ppm
O_2	%	-	-	-	-	-	-	-	0.4
CO_2	%	-	-	-	-	-	-	-	3.0

The LHV of the fuels listed in the table ranges from 39.18 MJ/kg to 48.5 MJ/kg, with the CBG fuel having the highest LHV. The higher the LHV, the more energy can be obtained from a given quantity of fuel. The flash point is the lowest temperature when a fuel gives off enough vapors to ignite in the air. It is an essential property because it affects the safety of fuel handling and storage. The flash point of the fuels listed in the table ranges from 18.1°C to 31.5°C. The higher the flash point, the less likely the fuel is to ignite. The fire point is the temperature at which fuel gives off enough vapors to sustain combustion. It is an essential property because it affects the safety of fuel handling and storage. The fire point of the fuels listed in the table ranges from 25.1°C to 31.48°C. Each of these characteristics collectively informs the selection and safe utilization of these fuels across various applications.

5.2.1 Gasoline

Gasoline, or petrol, is a hydrocarbon-based fuel used primarily for internal combustion engines. It is a complex mixture of hydrocarbons that varies in composition depending on the source and refining process. It is the most commonly used fuel for transportation globally and is used in various other applications, such as power generation and industrial processes. The primary gasoline components are hydrocarbons, molecules composed of hydrogen and carbon atoms. These hydrocarbons can be categorized into three main types: paraffins, olefins, and aromatics. Paraffins are straight-chain hydrocarbons, while olefins contain a double bond between two carbon atoms. Aromatics are hydrocarbons containing a ring of carbon atoms with alternating double bonds. The composition of gasoline varies depending on the refining process, but typically, it has about 20-50% paraffin, 20-30% olefins, and 20-40% aromatics [214].

Gasoline is produced by refining crude oil, separating the different hydrocarbons based on their boiling points. This process involves distillation, cracking, and reforming, among other techniques. The refining process can also include the addition of various additives to improve the fuel's performance and reduce emissions. These additives include detergents to clean engine parts, anti-knock agents to prevent engine knocking, and oxygenates to improve combustion efficiency and reduce emissions [215]. It is used primarily in internal combustion engines, which use the fuel to power the engine through combustion. When gasoline is burned in an engine, it releases energy through heat and pressure, turning the engine's crankshaft and generating mechanical power. The efficiency of this process can vary depending on the engine design and the fuel's composition.

However, gasoline use in internal combustion engines has been associated with air pollution and climate change. Gasoline combustion releases various pollutants into the air, such as carbon monoxide, nitrogen oxides, and volatile organic compounds, which can adversely affect human health and the environment [216]—furthermore, the combustion of gasoline releases carbon dioxide, a greenhouse gas that contributes to climate change. As a result, efforts are underway to reduce gasoline use and transition to alternative fuels and propulsion systems. In addition to gasoline, alternative fuels such as biofuels, natural gas, and hydrogen are being developed and implemented for transportation. These alternative fuels can potentially reduce greenhouse gas emissions and improve air quality. Additionally, electric and hybrid vehicles that use electricity as a fuel source are becoming increasingly popular as a way to reduce gasoline use and associated emissions.

5.2.2 Ethanol

Ethanol or bioethanol is a renewable, domestically produced, and environmentally friendly fuel. It, also known as ethyl alcohol or grain alcohol, is a clear, colorless liquid alcohol produced by the fermentation of sugars and starches in plant-based materials. It is a renewable fuel source used primarily as a fuel additive to reduce emissions and improve gasoline performance. Ethanol as a fuel additive began in the 1970s as a response to the oil embargo and concerns about air pollution. Ethanol is produced from various feedstocks, including corn, sugarcane, and switchgrass. In the United States, corn is the primary feedstock for ethanol production, accounting for over 90% of ethanol production in 2020 [217]. One of the direct benefits of using ethanol as a fuel additive is its ability to reduce emissions. Ethanol is an oxygenate, which contains oxygen that can help the fuel burn more completely, reducing harmful emissions such as carbon monoxide and particulate matter [218]. Additionally, ethanol has a higher octane rating than gasoline, which can improve gasoline performance by reducing engine knock and enhancing fuel efficiency [217].

However, using ethanol as a fuel additive is not without its challenges. One concern is the potential impact on food prices and availability, as the use of corn for ethanol production has been criticized for diverting corn from food and feed markets [218]. Additionally, the production and use of ethanol require significant amounts of water and energy. The environmental impacts of ethanol production can vary depending on the feedstock and production methods used [219]. Despite these challenges, ethanol remains an essential component of the renewable fuels industry. In the United States, the Renewable Fuel Standard [220] requires using renewable fuels such as ethanol to reduce greenhouse gas emissions and promote energy security [218]. Additionally, some countries, such as Brazil, have implemented policies to encourage ethanol as a transportation fuel, including mandating ethanol blends in gasoline [218].

5.2.3 Methanol

Methanol is a colorless, flammable liquid with a slightly sweet odor widely used as a feedstock for producing chemicals and fuels. It is also known as wood alcohol or methyl alcohol. It is made through the destructive distillation of wood, coal, or other organic matter or through the hydrogenation of carbon monoxide. It is a simple alcohol with the chemical formula CH3OH, composed of a single carbon atom, three hydrogen atoms, and one oxygen atom [221]. It has a variety of industrial uses, including as a solvent, antifreeze, and feedstock for producing formaldehyde, acetic acid, and methyl tert-butyl ether (MTBE). It is also used as a fuel, particularly in racing cars, boats, and other high-performance vehicles. It has a high octane rating and can be produced from renewable sources such as biomass and municipal waste [222]. In recent years, there has been growing interest in using methanol as a fuel for the transportation sector due to its potential to reduce greenhouse gas emissions and dependence on fossil fuels [223].

Methanol has several advantages as a transportation fuel. It is a high-octane fuel that can be used in spark-ignition engines, similar to gasoline, with only minor modifications. Methanol can also be blended with gasoline to produce methanol-gasoline blends, reducing emissions of harmful pollutants such as particulate matter, carbon monoxide, and nitrogen oxides [222]. Furthermore, methanol can be produced from various renewable sources, such as biomass, municipal waste, and carbon dioxide, making it a potentially sustainable fuel option [223].

However, the use of methanol as a fuel also has its challenges. Methanol has a lower energy content than gasoline, which can result in reduced fuel efficiency and range. Additionally, methanol is toxic and highly flammable, requiring specialized handling and storage. Methanol can also have negative environmental impacts if not produced and used responsibly, particularly concerning using non-renewable feedstocks and releasing pollutants during production and use [222]. Despite these challenges, methanol remains an important feedstock and fuel in many industries. The Methanol Institute promotes producing and using methanol as a sustainable fuel and feedstock in the United States. The organization advocates using methanol in transportation and supports research and development of new methanol technologies (MI). Additionally, some countries, such as China, have implemented policies encouraging using methanol as a transportation fuel, including mandating methanol-gasoline blends in certain regions [223].

5.2.4 Methyl acetate

Methyl acetate is a chemical compound used in various industrial applications, including as a solvent, flavoring agent, and intermediate in producing other chemicals. It is also gaining popularity as a biofuel due to its potential as a sustainable alternative to fossil fuels. Chemically, methyl acetate is an ester with the formula $CH3COOCH3$, and it is a clear and colorless liquid with a fruity odor. It can be produced from various sources, including biomass, waste, and natural gas [224]. Making methyl acetate from these sources is more sustainable than producing fossil fuels, as it reduces carbon emissions and utilizes renewable resources. It has several advantages over traditional fossil fuels as a biofuel. It is a cleaner-burning fuel that produces fewer greenhouse gases and pollutants, such as carbon monoxide, nitrogen oxides, and particulate matter [225]. It also has a higher-octane rating than gasoline, which allows for more efficient combustion in engines.

Additionally, it has a lower vapor pressure than gasoline, which reduces the risk of vapor lock in high-temperature conditions [226]. The use of methyl acetate as a biofuel is still limited due to its high cost of production and lack of infrastructure for distribution. However, research and development in this area are ongoing, and with further technological advancements, methyl acetate fuel may become a more feasible and sustainable option. In addition to its potential as a biofuel, methyl acetate has many industrial applications. It is commonly used as a solvent in producing paints, coatings, and adhesives. It is also used as a flavoring agent in the food industry and as an intermediate in making other chemicals, such as pharmaceuticals and fragrances. The safety of methyl acetate has also been extensively studied. According to the National Library of Medicine, methyl acetate is a low-toxicity compound generally safe for industrial and consumer applications. However, it can irritate the skin, eyes, and respiratory tract if inhaled or comes into contact with the skin [227].

5.2.5 Compressed biogas

Compressed biogas is a renewable natural gas produced from decomposing organic matter, such as agricultural waste, municipal solid waste, and wastewater. CBG can be used as a transportation fuel and has many benefits over traditional fossil fuels.

The production of compressed biogas starts with the collection of organic waste material. This waste is then processed in an anaerobic digester, a closed vessel that decomposes organic matter without oxygen [196]. The decomposition process produces biogas, a mixture of methane, carbon dioxide, and other trace gases. The biogas is then purified to remove impurities and moisture, and compressed to high pressures of up to 250 bar, to produce compressed biogas [228]. Compressed biogas is a clean, renewable, and sustainable fuel with several properties that make it attractive as a transportation fuel. The composition of CBG typically consists of 90-95% methane, 5-10% carbon dioxide, and small amounts of other trace gases such as hydrogen, nitrogen, and oxygen. It has a high energy content of around 44-49 MJ/kg, similar to natural gas [229]. It is also non-toxic, non-corrosive, and has a lower flammability range than other compressed gases such as propane. Compressed biogas can be used as fuel for compressed natural gas (CNG) vehicles. CNG vehicles have lower emissions of greenhouse gases and pollutants than traditional gasoline and diesel vehicles.

CBG is also a renewable fuel that can replace fossil fuels and, as such, can contribute to reducing carbon emissions and combating climate change [230]. The use of CBG as a transportation fuel is multiplying in many countries, including India, China, and the United States. Apart from its use as a transportation fuel, compressed biogas can also be used for cooking and heating. It can be used in domestic and commercial settings and is a clean-burning fuel that produces fewer pollutants than traditional fossil fuels [231]. The production and use of compressed biogas face several challenges. The availability of organic waste material for biogas production is inconsistent throughout the year, and the collection and transportation of waste can be expensive.

Additionally, the high cost of biogas production and the lack of infrastructure for distribution are barriers to its widespread use [232]. However, the future of compressed biogas is promising, as advancements in technology are making its production more efficient and cost-effective. Governments also support compressed biogas by providing incentives and subsidies to promote its use. The increasing demand for clean and sustainable energy sources is expected to drive the growth of compressed biogas as a viable alternative to traditional fossil fuels.

5.3 Details of equipment used during the experiment

Several pieces of equipment are typically used during the experiment to facilitate data collection and analysis. The specific equipment required may vary depending on the experiment's nature and the measured parameters.

5.3.1 Viscometer

The Anton Paar SVM 3000 is a capillary viscometer designed to measure the viscosity of opaque and transparent fluids. This instrument is widely used in the paint, coating, and adhesive industries to determine the viscosity of products and ensure quality control during manufacturing. The SVM 3000 is designed with a U-shaped glass tube filled with the sample, and the time required to flow through the tube is measured. The instrument uses the capillary flow principle, which states that the flow rate of a fluid is proportional to the pressure gradient in the tube. The fluid's viscosity is then calculated using the Hagen-Poiseuille equation, which relates the flow rate, pressure gradient, and tube dimensions to the fluid's viscosity.

The SVM 3000 is equipped with a digital display that shows the sample's viscosity in real-time. The instrument has a measurement range of 0.2-2000 mPa·s and can handle sample volumes as small as 0.5 ml. The apparatus also can measure temperature, which is essential for viscosity measurements, as viscosity is highly dependent on temperature. One of the key features of the SVM 3000 is its ease of use. The instrument is fully automated; the user only needs to input the sample volume and start the measurement. The device will then measure and display the results on the digital display. The SVM 3000 is also designed with a self-cleaning feature, which ensures that the glass tube is free of residual samples before the subsequent measurement. Another feature of the SVM 3000 is its flexibility. The instrument can be used with a range of tube sizes, from 0.6 mm to 1.2 mm, which allows users to measure samples with a wide range of viscosities.

Depending on the application's requirements, the instrument can also be used with different sample volumes, from 0.5 ml to 10 ml. The SVM 3000 is also equipped with various accessories that enhance its capabilities. One such accessory is the optional heating and cooling system, which allows users to control the temperature of the sample during the measurement. This is important, as viscosity is highly dependent on temperature, and temperature control ensures accurate and reproducible results. Another accessory for the SVM 3000 is the automated sample changer, which allows users to measure up to 30 samples in a single run. This feature is handy in high-throughput applications where many samples must be measured quickly and efficiently.

Figure 5.2: Viscometer- fuel density tester

In addition to the accessories, Anton Paar offers a range of software packages that enhance the capabilities of the SVM 3000. The software allows users to analyze advanced data, including viscosity vs. shear rate curves, viscosity vs. temperature curves, and time-dependent viscosity measurements. The software also enables users to create custom measurement protocols, which can be saved and reused for future measurements. Overall, the Anton Paar SVM 3000 is a versatile and reliable instrument for measuring the viscosity of opaque and transparent fluids. Its ease of use, flexibility, and range of accessories make it an ideal choice for various applications, including quality control, research, and development in the paint, coating, and adhesive industries.

5.3.2 Junkers calorimeter

The Junkers calorimeter is a laboratory apparatus to determine a fuel's calorific value. The calorific value is the heat released when a fuel is burned. This value is essential in the energy field because it determines the energy content of the fuel, which can be used to calculate the efficiency of energy conversion processes. The device consists of a cylindrical vessel made of brass or copper with a volume of around 1 liter. Inside the vessel is a coil of copper tubing, which is heated by a burner.

The fuel to be tested is injected into the coil and ignited, causing it to burn. The heat the combustion releases is transferred to the water surrounding the ring, causing it to heat up. The rise in temperature of the water is measured and used to calculate the calorific value of the fuel. The Junkers calorimeter is a relatively simple apparatus that requires careful calibration and precise measurements to obtain accurate results. The instrument must be thoroughly cleaned and dried before each use to prevent contamination of the fuel sample. The fuel must be injected into the coil constantly, and the burner must be adjusted to maintain a steady flame.

The water temperature must be measured before and after the combustion, and the temperature rise must be corrected for heat loss to the surroundings. The calorific value of the fuel is calculated using a formula that considers the fuel's mass, the water group, and the temperature rise. It is widely used in energy research and development, particularly in testing solid and liquid fuels such as coal, oil, and natural gas. It is also used to test biomass and biofuels, which are becoming increasingly important as renewable energy sources. Assessing the calorific value of fuels is crucial for gauging their energy potential and optimizing their combustion processes. H. L. Scientific Industries specializes in manufacturing and supplying a wide range of laboratory equipment, including the highly reputable Junkers calorimeter. This instrument is designed to deliver precise and dependable measurements of fuel calorific values. Specifically, the Junkers calorimeter by H. L. Scientific Industries is engineered to ascertain the calorific value of gaseous fuels, falling within the range of 1000 to 26000 kilocalories per cubic meter. Additionally, it comes equipped with a Measuring Jar featuring capacities of 2 liters and 50 milliliters, complete with rubber tubing to facilitate the connection of gas and water.

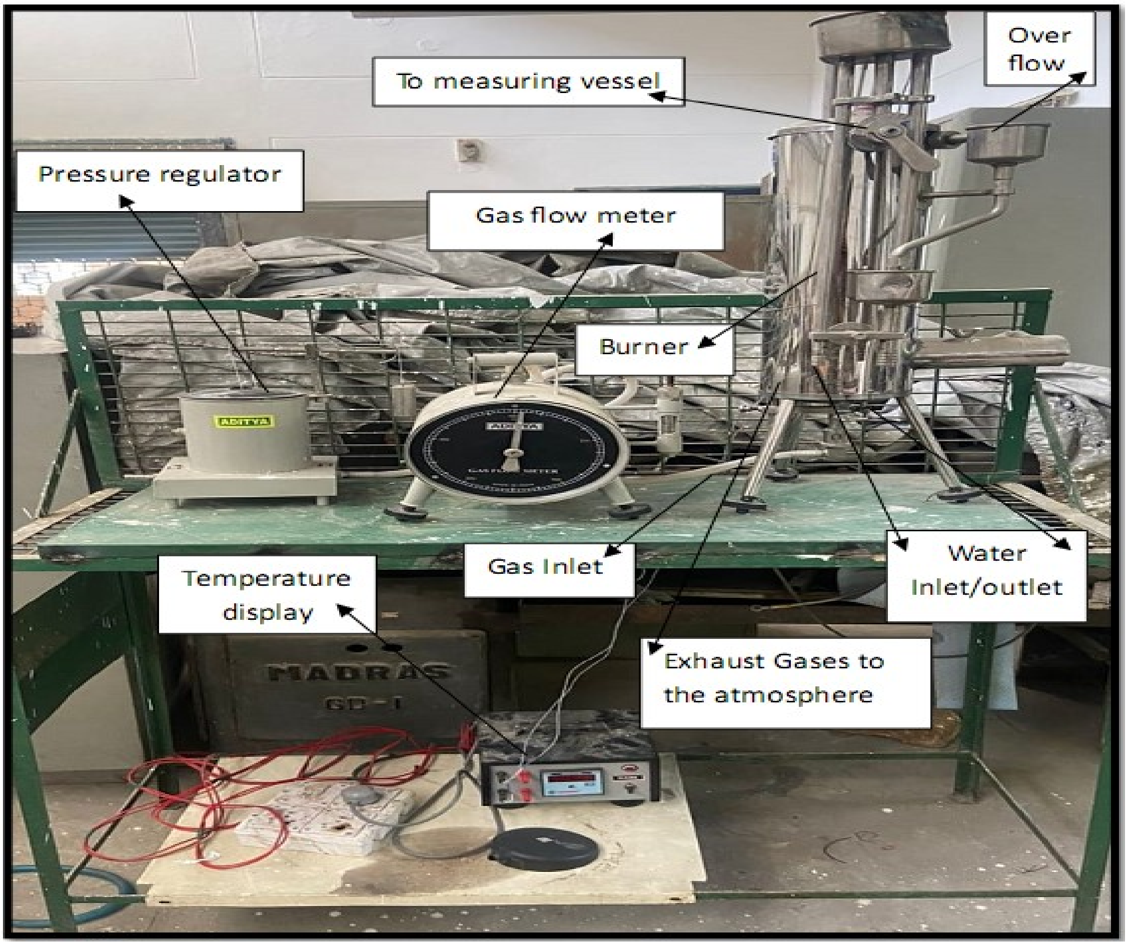


Figure 5.3: Calorimeter, equipment for checking the calorific value of a fuel

Scientific Industries is made of high-quality materials such as brass or copper, ensuring durability and corrosion resistance. The instrument is designed to be easy to use, with clear instructions and a user-friendly interface. The burner is adjustable and easily controlled to maintain a steady flame. The apparatus is equipped with a thermometer for measuring the temperature of the water and a pressure gauge for monitoring the pressure inside the vessel—the Junkers calorimeter-H. L. Scientific Industries is designed to meet international standards for calorimetry, ensuring that the measurements obtained are accurate and reliable.

5.3.3 Emission gas analyzer

An emission gas analyzer is a device used to measure the pollutants emitted from combustion engines. AVL is a company that produces emission gas analyzers for a wide range of applications, including automotive, marine, and power generation. AVL’s emission gas analyzer systems are designed to measure the concentration of various pollutants in exhaust gas, including carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and carbon dioxide (CO_2).

Figure 5.4: Fuel emission tester machine AVL

The AVL emission gas analyzer is a compact, portable device that can be easily transported and used in many testing environments. The apparatus comprises a sample probe, a gas conditioning system, and an analysis unit. The sample probe is inserted into the exhaust pipe of the tested engine, drawing a sample of the exhaust gas into the gas conditioning system. The gas conditioning system removes any moisture and cools the gas to a suitable temperature for analysis. The gas is then passed through filters and scrubbers that remove particulate matter and other impurities that could interfere with the investigation. The analysis unit of the AVL emission gas analyzer consists of a series of sensors and detectors that measure the concentration of various pollutants in the exhaust gas. The sensors are typically based on multiple technologies, including infrared spectroscopy, electrochemical sensors, and chemiluminescence. The sensors are calibrated to ensure accuracy, and the device is typically designed to provide real-time measurements of the pollutants in the exhaust gas. AVL emission gas analyzers are designed to be user-friendly and easy to operate. The device typically features a touch-screen display that provides real-time data and allows the user to control the device’s functions. The device is also designed to be rugged and durable, with high protection against shock, vibration, and environmental factors.

The AVL emission gas analyzer is widely used in the automotive industry to measure vehicle emissions during development and testing. Its key advantage is providing real-time pollutant concentration measurements, enabling real-time adjustments to engine parameters and test conditions for performance optimization and emission reduction. This device is highly accurate, ensuring reliable and consistent measures with adherence to international emissions testing standards like Euro 6 in the European Union and Tier 4 by the United States Environmental Protection Agency (EPA). It's also designed to work with various fuels, such as gasoline, diesel, and natural gas.

5.4 Experimental procedure

This study delves into the combustion characteristics of various fuel blends, encompassing gasoline, ethanol, methanol, methyl acetate, and CBG (Compressed Biogas). To assess these blends, different alcohols like ethanol, methanol, and methyl acetate were combined with gasoline at varying proportions, resulting in six distinct blends: G90E10, G80E20, G90M10, G80M20, G90MA10, and G80MA20. The quantification of gasoline and alcohol blends was conducted within a burette tube at one-minute intervals.

The experimental data collection involved setting the dynamometer load to 4 kg (equivalent to a torque of 8.24 Nm) and adjusting the speed from 2000 to 4500 rpm. The study also encompasses an investigation into the combustion properties of CBG. To procure pure biogas, raw biogas undergoes a purification process involving CO_2 and H_2S scrubbers, yielding a CH_4 concentration of up to 96.6%.

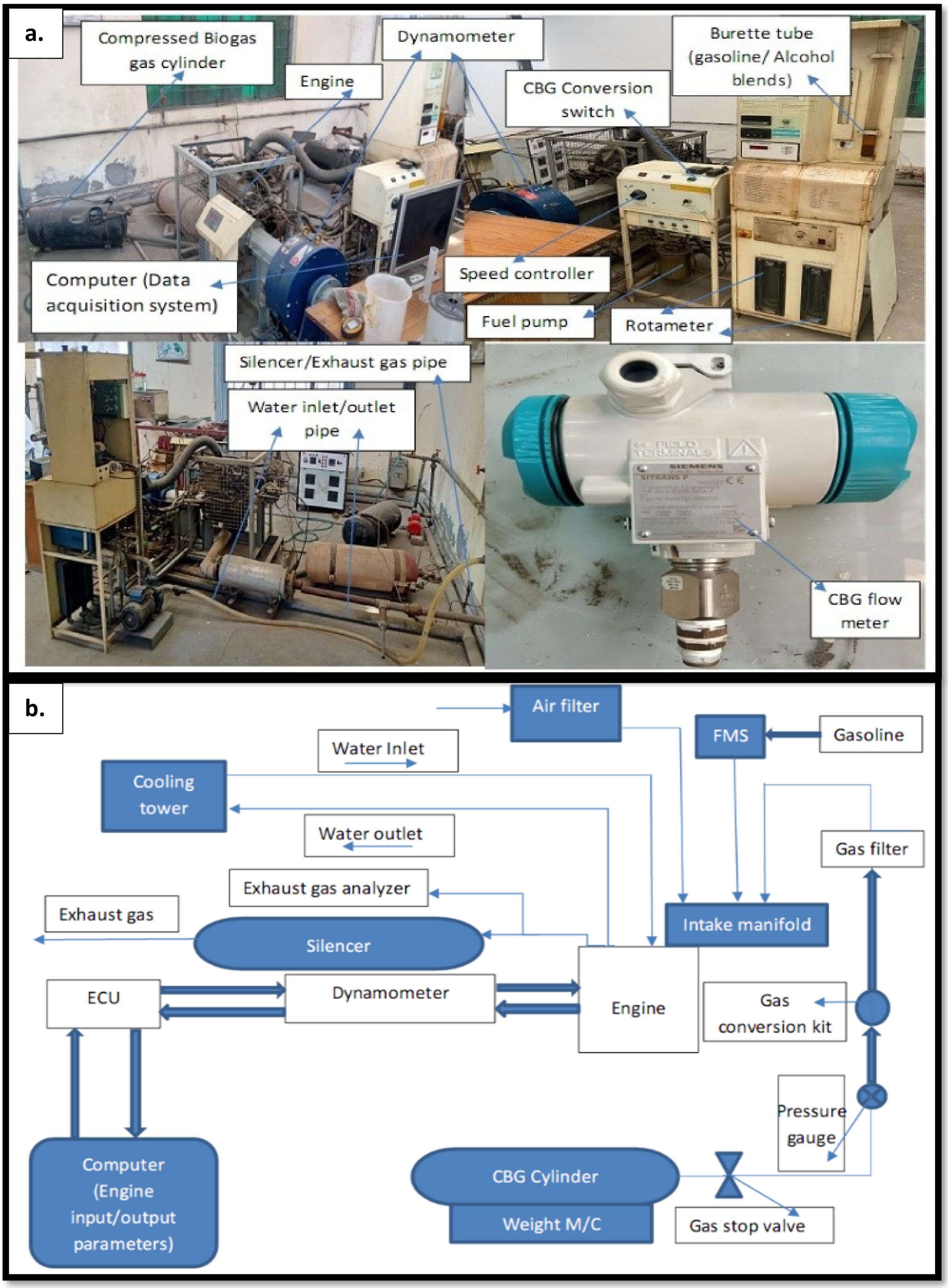


Figure 5.5: (a) Experimental setup with parameters measuring instruments (b) Schematic diagram of the experimental setup

This purified CBG is subsequently introduced into a high-pressure cylinder with the aid of a compressor. Various safety measures have been implemented, including a gas stop valve, pressure gauge, gas conversion kit, and gas filter. Throughout the experiment, a cooling system supplied water to maintain an optimal temperature within the engine setup. Rotameters were employed to fine-tune the flow rate of these cooling waters.

The study further encompassed comprehensive compression studies involving gasoline, alcohol blends, and CBG fuels. This entailed an analysis of crucial combustion parameters such as cylinder pressure, rate of pressure rise, mass fraction burned, pressure-volume relationships, mean gas temperature, thermal efficiencies, Brake Specific Fuel Consumption (BSFC), Brake Specific Energy Consumption (BSEC), among others. The acquired experimental data was logged from the National Instruments (NI) unit to a computer with the assistance of specialized IC Engine software, as depicted in Figure 5.5.

This software is tailored for analyzing internal combustion engines and is adept at scrutinizing engine performance across various operational conditions. This investigation addresses the combustion traits of a diverse range of fuel blends, spanning gasoline, alcohol, and CBG. The experimental protocol is meticulously outlined, incorporating specific details on blend proportions, data collection intervals, and safety precautions.

The study also emphasizes sophisticated analytical tools, including specialized software designed to dissect and understand internal combustion engine behavior under varying conditions.

5.5 Uncertainty analysis

Uncertainty analysis is a crucial process for assessing the accuracy of experimental data. It involves considering two main types of uncertainties: Type A, which pertains to random errors, and Type B, which relates to systematic errors. Type B uncertainty is the focus in this particular case, as the data follows a uniform distribution [1]. The standard uncertainty of the instruments used for measurement is determined using Equation (1), which states:

$$\text{Standard Uncertainty} = (\text{Accuracy of instrument})/\sqrt{3} \qquad (1)$$

Here, the instrument's accuracy is divided by the square root of three to find the standard uncertainty.

When a function Y is dependent on multiple input parameters or independent variables, the uncertainty in the measured value of Y is determined by Equation (2):

$$U(Y) = \sqrt{\left(\frac{\partial Y}{\partial x_1} \, . \, u(x_1)\right)^2 + \left(\frac{\partial Y}{\partial x_2} \, . \, u(x_1)\right)^2 \ldots\ldots\ldots \left(\frac{\partial Y}{\partial x_n} \, . \, u(x_n)\right)^2} \qquad (2)$$

U(Y) represents the uncertainty associated with the measured function Y in this equation. The terms $u(x_1)$ through $u(x_n)$ represent the uncertainties in the independent variables (x_1 through x_n) that influence the function Y. The partial derivatives ($\partial Y/\partial x_1$, $\partial Y/\partial x_2$, ..., $\partial Y/\partial x_n$) quantify how changes in each independent variable affect the function Y, and they are multiplied by their respective uncertainties before being squared. The results are then summed and square-rooted to obtain the overall uncertainty in the measured value of Y.

Sample calculations for exhaust gas composition (CO_2)

Uncertainty analysis for the emission analysis of CO_2 with the provided instrument specifications and repeated measurements, follow these steps:

Step 1: Collect Repeated Measurements

Multiple measurements taken during an experiment: 13%, 12.5%, 12%, 13%, and 12.5%.

Step 2: Calculate the Mean (Average)

Find the average (mean) of these measurements:

Mean ($\bar{x}$) = (13 + 12.5 + 12 + 13 + 12.5) / 5 = 63 / 5 = 12.6%

Step 3: Calculate the Variance and Standard Deviation (Type A Uncertainty)

Calculate the variance and standard deviation to quantify how much the measurements vary around the mean:

Variance (s^2) = $\Sigma(xi - \bar{x})^2 / (n - 1)$

Variance = $[(0.4)^2 + (0.1)^2 + (0.6)^2 + (0.4)^2 + (0.1)^2] / 4 \approx 0.1725\%$

Standard Deviation (σ) ≈ √(Variance) ≈ √(0.1725%) ≈ 0.4156%

Step 4: Calculate the Standard Error of the Mean (SEM)

Calculate the standard error of the mean (SEM) as follows:

SEM = $\sigma / \sqrt{n} \approx 0.4156\% / \sqrt{5} \approx 0.1858\%$

Step 5: Determine the Standard Uncertainty (Type B Uncertainty) of the Instrument

Given the instrument specifications:

Accuracy = ±0.1% (Type B uncertainty)

Standard Uncertainty of the Instrument = (Accuracy of instrument) / $\sqrt{3} \approx 0.1\% / \sqrt{3} \approx 0.0577\%$

Step 6: Combine Type A and Type B Uncertainties

Combine the standard uncertainty from the instrument (Type B) with the standard error of the mean (Type A) using the root-sum-of-squares method:

Combined Uncertainty (U) = $\sqrt{(\text{SEM}^2 + (\text{Standard Uncertainty of the Instrument})^2)}$

$U \approx \sqrt{((0.1858\%)^2 + (0.0577\%)^2)} \approx 0.1971\%$

Considering both Type A and Type B uncertainties, the combined uncertainty of approximately ±0.1971% represents the range within which the true value of CO_2 concentration is likely to fall. This value considers the random variability in measurements and the uncertainty associated with the instrument's accuracy. Similarly, other parameters will be calculated.

Uncertainty analysis for BSFC

Given Data:

Fuel flow rate (F) = 1.43 kg/hr

Brake power (BP) = 2.59 kW

Uncertainty in fuel flow rate (ΔF) = ±0.025 kg/hr

Uncertainty in brake power (ΔBP) = ±0.27 kW

1. Define the Formula for BSFC:

$$\text{BSFC} = \frac{\text{F}}{\text{BP}}$$

2. Identify the Measured Parameters:

Fuel flow rate (F) = 1.43 kg/hr

Brake power (BP) = 2.59 kW

3. Determine Uncertainties in Measurements:

Given uncertainties:

ΔF = ±0.025 kg/hr

ΔBP = ±0.27 kW

4. Calculate BSFC with Nominal Values:

Substitute the nominal values into the formula to find the nominal BSFC:

$$\mathrm{BSFC} = \frac{1.43}{2.59} = 0.551\ \mathrm{kg/kWh}$$

5. **Calculate Partial Derivatives:**

Calculate the partial derivatives of BSFC with respect to each measured parameter.

$$\frac{\partial \mathrm{BSFC}}{\partial \mathrm{F}} = \frac{1}{\mathrm{BP}}; \frac{\partial \mathrm{BSFC}}{\mathrm{BP}} = \frac{\mathrm{F}}{\mathrm{BP}^2}$$

6. Calculate Uncertainties in Measured Parameters:

Given uncertainties:

ΔF = ±0.025 kg/hr

ΔBP = ±0.27 kW

7. **Calculate Uncertainties in BSFC:**

Use the law of propagation of uncertainty to estimate the uncertainty in BSFC:

$$\Delta(\mathrm{BSFC}) = \sqrt{\left(\frac{1}{\mathrm{BP}} \,.\Delta\mathrm{F}\right)^2 + \left(\frac{\mathrm{F}}{\mathrm{BP}^2} \,.\Delta(\mathrm{BP})\right)^2}$$

$$\Delta(\mathrm{BSFC}) = \sqrt{\left(\frac{1}{2.59} \,.0.025\right)^2 + \left(\frac{1.43}{(2.59)^2} \,.0.27\right)^2} \qquad = 0.123\mathrm{kg/kWh}$$

8. Express Uncertainty:

The BSFC is estimated to be 0.551±0.123 kg/kWh at a 95% confidence level.

This analysis provides an estimate of the uncertainty associated with the BSFC measurement. It takes into account the uncertainties in the measured parameters (fuel flow rate and brake power) and their impact on the final result. Similarly, other parameters (Brake power, Brake thermal efficiency) will be calculated.

Table 5. 3: List of Utilized Instruments with Associated Uncertainties and Uncertainty in Observed Parameter

Instruments	**Observed Parameter**	**Accuracy**	**Range**	**Standard Uncertainty of the Instrument**	**Uncertainty calculated in observed parameter**
Tachometer	Engine speed	±1%	1000-6000 rpm	±0.55%	±1.3 %
Fuel flow meter	Mass flow rate	±0.02%	0-20 kg/h	±0.015%	±0.025%
Thermocouple	Temperature	±2°C	0°C - 800°C	±1°C	±2.5°C
Viscometer SVM 3000	Viscosity	±1%	0.2 - 600,000 mPa·s	±0.5%	±2.0%
Biogas Analyzer 5000	Gas Composition (CH_4)	±0.5%	0-100%	±0.3%	±0.70%
	Gas Composition (CO_2)	±0.2	0-100%	±0.11	±0.85%
	Gas Composition (O_2)	±0.1%	0-25%	±0.05%	±0.35%
AVL Exhaust Gas Analyzer	Gas Concentrations (CO)	±0.02%	0-10 %	±0.011%	±0.015%
	Gas Concentrations (CO_2)	±0.1%	0-25 %	±0.05%	±0.19%
	Gas Concentrations (HC)	±20 ppm	0-10000 ppm	±11 ppm	±12.5 ppm
Junkers Calorimeter	Calorific Value	±1%	1000-26000 kcal/m^3	±0.55%	±0.65%

5.6 Results

The study examines various parameters for evaluating engine performance, understanding combustion processes, and characterizing emission profiles. Among the pivotal performance metrics scrutinized, one stands out: Brake Power (BP), denoting the power produced by the engine and transmitted to the output shaft. Another vital parameter of interest is Brake Thermal Efficiency (BTE), which expresses the ratio of brake power to the total heat energy input into the engine. In addition, Indicated Thermal Efficiency (ITE) is a critical indicator in assessing the effectiveness of the combustion process within the engine.

Table 5.4: Experimental results for gasoline, alcohol blends (Ethanol, Methanol, Methyl acetate), and CBG fuels

G100	Speed (RPM)	Load (kg)	Torque (Nm)	BP (kW)	IP (kW)	BTE (%)	ITE (%)	ME (%)	BSFC (kg/kWh)	ISFC (kg/kWh)	Fuel flow rate (kg/h)
	2000	4	8.24	1.73	3.85	21.76	48.52	44.85	0.38	0.168	0.65
	2500	4	8.24	2.16	3.71	15.69	26.99	58.15	0.52	0.301	1.12
	3000	4	8.24	2.59	3.67	14.84	21.02	70.59	0.55	0.389	1.43
	3500	4	8.24	3.02	3.98	15.87	20.88	75.98	0.52	0.391	1.56
	4000	4	8.24	3.45	4.37	16.74	21.18	79.02	0.49	0.386	1.69
	4500	4	8.24	3.88	4.4	15.63	17.8	87.8	0.52	0.461	2.03
G90E10	Speed (RPM)	Load (kg)	Torque (Nm)	BP (kW)	IP (kW)	BTE (%)	ITE (%)	ME (%)	BSFC (kg/kWh)	ISFC (kg/kWh)	Fuel flow rate (kg/h)
	2000	4	8.24	1.73	3.85	15.87	35.54	44.65	0.54	0.238	0.92
	2500	4	8.24	2.16	3.71	15.41	26.5	58.15	0.55	0.32	1.19
	3000	4	8.24	2.59	3.67	13.87	19.6	70.76	0.61	0.433	1.59
	3500	4	8.24	3.02	3.98	12.95	17.08	75.82	0.66	0.497	1.98
	4000	4	8.24	3.45	4.37	13.87	17.6	78.8	0.61	0.482	2.11
	4500	4	8.24	3.88	4.4	14.4	16.32	88.24	0.59	0.52	2.29
G80E20	Speed (RPM)	Load (kg)	Torque (Nm)	BP (kW)	IP (kW)	BTE (%)	ITE (%)	ME (%)	BSFC (kg/kWh)	ISFC (kg/kWh)	Fuel flow rate (kg/h)
	2000	4	8.24	1.73	3.85	17.28	38.65	44.71	0.51	0.228	0.88
	2500	4	8.24	2.16	3.71	15.43	26.63	57.94	0.57	0.331	1.23
	3000	4	8.24	2.59	3.67	14.4	20.38	70.65	0.61	0.433	1.59
	3500	4	8.24	3.02	3.98	14.4	18.99	75.83	0.61	0.464	1.85
	4000	4	8.24	3.45	4.37	15.03	19.02	79.02	0.59	0.464	2.03
	4500	4	8.24	3.88	4.4	14.4	16.33	88.18	0.61	0.54	2.38
G90M10	Speed (RPM)	Load (kg)	Torque (Nm)	BP (kW)	IP (kW)	BTE (%)	ITE (%)	ME (%)	BSFC (kg/kWh)	ISFC (kg/kWh)	Fuel flow rate (kg/h)
	2000	4	8.24	1.73	3.85	13.25	29.5	44.92	0.65	0.293	1.13
	2500	4	8.24	2.16	3.71	14.35	24.7	58.1	0.6	0.35	1.3
	3000	4	8.24	2.59	3.67	14.76	20.9	70.62	0.59	0.414	1.52
	3500	4	8.24	3.02	3.98	16.29	21.4	76.12	0.53	0.404	1.61
	4000	4	8.24	3.45	4.37	14.35	18.19	78.9	0.6	0.475	2.08
	4500	4	8.24	3.88	4.4	14.35	16.28	88.14	0.6	0.531	2.34

G80M20	Speed (RPM)	Load (kg)	Torque (Nm)	BP (kW)	IP (kW)	BTE (%)	ITE (%)	ME (%)	BSFC (kg/kWh)	ISFC (kg/kWh)	Fuel flow rate (kg/h)
	2000	4	8.24	1.73	3.85	16.32	36.45	44.77	0.56	0.251	0.97
	2500	4	8.24	2.16	3.71	16.63	28.65	58.04	0.55	0.32	1.19
	3000	4	8.24	2.59	3.67	15.84	22.49	70.43	0.58	0.408	1.5
	3500	4	8.24	3.02	3.98	14.61	19.25	75.9	0.63	0.477	1.9
	4000	4	8.24	3.45	4.37	15.28	19.31	79.13	0.6	0.475	2.08
	4500	4	8.24	3.88	4.4	14.69	16.64	88.28	0.63	0.552	2.43
G90MA10	Speed (RPM)	Load (kg)	Torque (Nm)	BP (kW)	IP (kW)	BTE (%)	ITE (%)	ME (%)	BSFC (kg/kWh)	ISFC (kg/kWh)	Fuel flow rate (kg/h)
	2000	4	8.24	1.73	3.85	15.3	34.22	44.71	0.56	0.251	0.97
	2500	4	8.24	2.16	3.71	15.58	26.88	57.96	0.55	0.32	1.19
	3000	4	8.24	2.59	3.67	14.02	19.9	70.45	0.61	0.433	1.59
	3500	4	8.24	3.02	3.98	14.36	18.96	75.74	0.6	0.454	1.81
	4000	4	8.24	3.45	4.37	14.63	18.56	78.83	0.59	0.464	2.03
	4500	4	8.24	3.88	4.4	14.29	16.21	88.16	0.6	0.531	2.34
G80MA20	Speed (RPM)	Load (kg)	Torque (Nm)	BP (kW)	IP (kW)	BTE (%)	ITE (%)	ME (%)	BSFC (kg/kWh)	ISFC (kg/kWh)	Fuel flow rate (kg/h)
	2000	4	8.24	1.73	3.85	15.06	33.74	44.64	0.61	0.27	1.04
	2500	4	8.24	2.16	3.71	16.03	27.7	57.87	0.57	0.331	1.23
	3000	4	8.24	2.59	3.67	15.74	22.31	70.55	0.58	0.408	1.5
	3500	4	8.24	3.02	3.98	14.43	18.99	75.98	0.63	0.479	1.91
	4000	4	8.24	3.45	4.37	15.06	19.05	79.05	0.61	0.478	2.09
	4500	4	8.24	3.88	4.4	14.17	16.04	88.34	0.64	0.568	2.5
CBG	Speed (RPM)	Load (kg)	Torque (Nm)	BP (kW)	IP (kW)	BTE (%)	ITE (%)	ME (%)	BSFC (kg/kWh)	ISFC (kg/kWh)	Fuel flow rate (kg/h)
	2000	4	8.24	1.73	2.3	23.33	31.09	75.04	0.32	0.239	0.55
	2500	4	8.24	2.16	3.38	16.83	26.39	63.77	0.44	0.281	0.95
	3000	4	8.24	2.59	4.42	15.91	27.14	58.62	0.47	0.273	1.21
	3500	4	8.24	3.02	4.84	17.01	27.25	62.42	0.44	0.272	1.32
	4000	4	8.24	3.45	5.79	17.95	30.09	59.65	0.41	0.246	1.43
	4500	4	8.24	3.88	6.57	16.76	28.35	59.11	0.44	0.261	1.72

In addition, Brake-Specific Fuel Consumption (BSFC) and Brake-Specific Energy Consumption (BSEC) are of considerable importance in the engine's fuel utilization. Specifically, BSFC quantifies the amount of fuel expended per unit of brake power generated, while BSEC provides an analogous measure, but with energy production as the denominator. Moreover, the Fuel Flow Rate (FF) is a vital parameter used to gauge the engine's fuel consumption rate. This metric holds significant importance in accurately determining the engine's fuel utilization.

The study also delves into a comprehensive analysis of various combustion phenomena parameters. These encompass Cylinder Pressure, Crank Angle, Cylinder Volume, Mass Fraction Burned, Mean Gas Temperature, and the Rate of Pressure Rise. Each of these parameters uniquely provides invaluable insights into the intricate combustion processes transpiring within the engine. By these measurements, the study seeks to elucidate and quantify the engine's operational efficiency, shedding light on critical aspects of its combustion dynamics.

In addition to performance and combustion parameters, the study extends its purview to encompass emission characteristics. These emissions, comprising Hydrocarbons (HC), Carbon Monoxide (CO), Carbon Dioxide (CO_2), and Nitrogen oxide (NOx), bear substantial environmental implications and are subject to stringent regulatory controls in numerous countries. The study aims to meticulously measure and analyze these emissions under a spectrum of engine speeds and load conditions to understand their environmental impact comprehensively.

This investigation is multifaceted, probing into many parameters that collectively define and characterize engine performance, combustion processes, and emission profiles. Through the rigorous examination of these parameters, the study endeavors to unravel the intricacies of engine behavior, from power generation and fuel consumption to combustion efficiency and environmental impact. This comprehensive approach contributes to a more holistic understanding of internal combustion engine dynamics and their implications.

5.6.1 Engine performance

- The results of a test conducted at a constant load of 4 kg (torque= 8.24 Nm) with an engine speed ranging from 2000 to 4500 rpm and a brake power value of 1.73 kW.

The test compared the performance of different fuels, including CBG, G100, G80E20, G90M10, G90M20, and G80MA20. The highest brake thermal efficiency (BTE) value of 23.33% was achieved with CBG fuel. It explains that CBG fuel has unique characteristics that make it more efficient than gasoline or diesel. CBG has a higher-octane rating and better knock resistance than gasoline due to its higher percentage of methane. Additionally, CBG burns more efficiently, leaving very little unburned fuel. This means that engines designed explicitly for CBG can have higher compression ratios, resulting in higher stated efficiency.

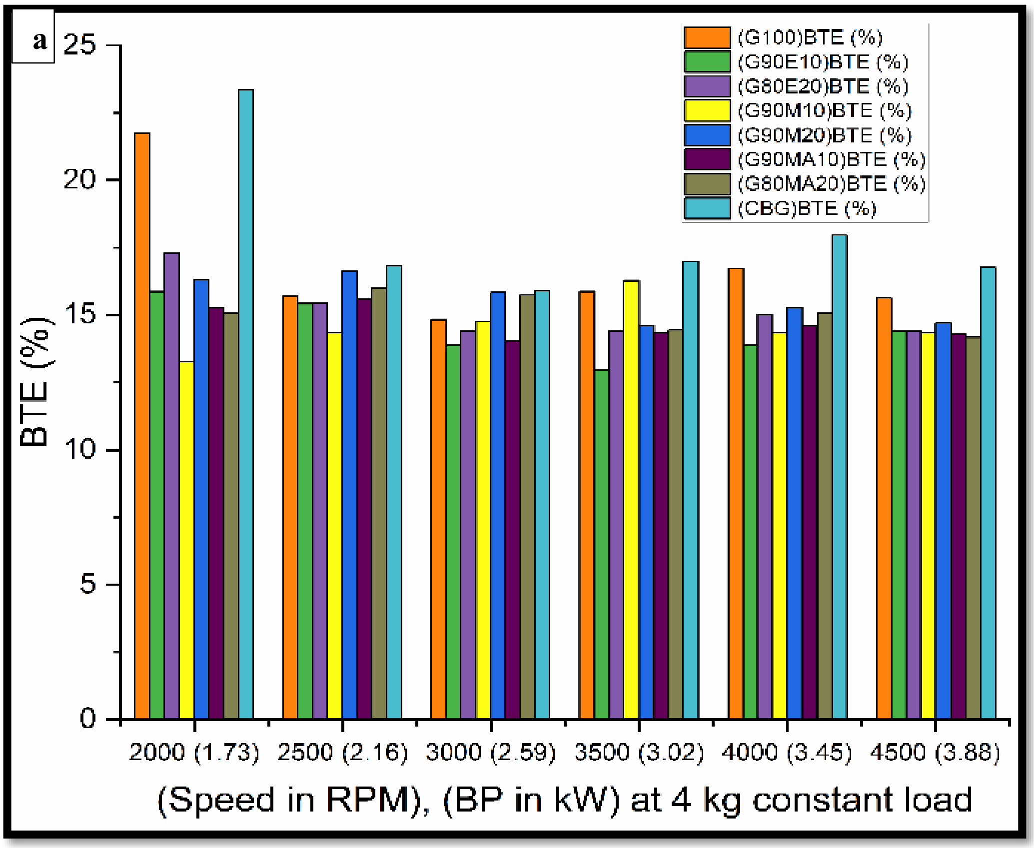


Figure 5.6: Brake thermal efficiency variations w.r.t speed and brake power

The BTE values of the various fuels were compared at different engine speeds. At 2000 rpm, CBG had the highest BTE value of 23.33%, followed by G100, with a value of 21.76%. G80E20 had the highest BTE value in the alcohol fuel category at 17.28%, while G90M10 had the lowest value at 13.25%. At the maximum speed of 4500 rpm, the BTE values of all the fuels decreased, with CBG still having the highest value at 16.76%, followed by G100 at 15.63%. G90M20 had the lowest BTE value at 14.69%.

Interestingly, the alternative fuels G90M20, G80MA20, and CBG had BTE values higher than G100 at 2500 and 3000 rpm, indicating that it has the potential to replace gasoline fuels in engines. The study concludes that CBG fuel provides the highest BTE at every speed compared to gasoline and alcohol blends. CBG fuel has a low mass flow rate or fuel consumption rate, resulting in more energy per unit of fuel. On the other hand, gasoline fuel has lesser fuel consumption than alcohol blends at lower and higher speeds. The study concludes that CBG fuel provides the highest BTE at every speed compared to gasoline and alcohol blends. CBG fuel has a low mass flow rate or fuel consumption rate, resulting in more energy per unit of fuel.

On the other hand, gasoline fuel has lesser fuel consumption than alcohol blends at lower and higher speeds. This is because alcohol blends have a lower energy density and require more fuel to produce the same energy as gasoline. Therefore, gasoline-fueled cases achieve higher brake thermal efficiency at high and low rpm than alcohol blends and lower brake thermal efficiency than CBG fuels.

- The study compared the performance of different fuels in an engine based on the Indicator Thermal Efficiency (ITE) at constant load and varying engine speeds. The fuels included CBG, G100, G80E20, G90M10, G90M20, and G80MA20. The results showed that CBG had a lower ITE value at lower engine speeds but a higher value at higher speeds than other fuels. At 2000 rpm, the maximum ITE value was achieved with G100, followed by G80E20 and CBG. This suggests that G100 and G80E20 were more efficient fuels than CBG at low speeds.
  However, CBG has a higher calorific value and fuel flow rate at minimum rpm and constant load, resulting in a lower ITE value at low speeds. At a maximum engine speed of 4500 rpm, the highest ITE value was achieved with CBG, followed by G100 and G90M20. The results suggest that CBG is a more efficient fuel at higher engine speeds than other fuels. CBG consumes less fuel than other fuels, resulting in less fuel consumed per unit of work and higher efficiency. Additionally, the higher calorific value of CBG contributes to its higher efficiency at high engine speeds. The study shows that CBG has the potential to be a highly efficient alternative fuel for internal combustion engines. Engines designed specifically for CBG can achieve higher efficiency than engines designed for gasoline or alcohol fuels.

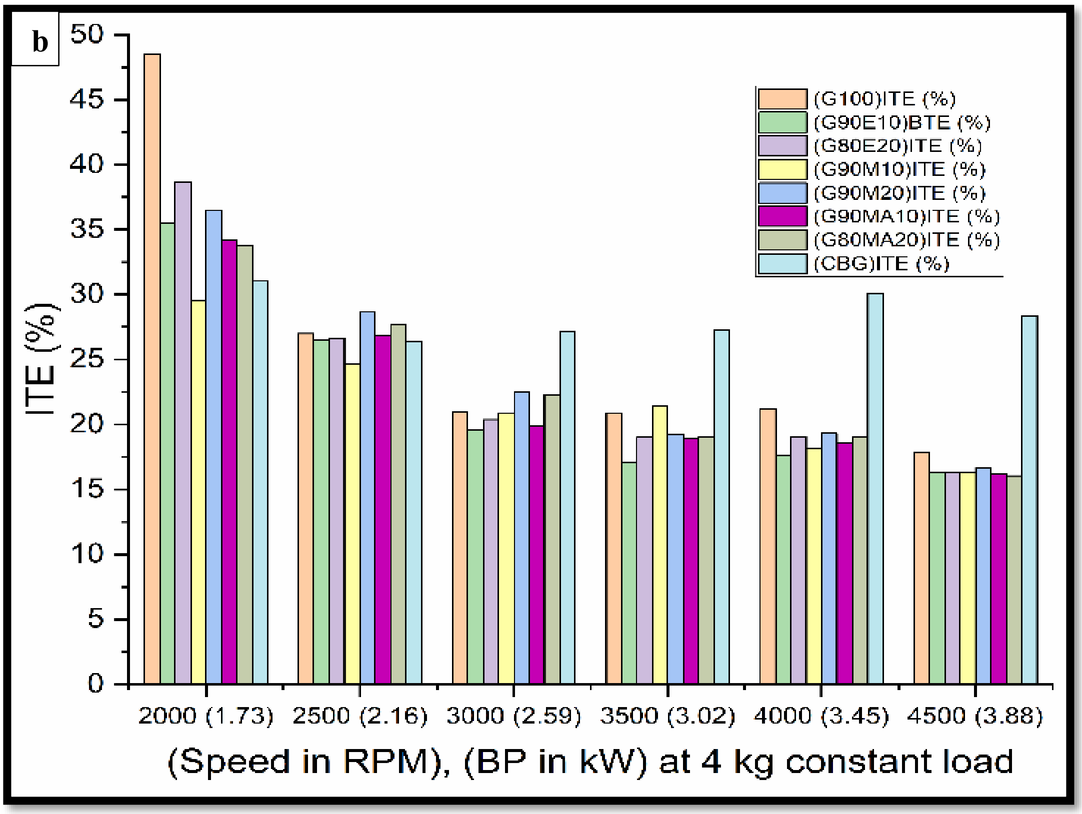


Figure 5.7: Indicated thermal efficiency variations w.r.t to speed and brake power

The maximum value of ITE was achieved with G100, G80E20, and CBG at 2000 rpm. The indicated power (IP) values for gasoline and alcohol blends were almost identical. In CBG, it gets minimum IP at low speed but the same brake power (BP), meaning less friction power (FP) is generated in CBG at low speed, but with speed FP, IP increases more compared to other fuels, resulting in a higher ITE value at higher speeds.

5.6.2 Brake-specific fuel consumption (BSFC) and Brake-specific energy consumption (BSEC)

- BSFC measures the fuel consumed per unit of energy an engine produces, while BTE measures the efficiency with which the engine converts fuel into energy. The lower the BSFC value, the more efficiently the engine uses the fuel, and the higher the BTE value, the more efficiently the engine converts fuel into work. The study results showed that CBG achieved the lowest BSFC value of 0.32 kg/kWh at 2000 rpm, the lowest value among all the fuels tested. This suggests that CBG is more efficient in fuel consumption than other fuels, including gasoline and alcohol blends. Furthermore, at the highest rpm of 4500, CBG outperformed other fuels with a BSFC of 0.44 kg/kWh, while G100 got 0.52 kg/kWh, G90M10, and G90MA10 got 0.6 kg/kWh. This indicates that CBG is a more efficient fuel than gasoline and alcohol blends at high engine speeds.

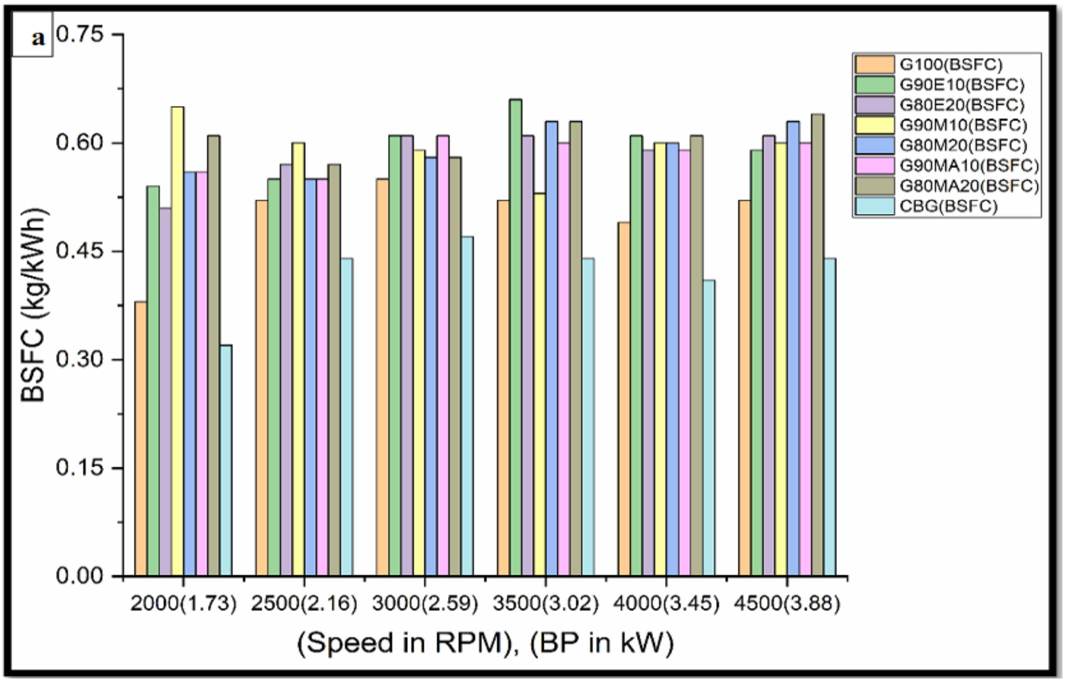


Figure 5.8: Brake specific fuel consumption variations w.r.t speed and brake power

One reason for the superior performance of CBG in terms of BSFC is that it has a higher calorific value than gasoline and alcohol fuels, which means it can produce more energy per unit of fuel consumed. This is important in reducing the fuel required to produce a given amount of work, resulting in lower BSFC values. Moreover, CBG has lower specific gravity than gasoline and alcohol fuels, meaning it is less dense and requires less fuel flow rate to produce a given amount of work. This means that CBG consumes less fuel per unit of work, resulting in a lower BSFC value. This is important in reducing the environmental impact of engines, as it reduces the fuel required to produce a given amount of work, resulting in lower emissions of greenhouse gases and other pollutants.

- The Brake Specific Energy Consumption (BSEC) values for different fuels have been analyzed to evaluate their energy efficiency in producing brake power in an internal combustion engine. The BSEC values for gasoline fuel were between 16.72 MJ/kWh and 24.2 MJ/kWh. Gasoline is a commonly used fuel for internal combustion engines, and these results indicate that it has a relatively high energy consumption rate to produce brake power. This implies that the gasoline fuel requires more energy input to produce a given output power, resulting in higher BSEC values. For alcohol blends, the minimum and maximum BSEC values were obtained as G80E20 (20.7876 MJ/kWh) and G80E10 (27.9708 MJ/kWh), respectively.

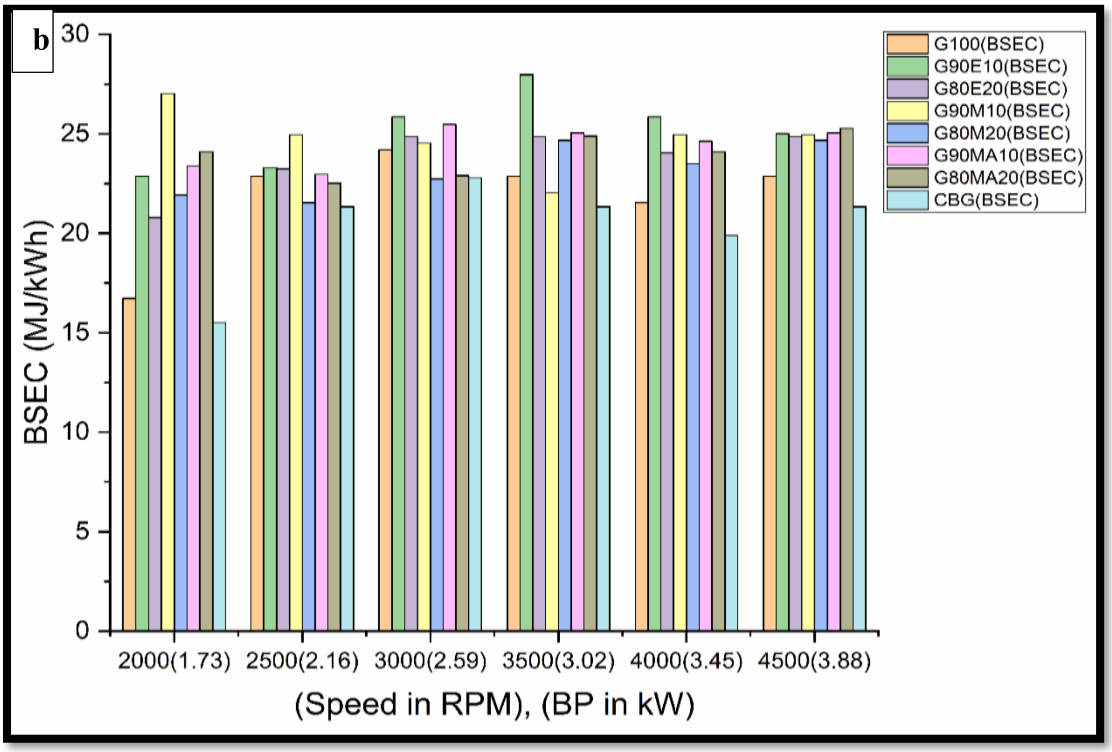


Figure 5.9: Brake specific energy consumption variations w.r.t speed and brake power

These results indicate that the energy consumption rate of alcohol blends is higher than that of gasoline fuel. The BSEC values for alcohol blends were higher than those for gasoline fuel, possibly due to the lower energy content of alcohol blends compared to gasoline fuel. Alcohol blends produce lower emissions compared to gasoline fuel. CBG fuel had the minimum and maximum BSEC values for producing brake power, which was found to be 15.52 MJ/kWh and 22.795 MJ/kWh, respectively. CBG fuel had the highest Brake Thermal Efficiency (BTE) value among the fuel types, indicating that CBG fuel has the lowest consumption rate to produce power in the engine, resulting in the lowest BSEC value compared to gasoline and alcohol blends.

CBG fuel is made by compressing biogas generated from organic waste, and it has been found to have a higher calorific value than gasoline and alcohol blends. This implies that CBG fuel requires less energy input to produce a given output power, resulting in lower BSEC values. The study results suggest that CBG fuel has the potential to be a highly efficient alternative fuel for internal combustion engines.

CBG fuel's high BTE values and low BSEC values indicate that it is an energy-efficient fuel that can help reduce the consumption of non-renewable fossil fuels. CBG fuel is also environmentally friendly as it is produced from organic waste and produces fewer emissions than gasoline fuel. CBG fuel could be a valuable alternative, especially for transportation and power generation applications.

5.6.3 Combustion phenomenon

- Cylinder pressure and crank angle are two crucial factors that affect the combustion process in an internal combustion engine. The start-of-burning (SOB) and end-of-burning (EOB) are critical stages of the combustion cycle that significantly determine the engine's performance and efficiency. In this context, the study found that the SOB for G100 and alcohol fuel occurred at cylinder pressures ranging from 30 to 37 bar and a crank angle of 335 degrees before the top dead center (TDC). The SOB for CBG, on the other hand, started at a cylinder pressure of 40.25 bar and crank angle of 335 degrees before TDC. This indicates that CBG requires a higher cylinder pressure to initiate the combustion process than gasoline and alcohol blends. The maximum cylinder pressure for CBG was found to be 60.06 bar at a crank angle of 377 degrees after TDC.

  This is significantly higher than the maximum cylinder pressure for gasoline and alcohol blends, which indicates that CBG produces more power per combustion cycle. Moreover, CBG had the earliest EOB cycle, meaning the combustion process completes earlier in CBG than in gasoline and alcohol blends. The reason for the earlier EOB cycle in CBG is the negligible amount of unburned particles in the combustion cycle. Since CBG is a cleaner fuel with lower particulate emissions, the combustion process completes faster, and the engine can move on to the next cycle earlier.

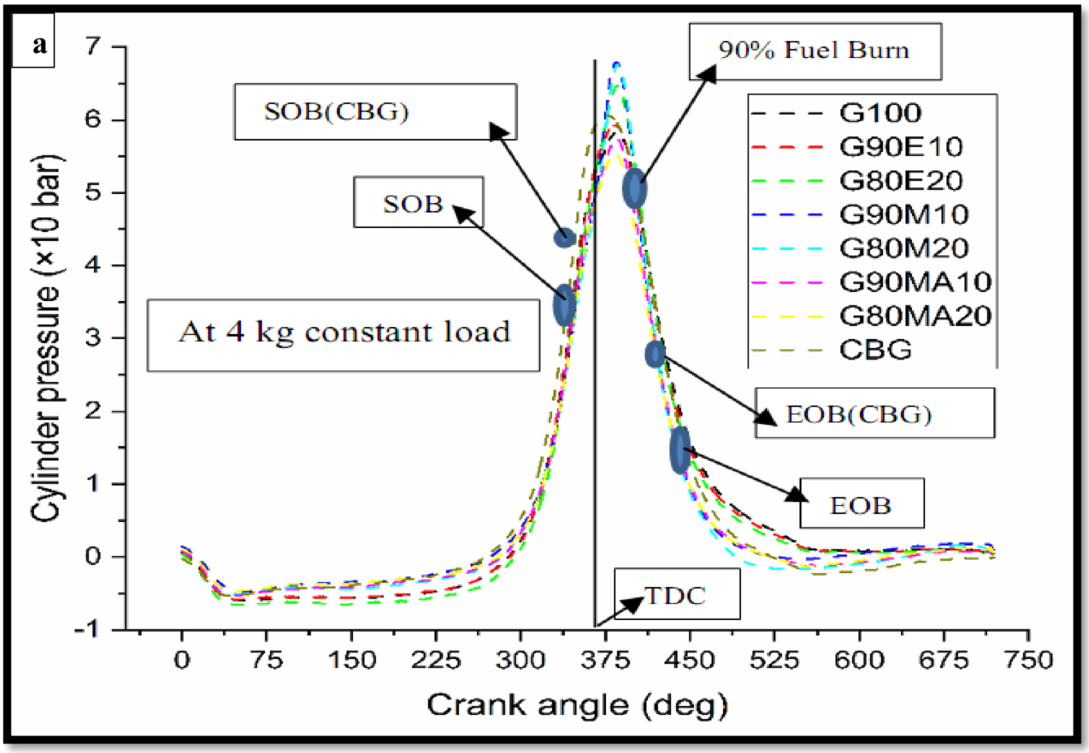


Figure 5.10: Cylinder pressure vs. Crank angle

Additionally, the study found that the engine starts with gasoline fuel first in CBG, and then CBG fuel is injected into the engine, increasing the engine pressure. This process leads to faster and more efficient combustion, resulting in a higher brake thermal efficiency (BTE) value for CBG than gasoline and alcohol blends.

The study reveals key insights into the combustion process of different fuels in internal combustion engines. Specifically, it demonstrates that CBG necessitates a higher cylinder pressure for combustion initiation compared to gasoline and alcohol blends. Additionally, CBG exhibits substantially higher maximum cylinder pressure, indicating enhanced power generation per combustion cycle. Moreover, CBG showcases an earlier completion of the combustion process due to its minimal unburned particles, a result of its cleaner composition with lower particulate emissions. The injection sequence, beginning with gasoline and followed by CBG, not only elevates engine pressure but also leads to swifter and more efficient combustion, ultimately resulting in a superior brake thermal efficiency (BTE) value for CBG when compared to gasoline and alcohol blends.

- The cylinder pressure and volume diagram are crucial parameters in determining an engine's performance. The study results indicated that the highest cylinder pressure was obtained in the G90M10 and G90M20 fuels. The maximum cylinder pressure was 60.79 bar in G90M10, with a volume of 48.58 cc; in G90M20, with a volume of 49.86 cc, the pressure value was 60.76 bar. The cylinder volume is essential in determining the maximum pressure generated during combustion. A larger cylinder volume provides more space for the fuel-air mixture, which can result in a higher-pressure during combustion.

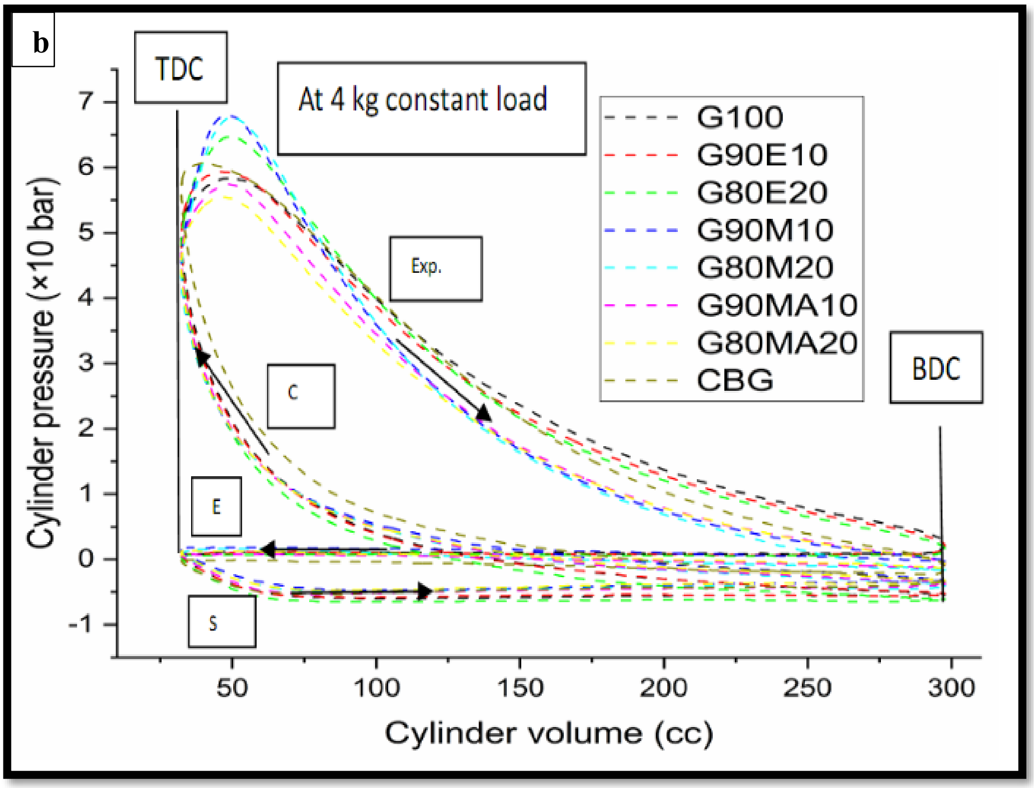


Figure 5.11: Cylinder pressure vs. Cylinder volume

The maximum cylinder pressure in G100 was 50.84 bar when the volume was 49.86 cc, which is relatively lower than the pressure generated by the G90M10 and G90M20 fuels. This can be attributed to the fact that G100 is a pure gasoline fuel with no alcohol blend and thus has a lower octane rating than alcohol blends. On the other hand, CBG fuel had the highest maximum pressure of 60.06 bar but with a smaller cylinder volume of 39.97 cc. This indicates that CBG fuel can generate a higher pressure in a smaller space, resulting in a more efficient combustion process. Among all the fuels tested, G80MA20 raised the lowest cylinder pressure of 50.54 bar when the volume was 46.15 cc. Methyl acetate, which is a component of G80MA20, is known to be less flammable than ethanol and methanol. This generates less pressure during combustion, resulting in lower cylinder pressure.

In summary, the study highlights the significance of cylinder pressure and volume in determining engine performance. G90M10 and G90M20 fuels exhibited the highest cylinder pressures, indicating superior combustion performance. G100, being a pure gasoline, had a lower pressure due to its lower octane rating than alcohol-blended fuels. CBG fuel achieved the highest pressure despite a smaller cylinder volume, showcasing its efficiency in generating high pressure within a confined space. Conversely, G80MA20, with the less flammable component methyl acetate, recorded the lowest cylinder pressure among the tested fuels, emphasizing the impact of fuel composition on combustion performance.

- The combustion process in an internal combustion engine is a complex process that involves a series of chemical reactions that convert fuel into useful work. The efficiency and performance of the engine depend on various factors, such as the fuel properties, engine design, operating conditions, and the combustion process's timing and duration. In this context, the mass fraction burned (MFB) and crank angle diagram are valuable tools for studying the combustion process's characteristics and optimizing the engine's performance. This essay will discuss the MFB vs. crank angle diagram and compare the combustion characteristics of gasoline, alcohol blends, and CBG. The MFB vs. crank angle diagram is a graphical representation of the combustion process's timing and duration. The horizontal axis represents the crank angle, the angular displacement of the engine's crankshaft from the top dead center (TDC) position. The vertical axis represents the MFB, the fraction of fuel burned in the combustion chamber at a particular crank angle. The MFB vs. crank angle diagram provides valuable information about the combustion process's characteristics, such as the start of burning (SOB), the rate of combustion, the peak pressure, and the end of burning (EOB). The SOB is the crank angle at which the combustion process starts.

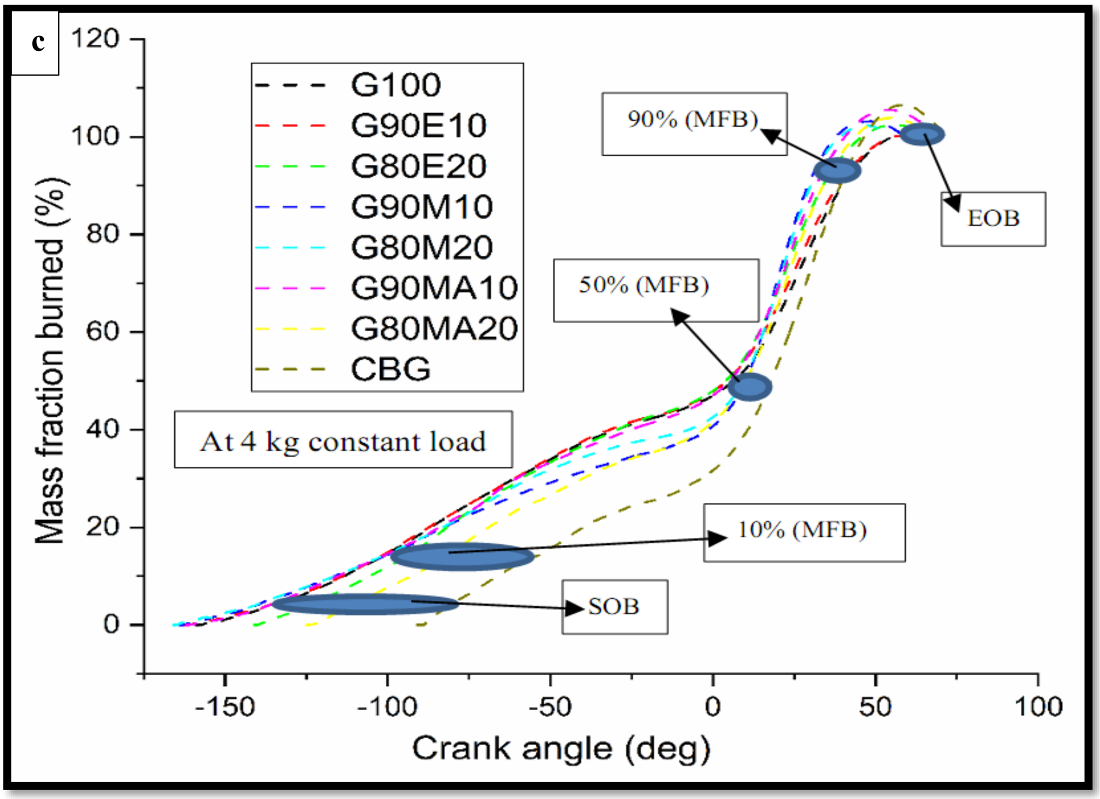


Figure 5.12: Mass fraction burned vs. Crank angle

In gasoline and alcohol blends, the SOB begins when the piston moves towards TDC during combustion. This is because the self-initiation temperature of gasoline and alcohol blends is relatively low, and the fuel-air mixture ignites spontaneously as the piston compresses it.

However, in CBG, the SOB starts when the piston is near TDC. This is because the self-initiation temperature of CBG is higher than that of gasoline and alcohol blends. Therefore, the fuel-air mixture must be heated to a higher temperature before it ignites spontaneously. The MFB is the fraction of fuel burned in the combustion chamber at a particular crank angle. The MFB vs. crank angle diagram provides valuable information about the combustion process's rate and duration. In gasoline and alcohol blends, the MFB peaks at around 50% of the combustion duration. This is because the combustion process in gasoline and alcohol blends is relatively fast and reaches its peak pressure quickly. However, in CBG, the MFB peaks at around 90% of the combustion duration. This is because the combustion process in CBG is slower than in gasoline and alcohol blends due to the delay in the SOB.

In conclusion, the combustion process in internal combustion engines is a multifaceted interplay of chemical reactions influenced by factors such as fuel properties, engine design, and operating conditions. The Mass Fraction Burned (MFB) vs. crank angle diagram is a pivotal tool for dissecting and optimizing combustion characteristics. This graphical representation unveils crucial insights into combustion's start, rate, and duration. Notably, the comparison between gasoline, alcohol blends, and CBG highlights distinctive behaviors, with CBG exhibiting a delayed start of burning and prolonged combustion duration, elucidating its unique combustion profile. Understanding these nuances is essential for fine-tuning engine performance and efficiency.

- Mean gas temperature (MGT) is an important parameter that determines the combustion process in an internal combustion engine. It represents the average temperature of the combustion gases in the engine's combustion chamber during the combustion process. The MGT is a critical factor influencing engine performance, fuel consumption, and pollutant emissions. The MGT is affected by various factors, including engine operating conditions, fuel type, fuel injection timing, air-fuel ratio, and compression ratio. The maximum MGT occurs at or near the peak pressure location in the engine cycle. The MGT can be measured directly using thermocouples or indirectly using pressure sensors and heat release analysis.

  Gasoline, alcohol blends, and CBG are the fuels tested for MGT in different crank angle positions. The maximum MGT values in G100, G80E20 alcohol blends, and CBG with 412°, 406°, and 411° crank angles were 384.2 °C, 390.20 °C, and 388.17 °C, respectively. These values show that alcohol blends and CBG have higher MGT values than gasoline. The higher MGT values in alcohol blends and CBG are due to their higher flame propagation speed and auto-ignition temperature.

  CBG and alcohol fuels are highly flammable as compared to gasoline fuels. It has a lower ignition delay time, which means it ignites faster than gasoline. This causes the combustion process to occur more quickly, resulting in higher MGT values. CBG has a higher auto-ignition temperature than other fuels, requiring a higher temperature to ignite spontaneously. This characteristic also contributes to the higher MGT values observed in CBG and alcohol blends. The MGT values of gasoline, alcohol blends, and CBG are affected by the engine's operating conditions, such as engine speed, load, and injection timing.

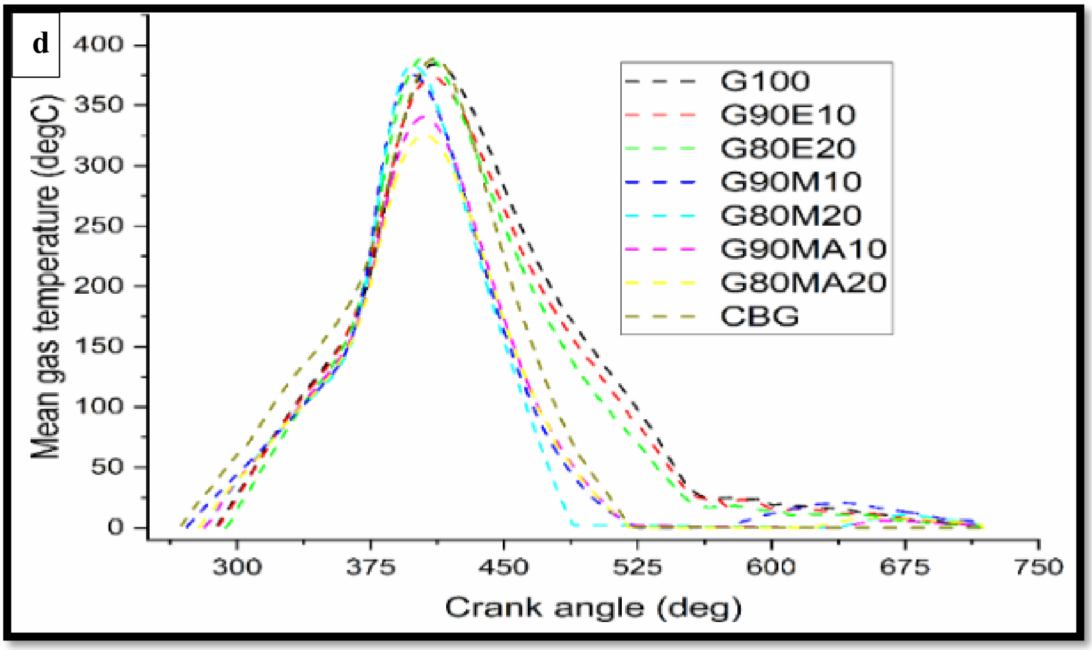


Figure 5.13: Mean gas temperature vs. crank angle

The MGT values of alcohol blends and CBG are typically higher at higher engine speeds and loads than at lower speeds and loads. The combustion process occurs faster at higher engine speeds and loads, resulting in higher MGT values.

In conclusion, Mean Gas Temperature (MGT) emerges as a pivotal determinant of the combustion process within internal combustion engines. It signifies the average temperature of combustion gases during the engine's operation. It profoundly impacts performance, fuel efficiency, and emissions—factors like engine conditions, fuel type, injection timing, and air-fuel ratio influence MGT. Notably, the study reveals that alcohol blends and CBG exhibit higher MGT values than gasoline due to their swifter ignition and higher auto-ignition temperatures. Moreover, engine speed and load play a significant role, with MGT typically escalating at higher speeds and loads due to accelerated combustion processes. Understanding these nuances is vital for optimizing engine performance across various operational scenarios.

- In internal combustion engines, the rate of pressure rise (RPR) is an important parameter determining the engine's performance, efficiency, and emissions. RPR measures how quickly the gas pressure inside the engine cylinder rises during the combustion process, and it is typically expressed in units of bar per degree of crank angle.

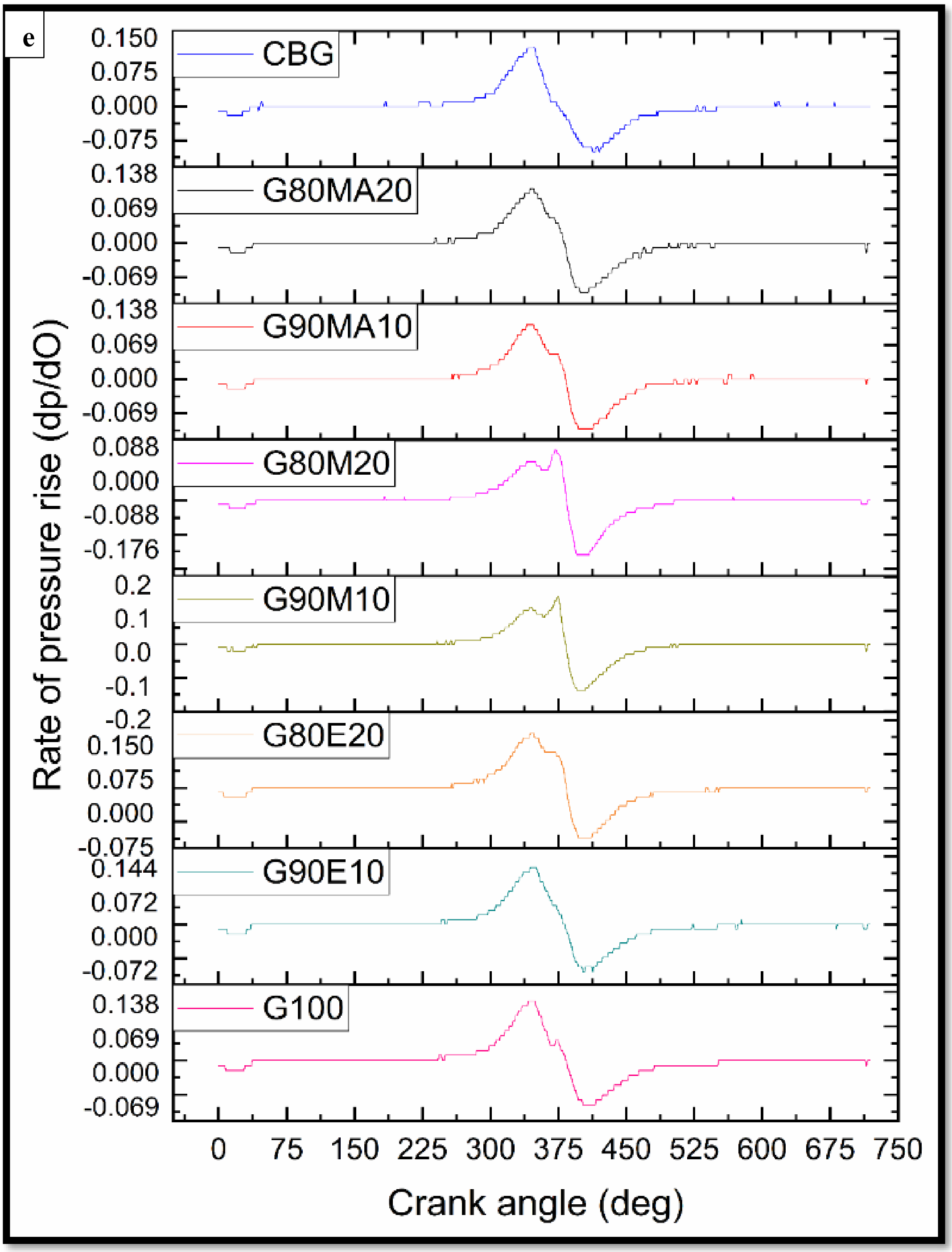


Figure 5.14: Rate of pressure rise vs. crank angle

The results showed that the RPR values varied depending on the type of fuel used and the engine operating conditions. The maximum RPR values were observed in gasoline, CBG, and methanol blends, ranging from 0.12 to 0.14 bar/degree at 344 to 374 degrees crank angles. These fuels have higher energy densities and combustion rates than other fuels, which leads to a faster pressure rise during combustion. On the other hand, methyl acetate had the lowest RPR values, with a minimum value of 0.11 bar/degree at crank angles of 344 and 346 degrees. This can be attributed to the lower energy density and slower combustion rate of methyl acetate compared to the other fuels tested. The results also showed that the RPR values depended on the engine operating conditions. At higher engine speeds and loads, the RPR values were generally higher, indicating a more rapid combustion process.

Higher engine speeds and loads result in higher temperatures and pressures inside the cylinder, leading to a faster combustion rate. Overall, the results of this study demonstrate the importance of choosing the right fuel for internal combustion engines. The Fuels with higher energy densities and faster combustion rates can increase RPR values, improving engine performance and efficiency. However, these fuels can also lead to higher emissions, so a balance must be struck between performance and environmental considerations. In conclusion, the Rate of Pressure Rise (RPR) is a pivotal parameter influencing internal combustion engine performance, efficiency, and emissions. The study underscores how RPR measures the rapidity of gas pressure increase during combustion, which is crucial for engine operation. Gasoline, CBG, and methanol blends exhibit the highest RPR values, indicating superior energy densities and combustion rates. Conversely, methyl acetate displays lower RPR values, attributed to its comparatively lower energy density and slower combustion rate.

Additionally, the study highlights the significance of engine operating conditions, with higher speeds and loads contributing to elevated RPR values. Striking a balance between fuel performance enhancements and environmental considerations is paramount in optimizing engine operation.

5.6.4 Emission parameters

- Carbon dioxide (CO_2) is a significant contributor to global warming, and the transportation sector is an essential source of CO_2 emissions. The use of alternative fuels can help reduce CO_2 emissions and mitigate the impact on the environment. In the study mentioned in the prompt, the CO_2 emissions of different fuels were compared in a spark-ignition engine at a constant speed of 2000 rpm and 4500 rpm. The results showed that at 2000 rpm, the highest CO_2 emissions of 20% and 22% were obtained in the G90M10 and G80M20 blends, respectively, while the lowest CO_2 emissions of 3% were obtained in CBG. At the highest speed of 4500 rpm, G100 and G80M20 had CO_2 emissions of 13% and 21%, respectively, while CBG produced only 6% CO_2.

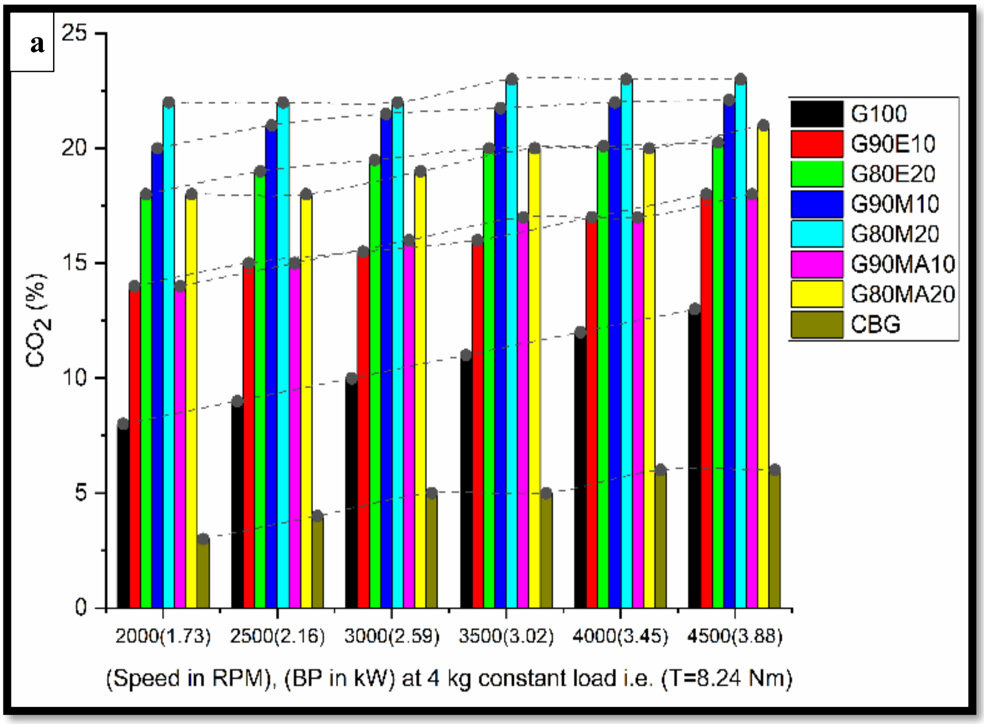


Figure 5.15: Carbon dioxide variations w.r.t speed

The study's findings suggest that the CO_2 emissions of alternative fuels depend on their composition and properties. Methanol-gasoline blends had higher CO_2 emissions than CBG at all engine speeds tested. CBG, on the other hand, had the lowest CO_2 emissions at all speeds, making it the best alternative fuel for CO_2

emissions reduction. CBG's low carbon content and complete combustion contribute to its cleaner burning and lower CO_2 emissions. In addition to its lower CO_2 emissions, CBG has other environmental benefits compared to petroleum-based products. CBG also has a lower environmental impact than other renewable fuels, such as ethanol and biodiesel, which require large amounts of land and water. Moreover, compared to gasoline and alcohol fuels, CBG emits 10 to 15% less CO_2. CBG is a renewable energy source produced from organic waste and agricultural residues. It has a lower carbon content than conventional fossil fuels. Therefore, CBG is considered a green energy source and an excellent alternative fuel for reducing CO_2 emissions.

- The statement provided describes the findings of a study that compared the amount of carbon monoxide (CO) emissions produced by gasoline, alcohol blends, and compressed biogas when used as fuel for an internal combustion engine. The study analyzed the emissions at different speeds, ranging from the lowest to the highest. The study results showed that CO emissions varied significantly among the fuels, with gasoline having the highest CO content and CBG having the lowest. Carbon monoxide is a colorless, odorless gas produced during the incomplete combustion of fossil fuels. It is a toxic gas that can cause serious health problems, including headaches, dizziness, nausea, and even death.

  The amount of CO emissions a fuel produces is determined by several factors, including the fuel's chemical composition, combustion efficiency, and oxygen concentration in the combustion chamber. The study found that gasoline had the highest CO content among the fuels tested, ranging from 1.64% to 2.63% at different speeds. This is because gasoline is a hydrocarbon fuel composed primarily of carbon and hydrogen atoms. When gasoline is burned in an internal combustion engine, it undergoes incomplete combustion, meaning that not all carbon atoms are fully oxidized to carbon dioxide (CO_2). Instead, some carbon atoms combine with oxygen to form carbon monoxide (CO), a byproduct of incomplete combustion. Alcohol blends, on the other hand, had lower CO emissions than gasoline. Alcohol is an oxygenate, meaning its molecules include oxygen atoms. When alcohol is burned in an internal combustion engine, it undergoes more complete combustion than gasoline, meaning that more carbon atoms are fully oxidized to CO_2, and less CO is produced.

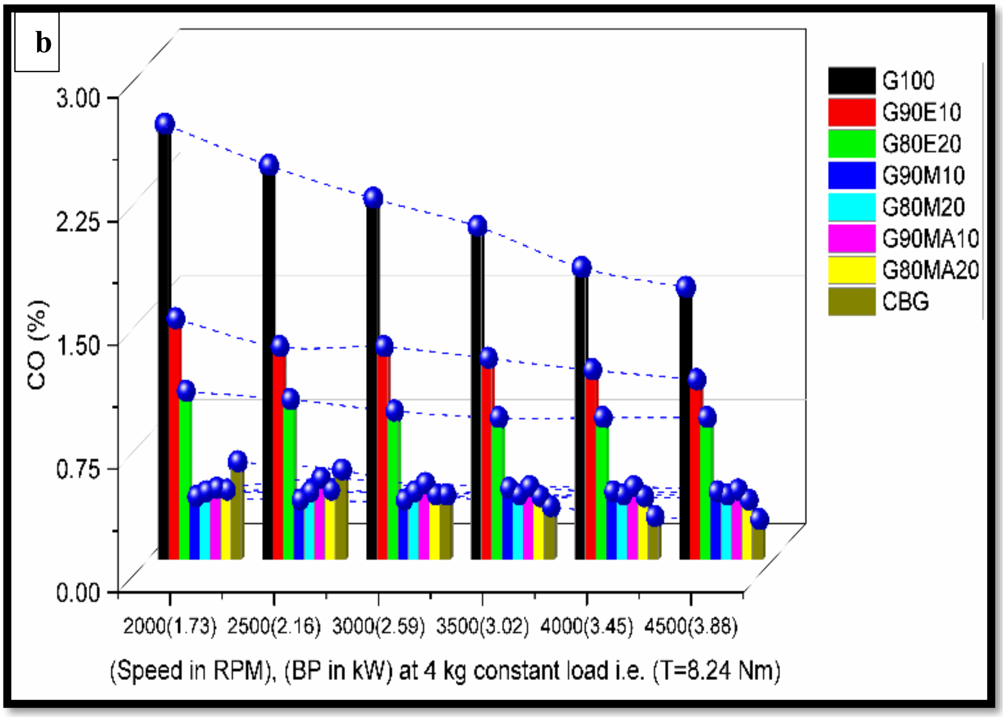


Figure 5.16: Carbon monoxide variations w.r.t speed

The study found that the highest CO content among the alcohol blends was in G90E10, ranging from 1.45% to 1.08% at different speeds. CBG had the lowest CO emissions among the fuels tested, with a maximum CO content of only 0.232% at the highest speed. CBG is composed mainly of methane (CH_4) and carbon dioxide (CO_2), with trace amounts of other gases. When CBG is burned in an internal combustion engine, it undergoes more complete combustion than gasoline, meaning that more methane is fully oxidized to CO_2, and less CO is produced. Additionally, CBG has a lower oxygen concentration than gasoline or alcohol blends, reducing the amount of CO produced during combustion.

- The study analyzed the emissions at different speeds, ranging from a minimum of 2000 RPM to the highest of 4500 RPM. The study results showed that NOx emissions varied significantly among the fuels, with CBG having the lowest NOx emissions. Nitrogen oxides are a group of toxic gases produced during fossil fuel combustion, including gasoline and alcohol blends. NOx emissions are harmful to human health and the environment, as it contributes to the formation of smog and acid rain and can also cause respiratory problems. The amount of NOx emissions a fuel produces is determined by several factors, including the fuel's chemical composition, combustion efficiency, and the concentration of oxygen and nitrogen in the combustion chamber.

The study found that G100 and alcohol blend G90M10 and G80M20 had high NOx values of 225 and 1425 parts per million (PPM) at a minimum of 2000 RPM. This is because as the combustion temperature in the engine increases, the nitrogen gas (N_2) that mixes with the oxygen in the air forms NOx. Gasoline and alcohol blend burn at higher temperatures, producing higher NOx values. In addition, the oxygen in the alcohol blends reacts quickly with the nitrogen in the air, resulting in higher NOx emissions. At maximum RPM, G80E20, G80MA20, and G100 had even higher NOx values of 2050, 1775, and 1275 ppm, respectively, while CBG achieved only 1125 ppm. This is because CBG has a lower combustion temperature than gasoline and alcohol blends, which results in less NOx emissions. Additionally, CBG has a lower oxygen concentration than gasoline and alcohol blends, reducing the amount of NOx produced during combustion.

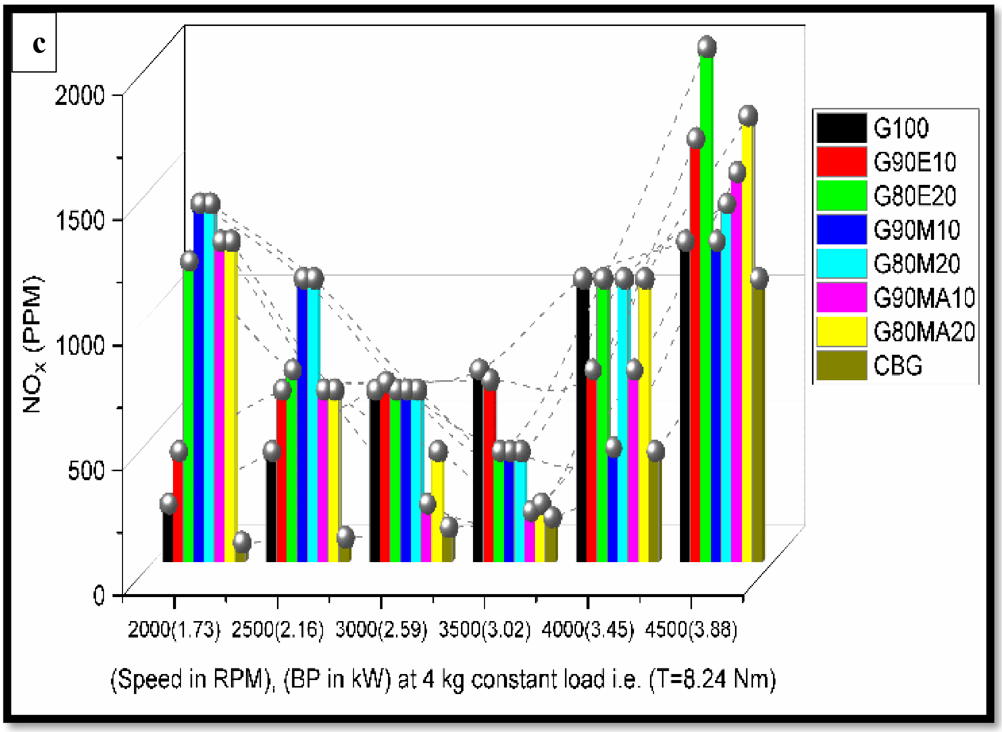


Figure 5.17: Nitrogen oxide variations w.r.t speed

The study also found that CBG had several advantages over gasoline and alcohol blends. CBG had lower fuel consumption, increased engine performance, and emitted less NOx. CBG has a lower carbon-to-hydrogen ratio than gasoline and alcohol blends, which means that it requires less oxygen to be combustible. This leads to a more efficient combustion process, which results in lower fuel consumption and higher engine performance. CBG emits fewer greenhouse gases and air pollutants than gasoline and alcohol blends, making it a more environmentally friendly fuel.

- The HC values were measured at both minimum and maximum engine speeds. The results show that the HC values vary significantly depending on the fuel blend and engine speed. Hydrocarbons are a pollutant that can harm human health and the environment. It is produced when fuel is burned incompletely, and some of the carbon molecules in the fuel are released into the atmosphere. This process is more likely to occur when the fuel is not burned at a high enough temperature or when there is insufficient oxygen for complete combustion.

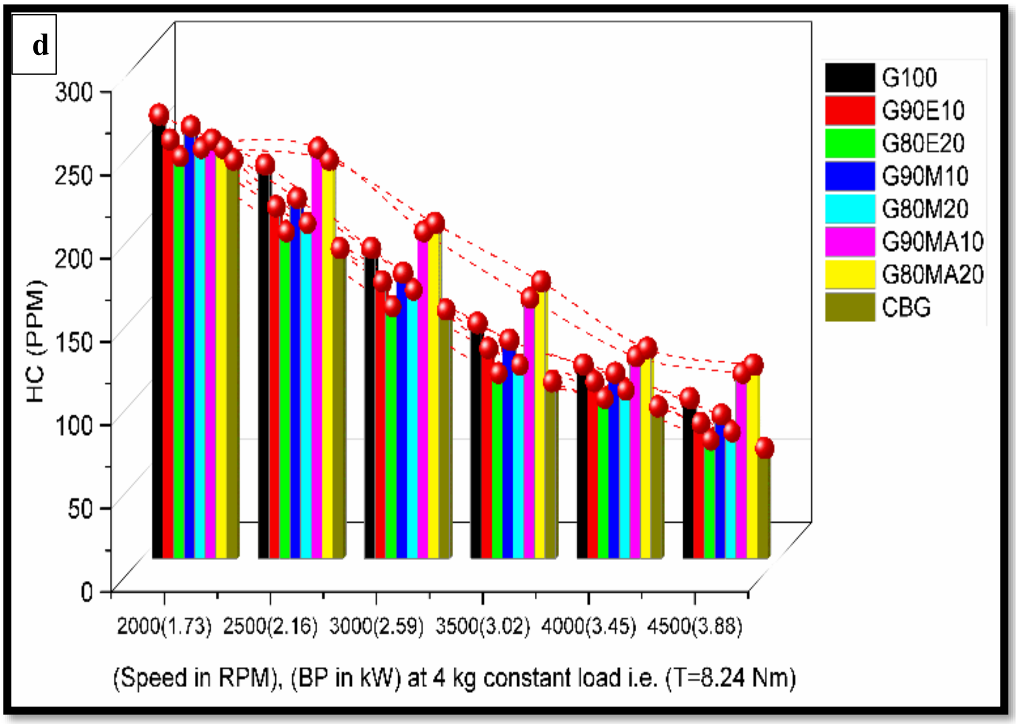


Figure 5.18: Hydrocarbon variations w.r.t to speed

The study found that gasoline and alcohol blends (G100 and G90M10) produced higher HC emissions than CBG at low engine speeds. This is because these blends have a higher likelihood of incomplete combustion at low speeds, which means that some of the fuel is not burned entirely, resulting in more HC emissions. As the engine speed increases, the fuel in the combustion chamber burns more efficiently, reducing HC emissions in all fuel blends.

The fuel burns more entirely at higher engine speeds, reducing the amount of unburned hydrocarbons released into the atmosphere. The reduction in HC emissions at higher engine speeds is observed in all fuel blends, although the extent varies between blends. In the case of CBG, the study found that this fuel burned well across various engine speeds, resulting in lower HC emissions than gasoline and alcohol blends. The HC values in CBG were rarely achieved at all RPMs because CBG fuel burns well at both minimum and maximum RPMs. Less unburned fuel is released into the atmosphere, lowering HC emissions.

5.7 Discussions

This study provides profound insights into the performance, efficiency, and environmental impact of a range of fuels in internal combustion engines, including gasoline, alcohol blends, and compressed biogas (CBG). It meticulously examined parameters like Brake Thermal Efficiency (BTE), Brake-Specific Fuel Consumption (BSFC), and Brake-Specific Energy Consumption (BSEC), offering pivotal data on their efficiency in internal combustion engines. The results unambiguously establish CBG's superiority over gasoline and alcohol blends in terms of BTE across all engine speeds, showcasing its potential as an efficient alternative fuel, especially when tailored to specific engine designs. CBG consistently demonstrated lower BSFC values, indicating reduced fuel consumption per unit of energy produced, making it an enticing option for reducing fuel usage in these engines. CBG's lower BSEC values underscore its energy efficiency and potential to reduce reliance on non-renewable fossil fuels.

The detailed analysis of combustion parameters revealed that CBG requires higher cylinder pressure for combustion initiation than gasoline and alcohol blends. This suggests a more controlled and efficient combustion process, resulting in elevated pressure levels and increased power production per cycle. The early end-of-burning (EOB) cycle observed with CBG signifies cleaner combustion with fewer unburned particles, enhancing its BTE and potential for heightened engine efficiency. Regarding emissions, CBG emerged as the environmentally responsible choice, consistently emitting lower CO_2, CO, and NOx levels across diverse engine speeds. Its reduced emissions make it a promising selection for mitigating the environmental impact of internal combustion engines. CBG's low carbon content, complete combustion, and decreased oxygen concentration contribute to its environmentally friendly emissions profile. Derived from organic waste, CBG holds excellent promise as a sustainable and eco-friendly alternative for transportation and power generation.

This study substantiates CBG's status as a high-performance, energy-efficient, and environmentally responsible alternative fuel for internal combustion engines. Its potential to reduce fuel consumption and emissions makes it a compelling choice for sustainable transportation and power generation, representing a significant step towards a greener and more efficient future for the automotive and energy sectors. However, further research and practical trials are requisite to unlock fully the potential of CBG and similar alternative fuels. Additionally, comparative data from various literature further highlights the potential advantages of CBG over other fuel blends.

In a four-stroke engine operating at 2000 to 3000 rpm, the BTE values for the G90E10, G80E20, and G70E30 blends were 16.2%, 18.9%, and 21.2%, respectively [233]. The BTE values for the G88M12 blend were 18.5% at 2000 rpm, 21.5% at 2500 rpm, and 23.5% at 3000 rpm [234]. Investigating the G90MA10 blend at a constant 1500 rpm, the BTE values ranged from 10% to 28% at adequate pressure levels (104 kPa to 414 kPa) [235].

A study examining ethanol-blended fuels with varying blending ratios (10%, 20%, and 30% by volume) in a four-stroke spark-ignition engine showed that combining ethanol with gasoline improved BTE and BSFC while reducing exhaust gas temperature. CO and HC emissions decreased, but NOx emissions increased. Additionally, engine torque and brake power (BP) increased with lower ethanol percentages, while BSFC increased with higher ethanol percentages [236]. A study investigated methanol mixtures (0-15%) in gasoline and found that they increased the octane rating, BTE, ITE, and reduced knocking. It also examined the impact of methyl acetate in a single-cylinder spark-ignition engine at various loads, reporting that adding methyl acetate to base gasoline increased BSFC and decreased BTE [237].

A study on gasoline emissions at 2000-5000 rpm reported CO_2 values ranging from 11% to 13%, CO values ranging from 1.5% to 4.5%, and HC values ranging from 180 ppm to 450 ppm [238]. Investigating blends G85M15 and G70M30 at 2000-4000 rpm, a study found that CO values ranged from 0.14% to 0.06%, CO_2 values ranged from 13.5% to 14.8%, and HC values ranged from 150 ppm to 90 ppm [239]. A study studied blends G90E10 and G80E20 at 2000-4500 rpm, finding CO values ranging from 0.5% to 0.75% and HC values ranging from 145 ppm to 65 ppm [240]. Examining blend G75E25 at 2000-4500 rpm, a study reported CO_2 values ranging from 12.5% to 13.75% and NOx values ranging from 800 ppm to 600 ppm [241]. Studying methyl acetate blends G95MA5 and G90MA10 at a constant 1500 rpm, a study observed CO values ranging from 0.3% to 3.8%, HC values ranging from 80 to 170 ppm, and CO_2 values ranging from 10.5% to 13% [235]. Another study found that adding methyl acetate increased NOx emissions [242].

5.8 Conclusions

CBG (Compressed Biogas) demonstrated superior engine performance and efficiency across various parameters compared to gasoline and alcohol blends.

Brake Thermal Efficiency (BTE):

- CBG achieved the highest BTE value of 23.33%, showcasing its exceptional efficiency in converting fuel into work. G100 followed with a BTE of 21.76%, outperforming alcohol blends.

Brake-Specific Fuel Consumption (BSFC) and Brake-Specific Energy Consumption (BSEC):

- CBG exhibited the lowest BSFC, indicating its efficiency in fuel consumption at both low and high speeds. BSEC values further emphasized CBG's energy efficiency in producing brake power, ranging from 15.52 MJ/kWh to 22.795 MJ/kWh.

Combustion Phenomenon:

- CBG's combustion process is initiated at higher cylinder pressures, producing more power per combustion cycle. It demonstrated earlier end-of-burning cycles, indicating cleaner combustion and faster transition to the next cycle.

Emission Parameters:

- CBG emits less CO_2 emission (10-15%), CO (60-70%), HC (20-25%), and NOx (50-60%) than gasoline. It less pollutes the environment than gasoline and alcohol fuels. And it burns cleaner than petroleum-based products. Therefore, CBG fuel is the best solution for solid organic waste, the best alternative to gasoline fuel, and is eco-friendly.

CHAPTER 6:
CONCLUSIONS AND FUTURE SCOPE

6.1 Conclusions

- The study assessed 73 distinct types of household waste on the DTU campus, examining Sample-set (S1 to S24) containing 1620 waste bags. This resulted in the collection and segregation of 518.53 kg of RVW, 263.57 kg of FW, and 249.94 kg of MCW into digestive and compost wastes. Strong correlations were observed between RVW, FW, and MCW, with coefficients of determination (R^2) of 0.90, 0.91, and 0.94, respectively (all with $p < 0.05$).
- The most favorable biomethane (CH_4) generation was observed under different temperature and feed ratio conditions: 40°C with FW (1:1.5), 35°C with RVW (1:1.5), and 35°C with MCW (1:2).
- The study's results highlight the optimal conditions for biomethane (CH_4) generation, emphasizing the importance of temperature and feed ratios for efficient biogas production.
- In the case of MCW, introducing a tumbling effect led to an average increase of 47.9% in CH_4 gas production. This finding underscores the significant impact of tumbling on CH_4 gas production and highlights its potential for accelerating the process.
- Furthermore, tumbling accelerated CH_4 gas production compared to non-tumbling methods, providing practical insights to enhance biogas production efficiency for real-world applications.
- In terms of Brake Thermal Efficiency (BTE), CBG led the way with an impressive 23.33%, followed by G100 at 21.76%, surpassing the performance of alcohol blends. CBG demonstrated exceptional fuel consumption efficiency, reflected in the lowest BSFC values, indicating its proficiency at various engine speeds.
- The combustion behavior of CBG was characterized by its ability to initiate at higher cylinder pressures, generating more power per combustion cycle. Additionally, it exhibited earlier end-of-burning cycles, indicating a cleaner combustion process and swift transition to the subsequent cycle.

- In terms of emissions, CBG outperformed gasoline with reductions of 10-15% in CO_2, 60-70% in CO, 20-25% in HC, and 50-60% in NOx. CBG fuel demonstrates lower emissions and higher efficiency than gasoline and alcohol blends. Its eco-friendly attributes make it a promising solution for solid organic waste, offering a superior alternative to traditional fuels. The study's results showcase CBG's exceptional engine efficiency, combustion, and emissions performance.
- The present study supports the recommendation for installing a fair number of biogas plants in societies and university campuses of metros worldwide, allowing organic waste from households to be utilized for green energy production. This approach can significantly address metropolitan areas' extensive solid waste problem.
- Governments and industries can collaborate to advance the development and deployment of biogas and CBG technologies, promoting sustainable energy practices.

6.2 Future scope

- Exploring the potential of utilizing enriched biogas in dual-fueling applications with various alcohols (such as ethanol, methanol, butanol, and methyl acetate) and diverse biodiesels presents a promising avenue for future research.
- During the purification of raw biogas, collecting and analyzing CO_2 gas can open doors to further applications and research.
- Investigating the feasibility of using enriched biogas in dual fuel systems with various nanoparticles, including aluminum, titanium, zinc, cerium, and cobalt oxides, offers a promising avenue for enhancing energy efficiency and reducing emissions.
- Biomethane production is contingent on the quality of the waste source. Investigating biogas generated from diverse organic waste streams in different countries can provide valuable insights and opportunities for further study.
- The annual wastage of millions of tons of flowers and leaves from trees and plants worldwide represents an untapped resource. Exploring biogas production from these organic materials presents a promising avenue for research and sustainable practices.

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LIST OF PUBLICATIONS

Journal Paper SCIE/SCI Published

(1) Pradeep Meena, Amit Pal, Samsher. 2022. "Characterization, Utility, and Interrelationship of Household Organic Waste Generation in Academic Campus for the Production of Biogas and Compost: A Case Study." Environment, Development and Sustainability (0123456789). https://doi.org/10.1007/s10668-022-02747-z.

(2) Pradeep Meena, Amit Pal, Samsher. 2022. "Investigation of Combustion and Emission Characteristics of an SI Engine Operated with Compressed Biomethane Gas and Alcohols." Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-022-24724-9.

Journal paper SCIE/SCI Under review

(1) Title-Zone-wise Biogas Potential in India: Fundamentals, Challenges and considering policies. Authors – Pradeep Kumar Meena, Amit Pal, Samsher

(2) Effect of Tumbling in Production of Biomethane from Fruit, Raw Vegetable, and Cooked Waste. Authors – Pradeep Kumar Meena, Amit Pal, Samsher

List of International conference papers in 2018-2022

(1) (Pradeep, Amit Pal, Samsher. (2019). Current Scenario of Solid Waste Management in India. International Conference of Advance Research and Innovation (ICARI-2019), held at Delhi State Centre, Institution of Engineering, New Delhi on January 20th, 2019. ISBN-978-93-5346-324-3.

(2) Pradeep, Amit Pal, Samsher. (2018). Present Status & Future Scope of Renewable Energy Source in India. International Conference of Renewable Energy for Sustainable Development, 98-103. Maharana Pratap College of Technology, Gwalior (M.P.) India, ISBN-978-935321-480-7.

(3) Pradeep, Amit Pal, Samsher. (2019). Present Scenario of Waste Organization System in the Most Diverse States of India. International Conference of Sustainable Technologies for Environmental Management (STEM-2019), held at Delhi Technological University on March 25th to 26th, 2019. 182

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Book

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Book chapter (2022)

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CURRICULUM VITAE

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- He is a highly motivated individual with a solid objective to pursue a career in leading engineering colleges and universities within a hi-tech environment. His educational background reflects his dedication and pursuit of excellence. He is pursuing a Ph.D. from Delhi Technological University (DTU) and has achieved a notable CGPA of 8.63. Before this, he completed his M.Tech in Thermal Engineering from Govt. College of Engineering (COEP), Pune, and his B.E. in Mechanical Engineering from S.K.I.T, Jaipur.
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- Notably, He has made significant research contributions, with several of his papers published in reputable journals. Some of his noteworthy articles include "Effecting parameters of biogas production," published in the International Journal of Innovative Computer Science & Engineering, "Deep drawing rectification process for a cylindrical cup using a blank holder" in the National Journal Paper in KITE Journal, and "Conversion of non-recyclable plastic waste synthetic fuel-A case study" in the IPI Journal.
- In addition to his academic achievements, He has received an appreciation award for presenting the best paper in a technical session. He has actively participated as a volunteer in a faculty development program on alternative energy sources. He has also been a reviewer at the 2nd International Conference on "Recent advances in mechanical engineering" (RAME-2020). These accomplishments highlight his commitment to professional growth and his active involvement in engineering.
- Pradeep Kumar Meena's career aspirations, educational background, work experience, research contributions, and accolades showcase his unwavering commitment to excel in engineering, particularly within a hi-tech environment. His diverse experiences in teaching, research, and active participation in academic events demonstrate his dedication to continuous learning and determination to thrive in challenging settings.