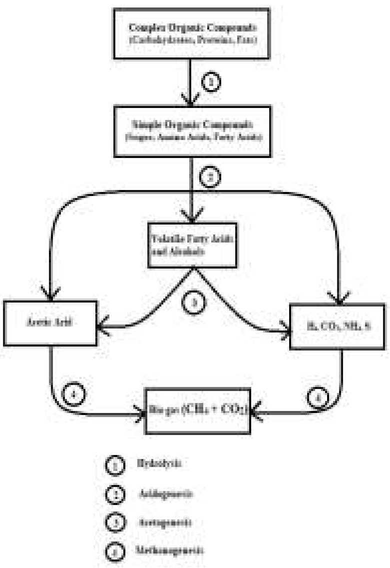
Global NEST Journal, Vol 25, No 10, pp 15-24

Effect of different inoculum and substrate inoculum ratios on biogas yield for anaerobic digestion of organic fraction of solid waste

Kapil Dev Sharma[1]* and Siddharth Jain[2]
[1]Department of Mechanical Engineering, Gurukul Kangri Vishwavidyalaya, Haridwar, Uttarakhand, India, Pin-249403.
[2]Department of Mechanical Engineering, College of Engineering, Roorkee, Uttarakhand, India, Pin-247667.
Received: 15/04/2023, Accepted: 24/06/2023, Available online: 24/09/2023
*to whom all correspondence should be addressed: e-mail: kapilshiva999@gmail.com
https://doi.org/10.30955/gnj.005076

Graphical abstract



Abstract

Municipal solid waste [MSW] has gained prominence in recent years as the rate of its generation has increased significantly. The serious problem of MSW management exists in almost all regions of India. This study aims to generate energy from MSW by selecting a suitable MSWM technology with the help of MSW characterization of Haridwar city. The suitable technique chosen was anaerobic digestion (AD) by physical and chemical characterization of MSW. The organic fraction of municipal solid waste (OFMSW) of 96 sub-samples with two different inoculums i.e., livestock dung and anaerobic sludge were used for AD experiments. A total of eight batch-type laboratory-scale anaerobic reactors were used in mesophilic conditions with different subtract-inoculum ratios (1/3, 1/2, 1/1, and 2/1). The S/I ratio of 1/1 was optimum for both inoculums. In this situation, the average cumulative biogas and methane yields for livestock dung were 461 NmL/g OM and 440 NmL/g OM, respectively, compared to 628 NmL/g OM and 474 NmL/g OM for anaerobic sludge. The anaerobic sludge inoculum was found to be better than livestock dung, with cumulative biogas production and methane yield being 3.5% and 4.2% higher, respectively.

Keywords: Municipal solid waste, waste characterization, waste management, anaerobic digestion, MSW

1. Introduction

Energy security, environmental protection, and resource depletion are important challenges at present. Generating electricity and heat from fossil fuels releases large amounts of greenhouse gases (GHGs) into the atmosphere (Kumar and Samadder 2017). Petroleum-based fuels have released 35,300 million tons of CO_2 into the atmosphere to date, with an estimated daily CO_2 release of 29,000 megatons (Yukesh Kannah et al. 2021). The negative effects of fossil fuel use can be reduced by using renewable energy sources more effectively. Currently, municipal solid waste (MSW) is seen as a renewable source of energy (Tyagi et al. 2018; Sharma and Jain 2020; Ravindran et al. 2022). Unsanitary landfilling release greenhouse gases (GHGs) such as CO2, CH_4, and leachate, all of which are a serious threat to the environment. The second most prevalent greenhouse gas is CH_4, which contributes to 14% of global GHG emissions and consequently climate change. CH_4 produces 21 times more global warming than CO_2. Over the long term, 1 ton of CH_4 is equivalent to 21 tons of CO_2, although, in the first year after emissions, CH_4 is 71 times more potent than CO_2 (Sharma and Jain 2019). Therefore, 18 EU countries have banned the landfilling of all recyclable solid waste in 2015, while several others (including the United States, France, and Poland) have imposed taxes on landfilling to make it a less desirable alternative for waste disposal (Scarlat et al. 2018; Zhao and Liu 2019). It is also because with aims to enhance the waste hierarchy, which first prepares to prevent waste generation, then prioritizes reuse, recycling, recovery, and disposal (WEC 2016).

In 2016, the World produced 2.01 BT (0.74 kg/person/day) of MSW, of which 33% was handled in an unsustainable and conservative manner. Additionally, it is anticipated that by 2030, this amount of MSW generation will rise to 2.59 BT (7.10 MT/day), and by 2050, it will reach 3.40 BT (9.32 MT/day). It has been estimated that every year around 15 metric ton of MSW is being added to the solid waste market (World Bank Group 2018). Organic waste, which includes food and green garbage, makes up the greatest portion of MSW in the world (44%), followed by paper and cardboard (17%), plastic (12%), glass (5%), metal (4%), wood (2%), rubber and leather (2%) and other (14%). (WEC, 2016; World Bank Group, 2018).

The energetic use of MSW plays an important role in reducing GHGs emissions as well as providing energy security (Amornsamankul et al. 2019; Kakadellis et al. 2022). It is estimated that by the year 2020, Europe and its former Soviet Union will have produced 250 billion cubic meters (m^3N) of bio-methane, which will be enough to cover half of the current consumption (Ferronato et al. 2018). Anaerobic Digestion (AD) is an attractive solution for biodegradable waste treatment. It is estimated that controlled AD produces 2-4 times as much methane in just 3 weeks from 1 metric tonne of MSW in comparison to what 1 metric tonne of waste in a landfill would produce in 6–7 years. AD is considered preferable to incineration if more than 50% of the waste is biodegradable (Khan et al. 2016). AD of the organic fraction of municipal solid waste (OFMSW) offers a dual benefit by producing biogas and treating the residues at the same time, hence decreasing the need of land for sanitary landfills (Lamnatou et al. 2019; Muhammad and Chandra 2021). According to the techno-scientific literature, the AD of OFMSW provides the best environmental and economic performance among the other biological treatment techniques of the OFMSW (Ardolino et al. 2018). Recent experimental research found that because of its bromatological, physical-chemical, and elemental composition, OFMSW is an appropriate carbon source for biorefinery systems (Rossi et al. 2022). Since OFMSW is a major part of MSW, employing OFMSW as a substrate for AD is a responsible choice for the management of MSW from an environmental standpoint. AD of OFMSW into high-volume but low-value products (such as biogas, biofuels, and electric power) and high-value but low-volume products (such as chemicals as fertilizers and volatile fatty acids (VFTs)) is an example of a biorefinery that is catalyzed by the bacterial community (Kumar and Samadder 2017; Taherymoosavi et al. 2017; Bala et al. 2019). When OFMSW contains a significant amount of food waste (FW), the accumulation of volatile fatty acids (VFAs) and long-chain fatty acids prevents the methanogenic activity, which can affect the stability of the AD process (Xiao et al. 2019; Amodeo et al. 2021).

In recent years, many studies have been carried out on the optimization of biogas production. For example, Zeshan found that 32 is the most feasible C/N ratio to avoid ammonia inhibition (Zeshan et al. 2012). The effect of the organic loading rate (OLR) on the generation of biogas has been studied by several authors. When food waste and rice husk were co-digested in a mesophilic environment, Jabeen found an inverse relationship between OLR and biogas production (Jabeen et al. 2015). The majority of research has also been done at the laboratory scale level on how operating parameters affect VFA production. For instance, during the fermentation of OFMSW at both thermophilic and mesophilic temperatures, alkaline conditions enhance the concentration of VFA.

There are just a few studies for Haridwar city that briefly characterize MSW and are mostly concerned with organic and inorganic wastes. However, there is currently no research that characterizes MSW in depth. Therefore, this paper is partitioned into two portions. Section 1 is focused on the detailed characterization of MSW and OFMSW and, section 2 is related to the AD of OFMSW under different conditions. The detailed characterization of MSW is extremely helpful to select the appropriate Municipal solid waste management (MSWM) technology and related issues. In this study, OFMSW has been used as a single substrate to produce biogas under mesophilic conditions. At the laboratory scale level, the AD of four different substrate/inoculum (S/I) ratios has been evaluated in terms of biogas production, methane yield, and stability of the process for two different inoculums i.e., livestock dung and anaerobic sludge.

2. Materials and methods

2.1. Description of study area

Haridwar is regarded as one of the seven holy towns in India. After Dehradun, Haridwar is the second-largest district in the state of Uttarakhand's southwest, with a total area of around 2,360 km^2.

Figure 1. MSW dumpsite of Haridwar City

It is located at 314 meters above sea level, its latitude and longitude are 29.96ºN and 78.15ºE respectively (Khabarwala and Jaintanwala 2019). The Ganges River exits the mountains and first flows into the Haridwar plains. Therefore, Haridwar is referred to as the "Gateway to God". The study was carried out at Haridwar, which is the second-largest city in the Uttarakhand State in terms of population after Dehradun City. The location of the MSW dumpsite in the city of Haridwar is close to the Sarai village, Bhagtanpur, with coordinates of Latitude: 29.9008 and Longitude: 78.092943 and a land area of 50.50 hectares, as shown in Figure 1.

2.2. Background of MSWM in haridwar

Thirty municipal wards in Haridwar City produce an average of 220 metric tons of MSW each day, most of which are discarded in the open at the Sarai Village Dump Site. So, according to statistics, every person generates around 0.94 kg of waste per day. By the year 2041, it is anticipated that this amount will have reached a daily average of about 370 MT (Government of Uttrakhand 2019). Although the problem of increasing solid waste in Haridwar is not very big at this time, it is necessary to pay attention to it before things get worse.

2.3. Sampling and sorting procedure

According to ASTM D5231-92, a total of 96 sub-samples (32 in winter, 32 in summer, and 32 in the rainy season) have been collected from 8 strata of the Sarai village dumping site above 1 foot (0.308 meters) of the MSW surface. The sample size has been determined using Cochran Eq. (1), which is stated in the ASTM D5231-92 (ASTM D 5231-92 2003). At a time, 8 sub-samples were collected (one from each strata) then all sub-samples were converted into a single sample using the “Quartering and Coining technique” (CPHEEO-Part I 2016). Similarly, there are 12 samples (A to L) in all 96 sub-samples, on which the study has been performed. Similarly, 12 samples (A to L) have been taken in this study, those are taken from 96 sub-samples. Four team members started manually sorting MSW at the dumpsite in accordance with ASTM D 5223-92 to determine the final sample size (ASTM D 5223-92 2014).

$$n = \left(\frac{Z_{\frac{\alpha}{2}} \times \sigma}{E} \right)^2 \qquad (1)$$

Where, n- Sample size, Z- Standard normal variant, α- standard deviation, E- Margin error

2.4. Characterization of MSW

The only way to solve the MSWM problem is to choose the proper technology to manage MSW; just technology is not a miracle cure. Sometimes, the incorrect choice of waste treatment method might result in the collapse of the entire waste management system. MSW generation rate, physical composition, and chemical characterization play a major role in the selection and adoption of an effective and environmentally friendly MSWM technique. During the study, MSW Samples were oven-dried in the oven at 105°C for physical characterization until the weight of each component become stable. Manual sorting has been done to know the physical composition of MSW samples for both RB (Received basis) and DB (Dry basis). After that proximity analysis was done to determine physical characteristics and ultimate analysis was performed for chemical characteristics. The calorific value was found using a bomb calorimeter for both the MSW and OFMSW samples. Proximate analysis, ultimate analysis, and heating values of MSW have significant importance for the assessment of the feasibility of energy recovery from the MSWM system (Adeleke et al. 2021).

2.5. Production of biogas

AD is an attractive solution to produce biogas from biodegradable waste treatment. It is estimated that controlled AD produces 2-4 times as much methane in just 3 weeks from 1 metric ton of MSW in comparison to what 1 metric ton of waste in a landfill would produce in 6–7 years. AD is considered preferable to incineration if more than 50% of the waste is biodegradable (Sharholy et al. 2008; Unnikrishnan and Singh 2010; Singh et al. 2011; Kalyani and Pandey 2014; Khan et al. 2016). AD is a biological conversion process where micro-organisms break down organic waste in the absence of an electron acceptor such as oxygen to produce biogas. Biogas that has been dried and is Sulphur-free can be used to generate heat and electricity in cogeneration unit combined heat and power (CHP) (Starostina et al. 2018).

Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four biochemical fundamental steps involved in the production of biogas as shown in Figure 2 (Qian et al. 2019; Van et al. 2020). The first step in the biogas decomposition process is hydrolysis., in which large organic polymer chains (carbohydrates) are broken down into smaller molecules (sugars, amino acids, fatty acids) (Cesaro et al. 2019). In the second step, the hydrolysis products undergo, in which acidogenic microorganisms further break down the substrate and generate an acidic environment, producing NH_3, H_2, CO_2, H_2S, fatty acids, organic acids, and alcohols (Cheng et al. 2016; Ge et al. 2016).

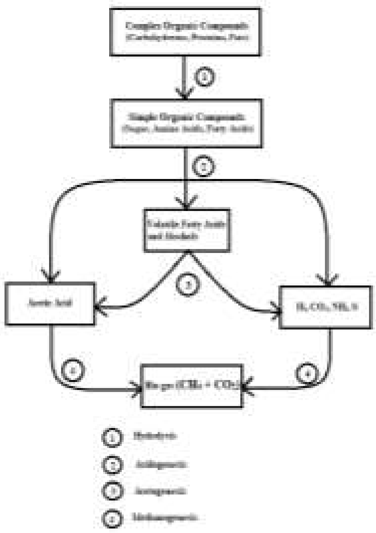


Figure2. Biochemical steps to produce Biogas

In the third step, acetogens produce acetate, an acetic acid derivative, from carbon and energy sources. It is a very min step that needs close cooperation between the organisms responsible for oxidation and the methane-producing organisms involved in the next stage of methane generation (Khalil et al. 2019). The final stage is methanogenesis, in which various methane-producing microorganisms known as methanogens produce carbon dioxide and methane (biogas) (Chen et al. 2016; Li et al. 2019; Liu et al. 2019; Zhang et al. 2019).

2.6. Substrates and inoculum

OFMSW was used as a single substrate for this study. The substrate was the mixture of OFMSW of all 12 samples in equal quantity. OFMSW is manually separated from the collected samples of MSW. It was basically the mixture of food waste, green waste, non-hazardous wood waste, etc. Equal samples of waste were collected in all three seasons i.e., winter, summer, and rainy. The particle size of the dried samples of OFMSW was reduced to an average particle size of 1 mm by a household electric grinder. Two fresh inoculums, livestock dung and anaerobic sludge were collected for AD experiments. When not immediately used, the inoculums were stored in a refrigerator under a temperature of 4°C for later use.

2.7. Experimental setup

Eight batch-type laboratory-scale anaerobic reactors with a capacity of 2 liters each were used for the AD experiments as shown in Figure 3.

Figure 3. Biogas production set-up (a) Top View and (b) Side View

All experiments were conducted at a time under the mesophilic condition (35 ± 2) °C. Each reactor was loaded with a substrate of the mixed OFMSW of all 12 samples and the required Inoculum fraction. After feeding, all-glass reactors were kept in a water-filled tub, in which the temperature of the water was maintained using the mini electric immersion rod connected with a thermocouple sensor in series. After the process started, the amount of biogas generated was daily measured using the water displacement method. Each reactor was manually shaken for 2 minutes thrice a day. Each reactor was manually shaken three times a day for two minutes.

The mass of VS fed to each reactor was 120 gm, which was the same for all the eight setups, while the substrate/inoculum (S/I) ratio has been changed. Four different S/I ratios were tested for both anaerobic sludge and livestock dung inoculums, which were 1/3, 1/2, 1/1, and 2/1. The feeding condition of each reactor is shown in Table 1. A digital pH meter with a combination electrode was used to measure the initial and final pH values of the mixture of substrate and inoculum. Biogas was collected in an inverted column to measure the amount of biogas generated from each reactor per day. All inverted column heads were fitted with a rubber cap from which the entire biogas was drawn out daily with the help of a syringe. Some of the biogas was filled in sampling bags and sent for gas chromatography, which measured the amount of methane present in the biogas.

3. Results and discussion

3.1. Physical and chemical characteristics of MSW and OFMSW

The detailed physical characterization of MSW has been presented in Table 2. Each MSW sample has been classified into various components and sub-components on the received basis (RB) as well as the dry basis (DB). It is clear that the MSW of Haridwar city contains almost all the components of the solid waste stream. The moisture content in the MSW samples was calculated from the difference between the weights of RB and DB, similarly used to calculate the moisture present in OFMSW. Which showed that MSW has a significant moisture content, which averages 28% of the total mass. The major component of the MSW for RB is organic waste (52%), followed by inert (18%), plastics (10%), paper & textile (9%), metal (5%), and others (5%); while for DB is organic waste (42%), inert (22%), plastics (12%), paper & textile (8%), metal (7%), and other (6%), as shown in Figure 4. The results show that the MSW of Haridwar city has about 40-60% wet biodegradable waste (organic waste), which is best suitable for energy recovery technology i.e., AD, Gasification, and Composting.

Table 1. Feeding conditions of all reactors

S.No.	Inoculum Type	S/I Ratio	Mass of VS (g)			pH Value	
			Substrate	Inoculum	Total	Subtract	Inoculum
1	Livestock dung	1/3	30	90	120	5.75	7.5
2	Livestock dung	1/2	40	80	120	5.75	7.5
3	Livestock dung	1/1	60	60	120	5.75	7.5
4	Livestock dung	2/1	80	40	120	5.75	7.5
5	Anaerobic Sludge	1/3	30	90	120	5.75	8.1
6	Anaerobic Sludge	1/2	40	80	120	5.75	8.1
7	Anaerobic Sludge	1/1	60	60	120	5.75	8.1
8	Anaerobic Sludge	2/1	80	40	120	5.75	8.1

Table 2. Physical composition (%) of MSW on Received Basis (RB) and Dry Basis (DB) in %

MSW Composition	MSW Samples Composition (%)																								Average (%)	
	Summer Season								Rainy Season								Winter Season									
	A		B		C		D		E		F		G		H		I		J		K		L			
	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB	RB	DB
Food Waste	60	50	56	50	39	28	42	32	39	30	43	30	39	28	50	40	42	32	56	45	55	40	54	45	**49**	**39**
Wood	1	2	2	2	0	0	2	1	5	4	1	1	0	0	9	9	2	1	3	2	4	6	0	0	**2**	**2**
Paper	1	1	8	9	14	9	10	8	13	11	2	2	14	9	5	4	10	8	0	0	4	4	2	2	**5**	**5**
Plastic	5	8	4	6	4	5	6	8	8	11	11	15	4	5	5	7	6	8	8	11	8	11	4	5	**7**	**10**
Metal	1	2	2	3	10	14	7	9	4	5	3	4	10	14	2	3	7	9	3	3	6	9	8	11	**4**	**6**
Thermocol	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	**0**	**0**
Polythene	10	9	0	0	0	0	2	2	4	4	0	0	0	0	5	4	2	2	0	0	2	2	2	3	**3**	**3**
Hair/Jute	2	2	0	0	2	3	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	1	2	**1**	**1**
Glass	5	7	2	3	0	0	2	2	4	5	10	12	0	0	1	1	2	2	0	0	0	0	6	7	**2**	**3**
Inert	14	19	0	0	23	31	22	27	16	21	27	32	23	31	20	28	22	27	25	31	21	26	12	13	**18**	**22**
Textile	0	0	11	12	0	0	5	5	6	7	3	4	0	0	0	0	5	5	4	5	0	0	9	10	**4**	**4**
Garden Waste	0	0	14	14	5	5	0	0	0	0	0	0	5	5	0	0	0	0	0	0	2	2	0	0	**2**	**3**
Wire	0	0	0	0	0	0	4	5	0	0	0	0	0	0	0	0	4	5	2	2	0	0	2	2	**1**	**1**
Rubber	0	0	1	1	3	5	0	0	1	1	0	0	3	5	0	0	0	0	0	0	0	0	0	0	**0**	**1**
Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	2	2	**1**	**0**
Al Foil	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	**100**	**100**
Total organic waste	60	50	70	64	44	33	42	32	39	30	43	30	44	33	50	40	42	32	56	45	56	42	54	45	**52**	**42**
Moisture Content MSW (%)	29		31		32		32		26		21		30		31		24		24		36		25		28	

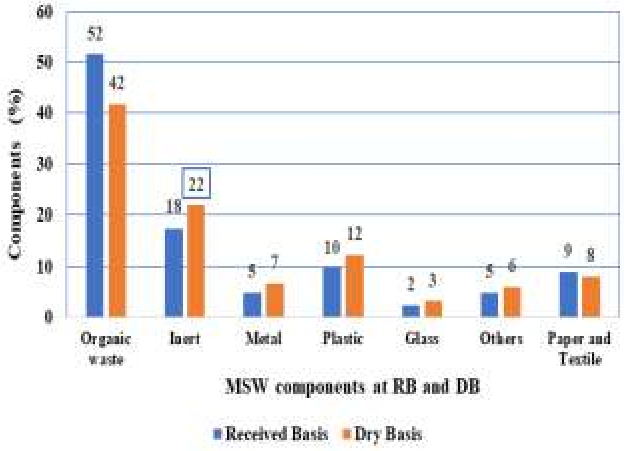


Figure 4. Composition of MSW at RB and DB

3.1.1. Proximate analysis

The approximate analysis is basically used to calculate the percentage of moisture content by heating the MSW to 105°C, volatile solid (VS) at 550°C, fixed carbon (FC) at 980°C, and ash content (Azam et al. 2020). TS is the sum of dissolved solids and suspended solids. TS and pH play an important role to evaluate the effectiveness of the AD process. VS is the organic portion of TS that biodegrade in the anaerobic process (Khabarwala and Jaintanwala 2019). The proximate analysis has been performed on Muffle Furnace according to the ASTM D7582-12 standard method (Titiladunayo, I. F, Akinnuli, B.O, Ibikunle, R. A, Agboola, O.O,Ogunsemi 2018). To determine the values of TS, VS, and MC, equations (2) to (4) have been used respectively. The results of the proximate analysis are presented in Table 3. According to the standard energy triangle, the best waste-to-energy conversion technology will be AD if MSW contains 5-50% moisture, 10-32% volatile matter, and 25-80% non-combustible material (Fetanat et al. 2019). The results of the proximate analysis indicate that AD is suitable for the MSWM of Haridwar city.

$$TS\ (\%) = \frac{M_{dried}}{M_{wet}} \times 100 \quad (2)$$

$$TS\ (\%) = \frac{M_{dried} - M_{burned}}{M_{wet}} \times 100 \quad (3)$$

$$MC\ (\%) = \frac{M_{wet} - M_{dried}}{M_{dried}} \times 100 \quad (4)$$

Where, M_{dried} = Mass of dried sample (mg), M_{wet}= Mass of wet sample (mg), M_{burned} = Mass of burned sample (mg).

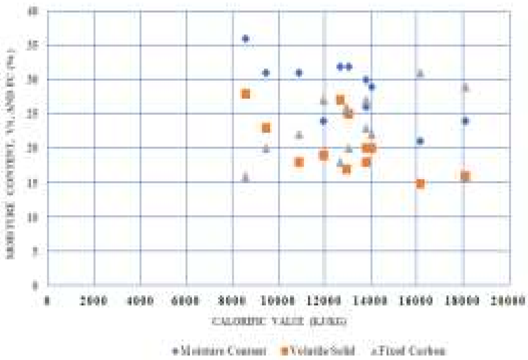


Figure 5. Calorific Value vs Moisture content, Volatile Solid, and Fixed carbon

Table 3. Results of Proximate analysis

Samples	Moisture (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash (%)
A	29	20	22	29
B	31	23	20	26
C	32	27	18	23
D	32	25	20	23
E	26	18	27	29
F	21	15	31	33
G	30	20	23	27
H	31	18	22	29
I	24	16	29	31
J	24	19	27	30
K	36	28	16	20
L	25	17	26	32
Average	**28**	**21**	**23**	**28**

3.1.2. Ultimate analysis

The ultimate analysis is basically used to find out the chemical constituents of MSW such as C, H, O, N, S, P, potash, and ash, as well as the C/N ratio and heating value. The ultimate analysis has been performed on the CHNSO analyzer (Model no. FLASH EA 1112) according to ASTM D3176-84 standard method. The results of the ultimate analysis have been presented in Table 4. The calorific value of each sample has been calculated through the Modified Dulong formula (eq. 2).

$$Heating\ Value (KJ/kg) = \left[337 \times \boldsymbol{C} + 1428\left\{\boldsymbol{H} - (\boldsymbol{O} \div 8)\right\} + 95 \times \boldsymbol{S}\right] \quad (5)$$

Normally, a C/N ratio between 20 to 30 would be considered the ideal condition for AD. In the results of the ultimate analysis, the average value of the C/N ratio is 27.9, which is most suitable for the process of

AD. The calorific value of MSW is also shown in Table 4, which ranges from 8550 KJ/kg to 18096 KJ/kg. The calorific value of MSW and OFMSW has also been calculated using a bomb calorimeter as shown in the Table 5.

It can be seen that there is no significant difference between the calorific value of MSW calculated by the modified Dulong formula and the bomb calorimeter. The trend of variation of calorific value with moisture content, fixed carbon, and volatile solids is shown in Figure 5. It is clear that calorific value is positively correlated with fixed carbon while negatively correlated with moisture content and volatile solids.

Table 4. Results of Ultimate analysis

Sample	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)	Phosphorus (%)	Potash (%)	Ash (%)	C/N Ratio	Calorific Value (KJ/kg)
A	38.6	5.0	34.5	1.4	0.5	0.7	1.1	18.2	27.6	14033.7
B	35.5	3.4	41.5	1.2	0.3	0.6	0.7	16.8	29.6	9441.4
C	34.8	5.7	40.5	1.4	0.4	1.3	0.6	15.3	24.9	12677.9
D	36.2	5.5	39.3	1.3	0.3	0.8	0.6	16.1	27.8	13063.1
E	42.3	3.6	31.6	1.2	0.4	1.1	0.9	18.9	35.3	13791.4
F	44.3	4.3	27.8	1.5	0.2	0.5	0.7	20.7	29.5	16128.1
G	38.5	5.0	35.7	1.4	0.4	0.9	0.7	17.4	27.5	13782.9
H	35.2	4.2	39.1	1.6	0.2	0.7	0.7	18.3	22.0	10903.5
I	43.8	5.8	27.9	1.3	0.4	1.0	0.7	19.2	33.7	18096.1
J	41.2	3.8	41.5	1.5	0.3	0.7	0.9	10.2	27.5	11929.7
K	31.5	4.2	45.5	1.3	0.6	1.3	0.7	14.9	24.2	8549.3
L	39.5	4.0	34.2	1.6	0.3	0.4	0.6	19.3	24.7	12949.2
Average	38.5	4.5	36.6	1.4	0.4	0.8	0.7	17.1	27.9	12945.5

Table 5. Heating value of MSW and OFMSW

Samples	Calorific value of OFMSW (KJ/kg)	Calorific value of MSW (KJ/kg)
A	15,588	13,990
B	13,909	10,020
C	15,230	12,980
D	16,145	13,320
E	15,220	14,150
F	16,490	15,880
G	17,163	14,850
H	14,356	11,350
I	18,609	17,540
J	14,647	12,280
K	13,150	9,120
L	15,168	12,485
Average	15,473	13,164

3.2. Biogas production and methane content

Experiments were carried out on all the reactors at one time to measure the daily and cumulative biogas production for different ratios of OFMSW and inoculum.

3.2.1. Biogas production and methane yield for OFMSW and Livestock dung inoculum

Cumulative biogas generation and methane content from each reactor with different S/I ratios and inoculum are shown in Table 6. The average daily and cumulative biogas yields were measured with different S/I ratios (1/3, 1/2, 1/1, and 2/1) for the Livestock dung shown in Figure 6. In each case, the reactors were fed, and the biogas generation started immediately after the feeding. It was found that the 1/3 S/I ratio lowest biogas generation, followed by 1/1, 2/1, and 1/1 as shown in Figure 6(a), 6(b), 6(d), and 6(c) respectively. The peak of biogas production was observed on the second day for S/I ratios 1/3 and 1/1, while it was on the third day for S/I ratios 1/2 and 2/1. After 18 days, the 1/3 S/I ratio had cumulative biogas production (461 NmL/g OM), while the 1/1 S/I ratio produced the maximum (607 NmL/g OM). The methane content was lowest in the S/I ratio of 2/1, followed by 1/3, 1/2, and 1/1. The cumulative biogas produced in the 1/1 S/I ratio was around 32% more than the biogas produced in the 1/3 S/I ratio. The average methane content of biogas was also maximum (72.5 %) when the S/I ratio was 1/1, while it was minimum (63.5%) for the S/I ratio of 2/1.

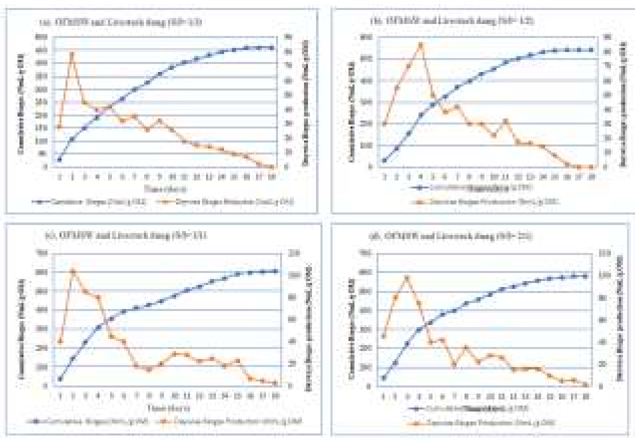


Figure 6. Average per day and cumulative biogas yield for livestock dung measured at four S/I ratio of 1/3, 1/2, 1/1, and 2/1

3.2.2. Biogas production and methane yield for OFMSW and anaerobic sludge inoculum

The average per day and cumulative biogas production for the anaerobic sludge inoculum were calculated using various S/I ratios (1/3, 1/2, 1/1, and 2/1) as shown in

Figure 7. In each condition, the reactors were fed, and the production of biogas began right away. The lowest biogas generation was determined to be at a 1/3 S/I ratio, followed by 1/2, 2/1, and 1/1 as in Figure 7(a), 7(b), 7(c), and 7(d). The peak of biogas production was observed for S/I ratios of 1/3 and 1/1 on the second day for anaerobic sludge, while it was seen on the third day for S/I ratios of 1/2 and 2/1. After 18 days, the cumulative biogas production was a minimum of 492 NmL/g OM for the 1/3 S/I ratio, followed by 552 NmL/g OM for 1/2, 578 NmL/g OM for 2/1, and 628 NmL/g OM for 1/1. The average biogas also had a maximum methane content of 75.5% when the S/I ratio was 1/1 and a minimum methane content of 64.6 percent when the S/I ratio was 1/2.

It has been found that the contents of methane in biogas were between 63% to 72% for OFMSW and livestock dung, while between 65% to 75.5% for OFMSW and anaerobic sludge. The S/I ratio of 1/1 was optimum for both the inoculums. Cumulative biogas production and methane yield were 3.5% and 4.2% higher, respectively, for the anaerobic sludge inoculum compared to livestock dung. The AD process remained stable for each S/I ratio. The pH value is a critical parameter for determining the stability of the AD process. In each experiment, the pH value of the OFMSW substrate (5.75) was slightly acidic, which has been balanced by the high pH value of the inoculum, which was 7.5 for livestock dung and 8.1 for anaerobic sludge. The initial pH values in all reactors ranged from 7.0 to 7.9, which is an acceptable range for the AD process. The final pH values at the end of the procedure ranged from 8.0 and 8.3, which is affected by the buffering capacity within the reactor.

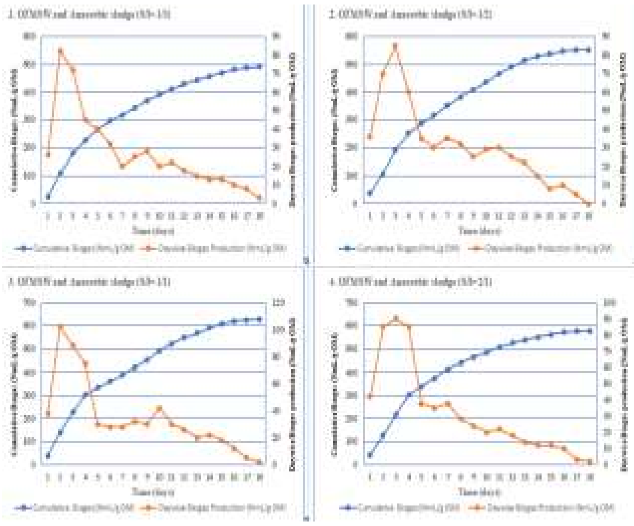


Figure 7. Average per day and cumulative biogas yield for Anaerobic sludge measured at four S/I ratio of 1/3, 1/2, 1/1, and 2/1

Table 6. Cumulative Biogas generation and methane content of reactors with different S/I ratios and conditions

S.No.	Inoculum Type	S/I Ratio	Temperature (°C)	Time (Days)	Cumulative Biogas (NmL/g OM)	Methane (%)	Cumulative Methane (NmL/g OM)	pH Value	
								Initial	Final
1	Livestock dung	1/3	35 ± 2	18	461	65.6	302.4	7.6	8.1
2	Livestock dung	1/2	35 ± 2	18	541	68.8	372.2	7.3	8.0
3	Livestock dung	1/1	35 ± 2	18	607	72.5	440.1	7.1	8.3
4	Livestock dung	2/1	35 ± 2	18	581	63.5	368.9	7.0	8.2
5	Anaerobic Sludge	1/3	35 ± 2	18	492	68.1	335.1	7.9	8.2
6	Anaerobic Sludge	1/2	35 ± 2	18	552	70.4	388.6	7.5	8.3
7	Anaerobic Sludge	1/1	35 ± 2	18	628	75.5	474.1	7.2	8.3
8	Anaerobic Sludge	2/1	35 ± 2	18	578	64.6	373.4	7.0	8.2

4. Conclusion

It was concluded that the present MSWM system in Haridwar city is not following the MSWM Rules 2016 set by the Indian government. Most of the waste is openly dumped without extracting the energy. OFMSW in Haridwar city is around 40-60% of the total MSW. The composition of MSW as well as the results of the proximate and ultimate analysis indicate that AD is the most suitable technology to manage OFMSW of Haridwar city. Experimental work of laboratory-scale anaerobic reactors indicates that a S/I ratio of 1:1 had an optimal biodegradation rate compared to other ratios (1/3, 1/2, and 2/1). Anaerobic sludge inoculum will be a better choice during the AD process than livestock dung. It is found that cumulative biogas production and methane yield are 3.5% and 4.2% higher for anaerobic sludge than for livestock dung, respectively.

Data availability statement

The authors confirms that the data generated during the study and used to support the findings are available within the article.

Acknowledgement

We are grateful to the Indian Academy of Environmental Sciences Hardwar and the Haridwar Nagar Palika Parishad (HNPP) for providing us with valuable solid waste information. We express our gratitude to colleagues, friends, and organizations from all over the world who have provided valuable information.

Declaration of Helsinki

Not Applicable

References

Adeleke O.A., Akinlabi S.A., Jen T.C., and Dunmade I. (2021). Evaluation and Prediction of Energy Content of Municipal Solid Waste: A review, *IOP Conference Series: Materials Science and Engineering*, **1107,** 012097. https://doi.org/10.1088/1757-899x/1107/1/012097

Amodeo C., Hattou S., Buffiere P. and Benbelkacem H. (2021). Temperature phased anaerobic digestion (TPAD) of organic fraction of municipal solid waste (OFMSW) and digested sludge (DS): Effect of different hydrolysis conditions. Waste Management, **126,** 21–29. https://doi.org/10.1016/j.wasman.2021.02.049

Amornsamankul S., Sirimangkhala K., Pimpunchat B., et al, (2019). A Review of Modelling and Computer Simulation of Landfill Gas, *International Journal of Simulation--Systems, Science & Technology*, 1–9. https://doi.org/10.5013/ijssst.a.20.04.09

Ardolino F., Parrillo F., Arena U. (2018). Biowaste-to-biomethane or biowaste-to-energy? An LCA study on anaerobic digestion of organic waste, *Journal of Cleaner Production*, **174,** 462–476. https://doi.org/10.1016/j.jclepro.2017.10.320

ASTM D 5223-92 (2014) Standard Test Method for Determining the Stability and Miscibility of a Solid , Semi- Solid , or Liquid Waste Material 1, **11,** 13–15

ASTM D 5231-92 (2003) ASTM D 5231 – 92: Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste, Current 06, 9–11

Azam M., Jahromy S.S., Raza W., et al. (2020). Status, characterization, and potential utilization of municipal solid waste as renewable energy source: Lahore case study in Pakistan, Environment international, **134,** 105291. https://doi.org/10.1016/j.envint.2019.105291

Bala R., Gautam V., Mondal M.K. (2019). Improved biogas yield from organic fraction of municipal solid waste as preliminary step for fuel cell technology and hydrogen generation, *International Journal of Hydrogen Energy*, 164–173. https://doi.org/10.1016/j.ijhydene.2018.02.072

Cesaro A., Belgiorno V., Siciliano A. and Guida M. (2019). The sustainable recovery of the organic fraction of municipal solid waste by integrated ozonation and anaerobic digestion, *Resources, Conservation and Recycling*, **141**, 390–397. https://doi.org/10.1016/j.resconrec.2018.10.034

Chen Y., Guo R., Li Y.C., et al. (2016). A degradation model for high kitchen waste content municipal solid waste, *Waste Management*, **58**, 376–385. https://doi.org/10.1016/j.wasman.2016.09.005

Cheng J., Ding L., Lin R., et al. (2016). Physicochemical characterization of typical municipal solid wastes for fermentative hydrogen and methane co-production. *Energy Conversion and Management*, **117**, 297–304. https://doi.org/10.1016/j.enconman.2016.03.016

CPHEEO-Part I (2016) Swachh Bharat Mission- Municipal Solid Waste Management Manual Part I: An Overview. In: CPHEEO Central Public Heal. Environ. Eng. Organ. Minist. URBAN Dev. India. http://cpheeo.gov.in/upload/uploadfiles/files/Part1(1).pdf. Accessed 26 Nov 2018

Ferronato N., Gorritty Portillo M.A., Guisbert Lizarazu E.G., et al (2018) The municipal solid waste management of La Paz (Bolivia): Challenges and opportunities for a sustainable development. *Waste Management & Research*, 36:1–12. https://doi.org/10.1177/0734242X18755893

Fetanat A., Mofid H., Mehrannia M. and Shafipour G. (2019) Informing energy justice based decision-making framework for waste-to-energy technologies selection in sustainable waste management: A case of Iran, *Journal of Cleaner Production*, **228**, 1377–1390. https://doi.org/10.1016/j.jclepro.2019.04.215

Ge S., Liu L., Xue Q, Yuan Z (2016) Effects of exogenous aerobic bacteria on methane production and biodegradation of municipal solid waste in bioreactors. *Waste Management*, **55,** 93–98

Government of Uttrakhand. (2019). Urban municipal solid waste management action plan for state of uttarakhand, In: Urban Dev. Dir. Dehradun

Jabeen M., Zeshan., Yousaf S., et al (2015) High-solids anaerobic co-digestion of food waste and rice husk at different organic loading rates. I*nternational Biodeterioration and Biodegradation*, **102,** 149–153. https://doi.org/10.1016/j.ibiod.2015.03.023

Kakadellis S., Lee P.H. and Harris Z.M. (2022). Two Birds with One Stone: Bioplastics and Food Waste Anaerobic Co-Digestion. *Environment- MDPI*, **9**, 1–14. https://doi.org/10.3390/environments9010009

Kalyani K.A. and Pandey K.K. (2014). Waste to energy status in India: A short review. *Renewable and Sustainable Energy Reviews*, **31**, 113–120

Khabarwala V., and Jaintanwala P.O. (2019). Environmental Baseline Study of Municipal Solid Waste Dumpsite solid waste characterization report for Environmental Baseline Study of Municipal Solid Waste Dumpsite Haridwar, Uttarakhand. Location: Haridwar Dumpsite at Sarai Road. submitted by econ labor

Khalil M., Berawi M.A., Heryanto R. and Rizalie A. (2019). Waste to energy technology: The potential of sustainable biogas production from animal waste in Indonesia. Renewable and Sustainable Energy Reviews, **105,** 323–331. https://doi.org/10.1016/j.rser.2019.02.011

Khan MMUH, Jain S, Vaezi M, Kumar A (2016) Development of a decision model for the techno-economic assessment of municipal solid waste utilization pathways. Waste Manag 48:548–564

Kumar A., Samadder S.R. (2017). A review on technological options of waste to energy for effective management of municipal solid waste, *Journal of Waste Management*, **69,** 407–422. https://doi.org/10.1016/j.wasman.2017.08.046

Lamnatou C., Nicolaï R., Chemisana D., et al. (2019). Biogas production by means of an anaerobic-digestion plant in France: LCA of greenhouse-gas emissions and other environmental indicators, *Science of the Total Environment*, **670**, 1226–1239. https://doi.org/10.1016/j.scitotenv.2019.03.211

Li Y., Chen Y., Wu J. (2019). Enhancement of methane production in anaerobic digestion process: A review, Applied energy, **240,** 120–137. https://doi.org/10.1016/j.apenergy.2019.01.243

Liu Y., Feng K., Li H. (2019.) Rapid conversion from food waste to electricity by combining anaerobic fermentation and liquid catalytic fuel cell, *Applied Energy*, **233–234**, 395–402. https://doi.org/10.1016/j.apenergy.2018.10.011

Muhammad M.B., Chandra R. (2021). Enhancing biogas and methane production from leaf litter of neem by co-digestion with vegetable waste: Focus on the effect of tannin, *Biomass and Bioenergy* **147,** 106007. https://doi.org/10.1016/j.biombioe.2021.106007

Qian M., Li Y., Zhang Y., et al (2019). Efficient acetogenesis of anaerobic co-digestion of food waste and maize straw in a HSAD reactor, *Bioresource technology*, 221–228. https://doi.org/10.1016/j.biortech.2019.03.032

Ravindran R., Donkor K., Gottumukkala L., et al. (2022). Biogas, Biomethane and Digestate Potential of By-Products from

Green Biorefinery Systems, Cleaner technology, 4:35–50. https://doi.org/10.3390/cleantechnol4010003

Rossi E., Becarelli S., Pecorini I., et al. (2022). Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste in Plug-Flow Reactors: Focus on Bacterial Community Metabolic Pathways, *Water* (Switzerland) **14,** https://doi.org/10.3390/w14020195

Scarlat N., Dallemand J.F., Fahl F. (2018). Biogas: Developments and perspectives in Europe, *Renewable energy*, **129**, 457–472. https://doi.org/10.1016/j.renene.2018.03.006

Sharholy M., Ahmad K., Mahmood G. and Trivedi R.C. (2008) Municipal solid waste management in Indian cities - A review, *Waste Management*, **28,** 459–467

Sharma K.D., Jain S. (2020). Municipal solid waste generation, composition, and management: the global scenario, *Social responsibility journal*,. https://doi.org/10.1108/SRJ-06-2019-0210

Sharma K.D., Jain S. (2019.) Overview of Municipal Solid Waste Generation, Composition, and Management in India. *Journal of Environmental engineering*, **145,** 1–18. https://doi.org/10.1061/(asce)ee.1943-7870.0001490

Singh R.P., Tyagi V.V., Allen T., et al. (2011). An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario, *Renewable and Sustainable Energy Reviews*, **15,** 4797–4808

Starostina V., Damgaard A., Eriksen M.K., Christensen TH. (2018). Waste management in the Irkutsk region , Siberia , Russia : An environmental assessment of alternative development scenarios. https://doi.org/10.1177/0734242X18757627

Taherymoosavi S, Verheyen V, Munroe P, et al. (2017). Characterization of organic compounds in biochars derived from municipal solid waste. *Journal of Waste Management*, **67,** 131–142. https://doi.org/10.1016/j.wasman.2017.05.052

Titiladunayo I.F., Akinnuli B.O., Ibikunle R.A., Agboola, O.O and Ogunsemi B. (2018). Analysis of F Combustible Mun Nicipal Solid Wast Te Fractions As Fue El for Energy Pr Roduction : Explorin Ng Its Physico-C Chemical and Ther Rmal. International Journal of Civil Engineering, **9**, 1557–1575

Tyagi V.K., Fdez-Güelfo L.A., and Zhou Y., et al. (2018). Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. Renewable and Sustainable Energy Reviews, **93,** 380–399. https://doi.org/10.1016/j.rser.2018.05.051

Unnikrishnan S., and Singh A. (2010). Energy recovery in solid waste management through CDM in India and other countries, *Resources, Conservation and Recycling*, **54**, 630–640

Van D.P., Fujiwara T., Tho B.L., et al. (2020). A review of anaerobic digestion systems for biodegradable waste: Configurations, operating parameters, and current trends, Environmental Engineering Research, **25,** 1–17. https://doi.org/10.4491/eer.2018.334

WEC (2016) World Energy Resources-2016. In: World Energy Counc. https://www.worldenergy.org/wp-content/uploads/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf. Accessed 11 Jan 2019

World Bank Group (2018) What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050-The Urban Development Series. In: Int. Bank Reconstr. Dev. / World Bank 1818 H Str. NW, Washington, DC 20433. https://openknowledge.worldbank.org/handle/10986/30317 . Accessed 14 Jun 2019

Xiao B., Zhang W., Yi H., et al. (2019). Biogas production by two-stage thermophilic anaerobic co-digestion of food waste and paper waste: Effect of paper waste ratio, *Renewable energy,* 132:1301–1309. https://doi.org/10.1016/j.renene.2018.09.030

Yukesh Kannah R., Kavitha S., Parthiba Karthikeyan O., et al. (2021). A review on anaerobic digestion of energy and cost effective microalgae pretreatment for biogas production, *Bioresource technology*, **332**, 125055. https://doi.org/10.1016/j.biortech.2021.125055

Zeshan, Karthikeyan O.P., Visvanathan C. (2012) Effect of C/N ratio and ammonia-N accumulation in a pilot-scale thermophilic dry anaerobic digester, *Bioresource technology*, **113**, 294–302. https://doi.org/10.1016/j.biortech.2012.02.028

Zhang Q., Wang M., Ma X., et al. (2019). High variations of methanogenic microorganisms drive full-scale anaerobic digestion process, *Environment international,* **126,** 543–551. https://doi.org/10.1016/j.envint.2019.03.005

Zhao Q, Liu Y (2019) Is anaerobic digestion a reliable barrier for deactivation of pathogens in biosludge?, *Science of the Total Environment*, **668**, 893–902. https://doi.org/10.1016/j.scitotenv.2019.03.063