2.1 Biogas scenario in India

India is a developing country. The population of India projected to approximately 1.37 billion in 2019, with a population growth rate of 1.08 %. According to United Nations (UN) projections, it will cross the 1.5 billion mark in 2029 (UN Population Division, 2019). The energy demand is increasing with population growth and economic development. The total energy consumption of India is expected to rise to 1921 million tons of oil equivalent (M toe) by 2040 as compared to 724 M toe in 2016 (Kumar and Majid, 2020). The principal goals of energy fuel for India are cost minimisation, efficiency maximisation, employment creation, system reliability, minimisation of petroleum products, increase usage of local resources and reduction of harmful emissions (Rajendran et al., 2012). Biogas technology is an appropriate option for energy generation as it includes all the above properties according to the Indian prospect. The biogas production in India was initiated by S.V Desai in 1939 on cattle dung at Indian Agricultural Research Institute, New Delhi. He successfully built a biogas plant based on cow dung in 1941 (Kharbanda and Qureshi, 1985). His experiments set the base for the development of the first biogas plant in India by the Khadi and Village industry commission known as KVIC digester in 1951 (Kharbanda and Qureshi, 1985). The establishment of the National Project on Biogas Development (NPBD) occurred in 1981-82 for the promotion of biogas. Consequently, 28.63 lakh family type and 2674 community type biogas plants were placed under this scheme, up to 1998-1999. The NPBD was renamed as National Biogas and Manure Management Program (NBMMP) in 2006 (Mittal et al., 2018). According to the Ministry of New and Renewable Energy, 47.5 lakh biogas plants were established under this scheme up to

March 2014. Additionally, 400 biogas off-grid power plants of 5.5 MW power generations were also established (Mittal et al., 2018). The target of 65,180 more plants was set that will accomplish during 2017-2020. The total biogas production is 2.07 billion m^3/year in India. However, the estimated potential was 29-48 billion m^3/year (Mittal et al., 2018). The main barriers to the development of biogas in India include financial, the competition to other fuels in the market, lack of social acceptance to the feedstocks like human excreta, dead animal carcass, etc., the climatic difference across the country, lack of awareness about the technology and associated benefits among the people.

2.2 Selection of feedstock

2.2.1 Criteria for feedstock selection

A variety of feedstock such as animal wastes, agricultural residues, industrial solid and liquid waste, municipal solid waste, fruit and vegetable waste, food waste, etc. can be used for biogas production. The quantity and quality of produced biogas are highly dependent on the biodegradability of feedstock. The criteria for feedstock selections are as follows:

1. **Availability**

   The substrate for biogas production should be available throughout the year. The presence of the substrate is essential for the stable operation of the biogas plant. It should be available on a low cost or no-cost basis to commercialise the process economically.

2. **Proper carbon to nitrogen (C/N) ratio**

   The C/N ratio should be appropriate for better biodegradability and process stability. A C/N ratio of 15-30 is considered suitable for biogas production (Li et al., 2013). If the C/N ratio is high, then microbes utilise the nitrogen rapidly and can't consume the leftover carbon that causes substrate inhibition to the process. In contrast, the less C/N ratio results in the accumulation of ammonia due to the high amount of nitrogen that hinders the process (Morales-Polo et al., 2020). Therefore, a proper C/N ratio is mandatory for better process performance. The C/N ratio of some organic substrates is depicted in Table 2.1.

Table 2.1 C/N ratio of different feedstock reported in the literature

Substrate	C/N ratio	Reference
Dairy manure	26.78	Sevik et al., 2018
Chicken manure	10.00	Dalkılıc and Ugurlu, 2015
Swine manure	13.36	Qian et al., 2019
Microalgae (*Selenastrum capricornutum)*	9.2	Caporgno et al., 2015
Municipal solid waste	18.7	Angeriz-Campoy et al., 2018
Sewage sludge	11	Angeriz-Campoy et al., 2018
Food waste	44.22	Deepanraj et al., 2017
Tannery waste	8.33	Mpofu et al., 2019
Slaughterhouse waste	8.41	Mpofu et al., 2019
Olive waste	67.77	Majbar et al., 2018
Rice straw	80	Shetty et al., 2017
Wheat straw	81.50	Dongyan et al., 2014
Corn stalk	30.63	Patowary and Baruah, 2018
Sawdust	102.4	Zhu et al., 2020
Sugarcane bagasse	88.65	Mustafa et al., 2018
Sorghum	29.00	Sambusiti et al., 2013

3. Adequate moisture content

The biogas yield is also dependent on the dry/wet content of the substrate. Various studies indicated that biogas production improved by increasing water content (Mao et al., 2019). The moisture content of 90-95 % (TS content of 5-10 %) was depicted as ideal for wet digestion (Deepanraj et al., 2015; Liu and Lv, 2016). If the substrate is too diluted, it may cause the washout of microorganisms in a continuous process. The standard pumps suitably can use to move the wet material quickly as compared to thick material that requires high concrete pumps and physical means of movement.

4. Substrate composition

Substrate composition is also an essential factor that determines the gas quality and production yield. Biogas composition varies with the variation of carbohydrates, lipids and protein content of the substrate. The feedstock should be enriched with micronutrients and macronutrients for microbial growth and enzyme activation. Micronutrients such as Fe, Zn, Ni, Cu, Co, Mn are required by methanogens that stimulates the metalloenzymes driven reactions and macronutrients like C, N, S, P, and H acts as buffering agent and enzyme component and are necessary for growth and metabolism of anaerobic microorganisms (Zieliński et al., 2019).

The complexity of the organic matter also determines the duration of digestion and production yield. Simple carbohydrates such as glucose are easily consumable by microbes, whereas the substrate enriched with cellulose, hemicelluloses and lignin (lignocellulosic material) requires a longer time for digestion. The digestibility of such type of material is improved by different pretreatment strategies.

2.2.2 Biogas production from liquid waste

Liquid waste includes industrial and household wastewater, sewage sludge (SS), etc. The solids in sewage sludge vary from 4-5 % in primary and 1-2 % in secondary (activated) sludge (Bora et al., 2020). The biogas production from SS is improved by introducing a co-substrate with it and several pretreatment techniques. Nabi et al. (2019) studied the effect of high-pressure homogenisation on SS. Biogas production from whole SS and with solid-liquid separation was compared. It was noted that gas was primarily generated from the solid portion, while the liquid portion synergistically increased the digestion of the solid sludge portion. The anaerobic digestion of the whole slurry (without solid-liquid separation) resulted in 25 % more biogas (409 mL) as compared to the sum of biogas production from the separated solid-liquid portion (371 mL). Moreover, the biogas production was increased by 82 % after treatment (60 MPa pressure) as compared to the untreated sample. Maragkaki et al. (2018) studied the co-digestion of SS with a thermally dried mixture of food waste, cheese whey and olive mill wastewater (FCO). An increment of 170 % was found in biogas when 93 % of *SS* was digested with 7 % FCO. 1181 mL/ L/d biogas was collected in this co-digestion. On the contrary, the co-digestion of SS with microalgae didn't improve the biogas yield as compared to individual digestion of substrates (Caporgno et al., 2015). The increased VS from microalgae and temperature rising in the digestion process showed a negative influence on microalgae digestion. However, the thermophilic temperature (55 °C) revealed better than mesophilic temperature (33 °C) in increasing the biogas production (566 ml/gVS) when the SS was digested alone.

Industrial wastewater includes the effluent received after different processing in dairy, textile, slaughterhouse (SWW), distillery and winery industries, etc. Dumping of wastewater directly causes underground water as well as other water bodies' pollution and causes significant ecotoxicological effects and health issues. Dairy wastewater is considered suitable for anaerobic digestion due to the presence of a high amount of organic compounds (COD concentration up to 80 g/L) and elevated temperature of 30-40 °C (Sarkar et al., 2006; Karadag et al., 2015). Treatment of effluents containing high-fat and solid by upflow anaerobic sludge blanket has a limitation of sinking and accumulation of higher density solids as compared to water in the first chamber and formation of fatty layers in digesters due to lack of mixing/stirring. The organic components become inaccessible to microbial species in both cases. Jürgensen et al. (2018) studied the biogas production from dairy wastewater in1 m^3 continuous stirred tank reactor (CSTR) and 0.2 m^3 anaerobic baffled reactor operating in series to improve the associated problem of such anaerobic digesters.

Distillery wastewater is characterised by high biochemical oxygen demand (BOD), chemical oxygen demand (COD), high solids, sulphates, phosphates, phenolic compounds, toxic metals and protein (≈ 22 %). A large amount of ammonia is produced during anaerobic digestion due to high protein content that often leads to process inhibition (Calli et al., 2005). Jiang et al. (2013) studied biogas production from protein-rich distillery wastewater in a thermophilic CSTR reactor. They developed a novel technique to reduce the ammonia inhibition by recirculation of the water washed biogas in the headspace and bottom (liquid phase). The effect of the substrate to the inoculum (S/I) ratio was studied by Caillet et al. (2019) on the biomethane potential of sugarcane distillery wastewater by varying it in the range of 3.9 to 1.0 $gVS_{substrate}/gVS_{inoculum}$. The S/I ratio of 1/1 ($gVS_{substrate}/gVS_{inoculum}$) was found to be best among all in improving the biogas production. The biogas yield obtained at this ratio was 216.18 $NmLCH_4/gVS$. The CSTR is the most appropriate digesters for the anaerobic digestion of distillery wastewater. It can be used as a single or biphasic treatment system (Chowdhary et al., 2018).

The characteristics of SWW depend on some factors that include the type of animal that to be slaughtered, the size of the slaughtering facility, water consumption per animal and washing of slaughtering tools (Aziz et al., 2019). It is expected to produce high biogas yield from SWW due to the presence of high protein and fat content. Therefore, it is considered a suitable substrate for biogas production. However, the creation of inhibitory substances like ammonia, long-chain fatty acids etc. are problematic during anaerobic digestion as they hinder the process. This problem is mitigated by using co-digestion approaches (Palatsi et al., 2011). The biogas potential of SWW is differed by type of its origin such as slaughter floor (0.5 m^3 CH_4/kgVS), paunch and cattle yard wastewater (0.25-0.3 m^3 CH_4/kgVS), etc. (Martí-Herrero et al., 2018).

2.2.3 Biogas production from solid waste

Solid waste such as food waste, lignocellulosic waste, organic fraction of municipal solid waste (OFMSW), animal manure, microalgae and industrial solid waste is used for biogas production. Food waste characteristics vary with the eating habits of a particular area. Food waste contains a high amount of moisture that requires a large amount of energy for incineration. Therefore, anaerobic digestion is the most appropriate option for its treatment. The VS content in food waste varies in the range of 29.5-71.34 % (Okoro-Shekwaga et al., 2019; Joshi and Gogte 2019; Deepanraj et al., 2017) that indicates the applicability of anaerobic digestion. It contains a varied amount of carbohydrate, protein and fats and requires a pretreatment step for better utilisation of substrate by microorganisms.

Lignocelluloses are the biomass that contains lignin, cellulose and hemicellulose in it. Yard waste, water hyacinth, agricultural residue, falling leaves, forest residue, etc. contribute to lignocellulosic waste. Lignin is the main component that is responsible for the rigidity of lignocellulosic waste. The detailed structure of this type of waste is discussed in section 2.3.

OFMSW includes a wide variety of waste such as food waste, fruit and vegetable waste, paper waste, waste textiles, cotton, garden waste, etc. India generated 55 million tonnes per year (EAI) of municipal solid waste (MSW) due to its 1.37 billion populations in 2019. MSW characteristics vary from site to site depending upon the climatic conditions. The presence of lignocelluloses increases its complexity. Therefore, various pretreatment strategies are required to break the complexity of MSW. The biogas production from lignocellulosic waste and MSW are discussed in detail in sections 2.3 and 2.4, respectively.

Animal manure is the traditional substrate of biogas production and significantly contributes to sustainable development in rural areas. High water content and fibrous material are the main factors that are responsible for the low methane yield (Ormaechea et al., 2018). Therefore pretreatment steps are required to improve the production. High viscosity, presence of sand and feathers and ammonia accumulation due to high nitrogen content is the main limitation of anaerobic digestion of chicken manure (Fuchs et al., 2018). The inhibiting concentration range of total ammonia nitrogen is 1.5-7 g/L (Fuchs et al., 2018). To improve the biogas production from manure several techniques are employed that include dilution of the manure by water addition, temperature enhancement of digester, several pretreatment technologies and balancing the nitrogen of manure by co-substrate (Dalkilic and Ugurlu, 2015).

Algae is the third generation substrate that has several advantages over other feedstock such as no competition with food vs fuel, use of nonarable land to grow, better ability to consume CO_2 than other plants, and better biodegradability than lignocelluloses because they are devoid of lignin (Mussgnug et al., 2010). Macroalgae like *Ulva rigida*, *Laminaria sp., Macrocystis pyrifera, Chaetomorphalinum, Chlorella sp*., *Scenedesmus sp., Chlamydomonas reinhardtii, Spirulina, N. gaditana, etc.* is used for biogas production. The biogas production from algae is highly dependent on the selected strain (Mussgnug et al., 2010). The presence of complex carbohydrates and low C/N ratio are the main reasons for low biogas production (Ramos-Suárez and Carreras, 2014). The nutrients requirement during algae cultivation increases the cost of the process.

Industrialisation is the need for a developing world. Industrial waste such as textile, tannery, olive mill, slaughterhouse solid waste, paper, and pulp waste, etc. are also utilised for biogas production (Table 2.2). Tannery waste produced from the different operations of beam house, tanning and finishing. Tannery and slaughterhouse waste consists of high organic matter and is treated effectively by anaerobic digestion. Solid waste from the olive mill is known as olive pomance that is produced by the solvent extraction of cold-pressed oil. It is rich in high content of lignin (37 %), cellulose and hemicellulose (49.5 %), minerals (6 %) and 7. 5 % of oil content remained in pulp (Battista et al., 2016). Olive mill effluent is the widely used industrial waste for biogas production. The potential of some solid waste is summarised in table 2.2.

2.3 Lignocelluloses as biogas substrate

Agricultural residue, forest residue, sawdust, grass, etc. are the contributor to lignocellulosic waste. Lignocelluloses are the complex structure that is rigid to microbes and hinders the accessibility of microorganisms and thus reduces the product yield.

2.3.1 Composition of lignocellulosic residue

The cell wall compositions vary from one plant species to another. Generally, woody biomass is rich in lignin and cellulose whereas herbs like grasses are composed of hemicelluloses mainly (Zhao et al., 2012). Cellulose is formed by D-glucopyranose units linked with β-1, 4-glycosidic bonds in the form of microfibrils which in turn entwined into fibrils in such a way that cellulose gets crystalline properties (Chen, 2014). It presents in two forms including amorphous and crystalline. Besides cellulose, lignin is the other main component of the cell wall. It is a complex, irregular and amorphous structure of phenylpropane by the irregular pairing of C-O and C-H bonds (Chen, 2014). The basic structural monomers of lignin are p-phenyl monomer (H type) obtained from coumaryl alcohol, guaiacyl monomer (G type) obtained from coniferyl alcohol and syringyl monomer (S type) obtained from synapyl alcohol (Chen, 2014, Novaes et al., 2010). Hemicellulose is the amorphous component of the cell wall. Xylan, xyloglucan, glucomannan, galactomannan, callose, etc. are present as hemicelluloses in cell-matrix (Yin and Fan, 1999). Cellulose, lignin and hemicelluloses are connected by hydrogen bonds. Other chemical bonds are also present in between hemicelluloses and lignin; these are galactose residues, arabinose residues on the side chain of hemicelluloses and lignin (Yang, 2008). The presence of crosslinks among lignin-cellulose-hemicellulose, the degree of polymerisation and the protecting nature of lignin are responsible for the recalcitrance of lignocelluloses and make them unsuitable and inaccessible to microbial enzymes resulting in less hydrolysis that in turn causes less production of biogas (Behera et al., 2014). A review of the composition of different lignocelluloses is depicted in Table 2.3.

2.3.2 Pretreatment methods for lignocelluloses and biogas production

Pretreatment is the mandatory step when lignocelluloses are used as biomass for biogas production. The pretreatment is used to increase the surface area, reduce the rigidity, and enhance the porosity with the main goal of delignification and hence increase the utilisation of substrate by microorganisms (Behera et al., 2014). Mechanical, chemical thermal, biological and their combinations are used to solubilise the lignocelluloses.

Table 2.2 Biogas production from solid waste

Substrate	Digester mode	Working volume (L)	Substrate loading	Temperature (°C)	Time (d)	Biogas yield (mL/gVS)	Methane content (%)	Reference
Chicken manure	Semi-continuous mode, 2 stage	0.5 (2.5)	2.2 gVS/L/d	37 (53)	12	554	74	Dalkılıc and Ugurlu, 2015
Poultary manure	Semi-continuous STR	19	2gVS/L/d	34.5	28	330	62.6	Bres et al., 2018
Cattle manure	Pilot-scale, Induced bed reactor	1250	3.1gVS/L/d	55	20	590 (CH_4)	64.3	Ormaechea et al., 2018
Swine manure	Batch digestion	0.5	8.1 gVS	35	66	456.8	60	Qian et al., 2019
Algae (*Chlamydomonasreinhardtii)*	Batch digestion	0.06	0.5 g dry biomass	38	32	587	66	Mussgnug et al., 2010
Algae (*Ulva rigida*)	Batch mode	0.5	2 g COD	37	48	*626.5	-	Karray et al., 2015
Filamentous algae (*Hydrodictyonreticulatum*)	Batch reactor	0.2	8.7 gVS/L	35	-	384	-	Lee et al., 2014

*mL/g COD, The values under brackets are for methanogenic stage

Table 2.2 continued

Substrate	Digester mode	Working volume (L)	Substrate loading	Temperature (°C)	Time (d)	Biogas production (mL/gVS)	Methane content (%)	Reference
Tannery waste	Batch	225	13 gVS	35	170	16.3	61.8	Agustini at al., 2018
Cattle slaughterhouse waste	Batch	0.9	-	39	50	651 (CH_4)	69	Ware and power, 2016
Olive waste	CSTR	6	4.6 COD g/L sludge/d	37	28.7	503.6 (CH_4)	70	Al-Mallahi et al., 2016
Olive pomance	Semi continuous	1	9.3 COD g/L/d	37	20	*76	80	Tekin and Dalgıc, 2000
Cotton industry waste	Batch mode	0.5	24.36 gVS	55	90	51.6	70	Ismail and Talib, 2016
Food waste	Batch	0.5	-	35	15	**4000	-	Joshi and Gogate, 2019
Food waste	Batch	1.6	71.3 gVS/L	50	30	139.2	62.5	Deepanraj et al., 2017

*mL/gCOD, **(mL), Table is showing the potential of different solid feedstocks for biogas production

Table 2.3 Compositional characterisation of some lignocelluloses

Substrate	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Rice straw	34.2	28.8	19.4	Patowary and Baruah, 2018
Water hyacinth	56.9	-	10.4	Sarto et al., 2019
Sugarcane rind	31.5	31.7	12.4	Wang et al., 2019
Corn stalk	30.6	38.5	20.1	Patowary and Baruah, 2018
Sorghum	32.2	16	25.7	Sambusiti et al., 2013
Wheat straw	45.6	35.4	9.5	Dongyan et al., 2014
Sawdust	45.1	20.5	26.4	Ali et al., 2019
Corn straw	41.3	21.3	14.7	Fu et al., 2015
Sugarcane bagasse	35.8	24.4	14.5	Mustafa et al., 2018

Data given are in wt %

Chemical treatment is the extensively employed technique on lignocellulosic biomass as it effectively degrades the lignin and breaks the robustness of biomass. Chemical pretreatment with different combinational treatments such as hydrothermal, microwave, biological, etc. can improve the efficiency of the pretreatment (Table 2.4).

Alkali pretreatment

Alkali such as NaOH, ammonia, $Ca(OH)_2$, KOH, etc. are used widely to treat the feedstock as they can effectively dissolve the lignin, cause an increase in surface area by swelling of biomass and conserve the cellulose. It is highly dependent on the operating temperature, time and concentration. Alkali dose in the range of 1-10 % is generally used to solubilise the biomass at a varying range of 20-200 ℃. However, the treatment at low temperature requires a longer retention time for effective results (Salehian et al., 2013). Pretreatment of rice straw by 1 % NaOH for 3 h at ambient temperature increased the biogas yield from 370 mL/gVS (untreated) to 506 mL/gVS with a 20 % increase in the methane content of biogas. However, further increasing the concentration decreased the methane yield due to excessive sodium inhibition (Shetty et al., 2017). The NaOH treatment in combination with fungal treatment enhanced the lignin degradation as compared to fungal treatment alone and also improved the biogas production by 50.1 % (Alexandropoulou et al., 2017). Ammonia with sufficient moisture content can synergistically increase the chemical reactions, the effectiveness of the pretreatment, C/N ratio and biodegradability of the substrate (Dongyan et al., 2014). Alkali treatment causes lignin destruction by cleaving the phenol-type α-aryl ether or α-alkyl ethers, phenol-type β-aryl ethers and non-phenol-type β-aryl ethers. It also degrades carbohydrates through peeling reactions (Xu et al., 2016). Lignin solubilisation resulted in the production of the phenolic by-products that are inhibitory to microorganisms (Jönsson et al., 2016). The neutralisation step of biomass by several washing is essential before the anaerobic digestion after chemical treatment to stop the reaction, washing off the chemical and providing a neutral pH to the substrate (Mancini et al., 2018).

Acid treatment

Sulphuric acid is extensively used as the pretreatment agent due to its effective results and low cost (Syaichurrozi et al., 2019). Other acids such as HCl, H_3PO_4, $SO_2$and organic acids like CH_3COOH can be employed for biomass hydrolysis. H_2SO_4 in the range of 2-6 % can decrease the lignin, increase the carbohydrate and improves the C/N ratio (Syaichurrozi et al., 2019). Acid treatment can cause variation in biomass properties such as cellulose degradation by breaking the covalent bonds, wander wall forces and hydrogen bonds with increasing the concentration (Sarto et al., 2019). The generation of furfural and hydroxymethylfurfural also took place in acid pretreatment that is inhibitory to microbes (Jönsson et al., 2016).

Other chemicals

Other chemicals such as organic solvents, NMMO, salts, Fenton's oxidation, hydrogen peroxide etc. are used to improve the biodegradability of the substrate. Organosolv treatment using organic solvents such as ethanol, methanol, isopropanol, etc. are used to disorganise the biomass structure. Methanol prioritises over ethanol due to its less toxicity, low cost and easy recovery. H_2SO_4 is added as a catalyst to improve pretreatment and biogas production (Hesami et al., 2015). An increase of total carbohydrate was found when the sunflower stalks were pretreated with the iso-propanol in combined with hydrothermal treatment at 200 °C in presence of H_2SO_4 (Hesami et al., 2015).

Table 2.4 Biogas production from different lignocellulosic residue

Substrate	Pretreatment condition	Findings	DM	WV (L)	SL	T (°C)	t (d)	BP (mL/gVS)	IP (%)	Reference
Rice straw	NaOH- 1 % Time- 180 min	COD increased, low methane yield NaOH>1	Semi continuous	1	-	37	15	514	36.76	Shetty et al., 2017
Sawdust (Casuarina and Pine)	Microbial consortium isolated from rotten sawdust	56.7 % lignin removal	Batch	-	-	30	35	312	86.4	Ali et al., 2017
Sawdust (Willow sawdust)	*Abortiporusbiennis*-30 d NaOH-20 g/100 gTS, T-80 °C, t- 24 h	54.2 % lignin removal	Batch	0.1	2 gVS/L	35	-	218 (CH_4)	115	Alexandropoulou et al., 2017
Rice straw	Hydrothermal : 200 °Ct: 10 min NaOH: 5 %, t: 120 h	80 % increase in VS conversion efficiency to biogas	Batch	1	-	37	60	315.9	225.6	Chandra et al., 2012
Corn straw	Microaerobic T-55 °C, Oxygen load-5 ml/gVS$_{substrate}$	63.25 % increase in VFA, VS decrement	Batch	0.2	5 gVS	37	60	325.7 (CH_4)	16.24	Fu et al., 2015
Wheat straw	Ammonia - 4 % Time: 7 d	Improved C/N ratio	Batch	-	-	35	25	199.5 (CH_4)	60	Dongyan et al., 2014
Sorghum	NaOH -10 g/ 100 g TS, T-40 °C, t-24 h	25 % methane increased	Semi-continuous	1.5	-	35	21	346 (CH_4)	25	Sambusiti et al., 2013

Where DM=Digester mode, WV=Working volume, SL=substrate loading, T=Temperature, t=Time, BP=Biogas production, IP=Improvement in production

Table 2.4 Continued

Substrate	Pretreatment	Findings	DM	WV (L)	SL	T (°C)	t (d)	B P (mL/gVS)	IP (%)	Reference
Sugarcane rind	$Ca(OH)_2$- 4 % microwave-700 W t-10 min	37, 59 % reduction in cellulose and lignin respectively.	Batch	0.4	-	37	35	471.67 (CH_4)	41.13	Wang et al., 2019
Corn stalk, Rice straw	Banana peel ash- 20 g, $Ca(OH)_2$ -10 g, t: 7 d Thermal- 60-90 °C t- 2, 6, 10 h	A longer time at high temperatures was effective. Corn stalk(47 %) lignin degraded better than rice straw (39 %)	Batch	-	-	37	50	Rice straw : 390 Corn stalk: 480	Rice straw: 62 Corn straw: 66	Patowary and Baruah, 2018
Salviniam olesta (weed)	H_2SO_4-4 %, t-2 d	Decreased lignin and increased, improved C/N ratio	Batch	-	6.38 gVS	30	30	24.14	81.78	Syaichurrozi et al., 2019
Water hyacinth	H_2SO_4 -5 % t- 60 min	Cellulose degradation	Batch	0.6	-	28	90	*420.30	131.45	Sarto et al., 2019
Sunflower stalks	isopropanol-50 % + H_2SO_4-1%, T- 160 °C, t-30min	Lignin removal-21 %	Batch	0.25		37	45	264 (CH_4)	124	Hesami et al., 2015
Wheat straw	Ethanol-50 % T-180 °C, t- 1h NaOH-1.6 % T- 30 °C, t-24	Ethanol dissolved the hemicellulose and NaOH dissolved the lignin	Batch	0.07	1 g	37	40	Ethanol-316 (CH_4) NaOH-315 (CH4)	Ethanol : 15 NaOH: 15	Mancini et al., 2018

Where DM=Digester mode, WV=Working volume, SL=substrate loading, T=Temperature, t=Time, BP=Biogas production, IP=Improvement in production, *mL

2.4 Organic fraction of municipal solid waste as biogas substrate

2.4.1 MSW composition and characteristics

An enormous amount of MSW is produced each year due to rapid urbanisation and population growth. The amount of waste generated varies according to the country, population size, size of the city, lifestyle and community income (Jain and Sharma, 2011). According to World Bank data, the global MSW generation was 2.01 billion tonnes per year in 2016 and is expected to increase up to 3.4 billion tonnes per year by 2050. India and China are the great contributors of generated waste. The total waste production in India is 55 million tonnes per year (EAI). According to the Central pollution control board (CPCB), the waste generated in the metro cities of India was 8700, 11000, 4000, and 5000 tonnes/d in Delhi, Mumbai, Kolkata and Chennai, respectively in 2015-16. The composition of MSW is divided into biodegradable, paper, plastic, glass, metal, inerts and bio-resistant materials. Biodegradables also are known as an organic fraction of municipal solid waste (OFMSW) include food waste that can be produced from households or restaurants, yard waste, kitchen waste, etc. and are easily digested by microbial enzymes. Paper, plastics, glass and metals are recyclable. Inert materials include impurities like sand, bricks, etc. Leather, rubber, bones etc. are present as bio-resistants in MSW. The compositional study of MSW of metro cities of India and different countries are given in Table 2.5 and 2.6, respectively. The MSW composition of India in 2011 was biodegradable-52.3 %, paper-13.8, plastics-7.9 %, metals-1.5, glass-0.9 and inerts-22.6 (Sharma and Jain, 2019).The OFMSW fraction of MSW is widely studied by researchers to produce biofuel to mitigate waste management and energy-related issues. The physico-chemical properties of OFMSW are highly variable according to the seasons and the lifestyle of the community. OFMSW characteristics from some studies are summarised in Table 2.7.

Table 2.5 Composition of MSW in metro cities of India (CPCB, Saini et al., 2012)

City	Waste generated (tonnes/d)		Composition in 2004-05		
	2015-16	2004-05	Biodegradable (%)*	Recyclable (%)*	Inert (%)*
Delhi	8700	5922	31.78	16	51.82
Mumbai	11000	5320	40	16	44
Chennai	5000	3036	49.06	14	36.09
Kolkata	4000	2653	40	25	35
Bangalore	3700	1669	45	28	27
Varanasi	500	425	48	17	35

*The data are provided by wt %

Table 2.6 Composition of MSW in different countries reported in literature

City/Country	Biodegradable (%)	Paper (%)	Plastics (%)	Glass (%)	Metal (%)	Inert (%)	Bio-resistant (%)	References
India	52.3	13.8	7.9	0.9	1.5	22.6	14	(Sharma and Jain, 2019)
China	55	10	10	4.5	o.5	20	-	Xu et al., 2016
Iran	70.2	4.2	14.0	1.17	0.65	-	0.55	Dehkordi et al., 2019
USA	34.6	25.9	13.1	4.4	9.1	3.6	9.3	US Fact sheet, 2015

The data are provided by wt %

Table 2.7 Physico-chemical characteristics of OFMSW reported in the literature

City	TS (%)	*VS (%)	Moisture (%)	Other (Fixed carbon+Ash)	C/N ratio	pH	Reference
Delhi, India	14.08	10.3	85.9	3.8	32.5	-	Ghosh et al., 2020
Mumbai, India	46.1	38.8	53.9	7.3	-	6.84	Dasgupta and Chandel, 2019
Dhanbad, India	74.5	45.3	25.5	29.2	19.4	-	Mboowa et al., 2017
Varanasi, India	16.9	10.2	83.1	6.7	26.4	-	Dasgupta and Mondal, 2012
Brazil	63	45	37	18	40	-	Leme et al., 2014
China	56	35	44	21	-	-	Xu et al., 2016
Italy	18.9	15.8	81.1	3.1	-	-	Fantozzi and Buratti, 2011

*Data is given as % dry basis

2.4.2 MSW management methods

The direct combustion and degradation of MSW in open sites lead to emissions of harmful gases such as methane and cause the contamination of soil and groundwater. The presence of high organic matter in MSW can stimulate the growth of pathogens and cause serious health issues (Pujara et al., 2019). Therefore, disposal of waste and management is a serious concern. Landfilling, incineration, Refuse derived fuel (RDF), biomass gasification, composting and anaerobic digestion are the common practices employed for waste management. Landfilling is the widely used method for

Table 2.8 Waste treatment strategies applied in Indian states (CPCB, 2016)

State	Waste generated (tonnes/d)	Waste collected (tonnes/d)	Waste treated (tonnes/d)	Landfilled (tonnes/d)	Treatment methods
Madhya pradesh	6773	5480	1141	4339	Vermi-composting, anaerobic digestion, refused derived plant (RDF)
Meghalaya	187	156	36	120	Vermi-composting, composting
Punjab	4544.35	4520.35	39.175	3278.6	Vermi-composting, RDF plant
Tamil Nadu	14658.466	14416.63	4776.18	7336.95	Aerobic composting, RDF, sanitary landfill, Vermi-composting,
Uttar Pradesh	15500	12000	3115	-	Composting, RDF plants
West Bengal	14000	12600	830	515	Composting
Haryana	4514	3159.4	188	2371.8	Composting and vermi-composting

waste disposal. These are often associated with the contaminated leachate that is comprised of heavy metals (toxicity level, Cd < N <Pb< Ni < Cr < Zn < Cu) and toxic gaseous emissions (Mishra et al., 2019). The transformation of the landfill to a sanitary landfill is the scientific way of minimising the harmful effects associated with them. Incineration is the heat treatment of the waste at 850 ℃ in the presence of air. It is not successful for the wastes having high moisture and low calorific value (Pujara et al., 2019). Incineration has many problems such as incomplete combustion, emission of toxic gases to the atmosphere, high operating cost and requirement of an energy resource to provide the temperature (Potdar et al., 2016). RDF is produced from combustible materials such as non-recyclable plastics, paper cardboard, etc. by burning the waste in an incinerator and cement kiln. RDF production has several steps such as separation at source, mechanical separation, size reduction, screening, blending, drying and palletising (Kara, 2012). Biomass gasification and pyrolysis are the thermochemical conversions of waste to produce syngas, bio-oil and biochar. Composting has various types such as home composting, aerobic and anaerobic full scale composting and vermin-composting (Kumar and Goel, 2009). Home composting requires the separation of household waste into a wet fraction that is comprised of kitchen waste, food etc. and is a highly biodegradable and dry portion that includes paper, plastics, metals, soil, etc. Home composting decreases the labour and cost associated with the transport of waste to the disposal sites (Kumar and Goel, 2009). However, if the home composting cannot be done, the full-scale composting can be applied to the huge amount of biodegradable portion and the compost can be sold to the farmers (Kumar and Goel, 2009). Anaerobic composting is occurred in the absence of air by dumping the organic material into a hole and covered with it by soil. It takes more time than aerobic composting that occurred in the presence of air. The vermi-composting is the type of aerobic composting done by using worms. Anaerobic digestion is the most attractive technology for waste management and energy production due to the flexibility of reactor conditions, environment friendly and economical. The biodegradable fraction of MSW is directed to anaerobic digestion or composting process.

Waste management methods employed in India are composting, vermi-composting, anaerobic digestion, RDF, and landfilling. Table 2.8 is representing the waste production and management in different states of India. According to the report of CPCB (2016), Uttar Pradesh generated total waste of 15500 tonnes/d, waste collected was 12000 tonnes/d and waste treated was 3115 tonnes/d. The treatment methods employed were composting and RDF plants. Landfilling was the most used option for waste disposal in every state. The material recovery facility and composting combined with landfilling was the most appropriate option as it had the least environmental impact including global warming, eutrophication, human toxicity and photochemical ozone formation in the life cycle assessment of MSW management options studied in Nagpur, India (Khandelwal et al., 2019). In a study of environmental impact assessment done on MSW disposal in Varanasi, India, a mathematical model was applied by considering Rapid Impact Assessment Matrix to determine the sustainability of the waste disposal option. Gasification was the most promising sustainable option out of the five studied methods with the *S*-value of 0.069 (Phillips and Mondal, 2014).

2.4.3 OFMSW Pretreatment and biogas production

A pretreatment step is necessary to improve the biogas production from OFMSW because of its robustness due to the presence of lignocelluloses and other materials like protein and fats. The chemical, physical, biological and thermal treatments and their combination are widely used on OFMSW (Table 2.9).

Table 2.9 Biogas production from OFMSW through different pretreatment

Pretreatment methods	Pretreatment condition	Finding	DM	WV (L)	SL	T (°C)	t (d)	Biogas production (mL/gVS)	IP (%)	Reference
Hydrothermal treatment	T: 145 °C t- 30 min, 1 Substrate: 1kg	sCOD: 81 % and VFA: 13 % increased	Batch	0.25	-	37	30	200	31.6	Dasgupta and Chandel, 2019
Aeration pretreatment	Air flow: 150 mL/min, t: 2 h for 50 dayssubstrate:2 Kg	COD and VFA reduction during the methane generation phase	Bioreactor landfills	3.14	800 Gvs	30	130	75 (CH_4)	-	Xu et al., 2016
High pressure extruding	Pressure: 40 MPa	COD, VFA was increased, pH was reduced	Batch	0.4	7.5 gVS	35	24	674 (CH_4)	33	Xu et al., 2016
Sodium hydroxide	NaOH-0.5 %, T- 30 °C t- 6 day	sCOD and pH increased initially then decreased, VFA increased, VS reduction-80 %	Batch	-	-	30	15	400	-	Dasgupta and Mondal, 2012
Microwave, hydrogen peroxide	(a)T-115-175 °C Ramp time- 40 min, hold-1 min (b)H_2O_2-30 %t-1 h, microwave treatment-85 °C	175 °C-Highest solubilisation but reduced biogas yield, H_2O_2 increased the lag phase, 145 °C- best for production	Batch	0.16	-	33	30	*134.5	7	Shahriari et al., 2012

*mL/g substrate, Where DM=Digester mode, WV=Working volume, SL=substrate loading, T=Temperature, t=Time, BP=Biogas production, IP=Improvement in production

Table 2.9 Continued

Pretreatment method	Pretreatment condition	Findings	DM	WV (L)	SL	T (°C)	t (d)	B P (mL/g VS)	IP (%)	Reference
Biological	mature compost- 2.5 % V/V t- 24 h	DOC removal: 61.2% VS removal: 35.3	Semi-continuous	4.5	-	55	15	*420 (CH_4)	35.5	Fdez.-Güelfo et al., 2011a
Thermochemical, biological	NaOH-30 min, 1 L non stirred pressure vessel Mature compost, *A. awamori*, Waste activated sludge: 2.5-10 % for 24 h	180 °C, 5 bar, 3 g NaOH/L was best, Solubilisation (DOC, TVFA , sCOD) decreased with increasing the inoculums, 2.5 % was best	-	-	-	-	-	-	-	Fdez.-Güelfo et al., 2011b
Ultrasonic pretreatment	power density- 0.2-0.6 W/ mL t-10-30 min, TS-6-10 %	VFA increased linearly with treatment time, 10 % TS, 0.4 W/mL power density, 30 min was the best condition,	Batch	-	-	37	35	455	-	Rasapoor et al., 2016
Acid treatment and Enzymatic hydrolysis	H_2SO_4: 0.5, 1 % T:130, 160 °C, Enzyme loading: 20 FPU, T: 45 °C, 120 rpm, 72 h	Xylan and lignin removal, 1 % H_2SO_4, 130 °C for 60 min was best condition,	Batch	25 ml	0.25 g VS	37	50	295 (CH_4)	-	Mahmoodi et al., 2018

*mL/gVS$_{removed}$,Where DM=Digester mode, WV=Working volume, SL=substrate loading, T=Temperature, t=Time, BP=Biogas production, IP=Improvement in production

Chemical addition proved to be the effective and widely used method of substrate improvement for biogas production. The breakdown of carbohydrate, protein and fats resulted in enhancement of sCOD, VFA yields and reduced the pH and VS content and increased the biogas production when OFMSW was treated with NaOH (0.1-1 %). The NaOH dose of 0.5 % was the best to improve biogas production. After exceeding the concentration upto 1 % biogas production was reduced due to the reduction of pH below 5 (Dasgupta and Mondal, 2012). Dilute acid treatment (H_2SO_4 -0.5, 1 %) done on OFMSW at high temperature resulted in hemicellulose and lignin reduction (Mahmoodi et al., 2018). The xylan was completely degraded at the treatment of biomass temperature 160 ℃, 1 % NaOH for 30 min. The enzyme loading of 20 filter paper unit (FPU) was also done to increase the saccharification. The highest sugar concentration reported was 46.7 g/L for the treatment of 1 % H_2SO_4 at 130 ℃ for 60 min.

Microwave treatment alone (115-175 ℃) and in combination with H_2O_2 (30 %) at 85 ℃ increased the solubilisation of OFMSW (Shahriari et al., 2012). A significant increase in solubilisation in terms of sCOD yield was noted. However, the rate of anaerobic digestion didn't alter by either of the treatment. The H_2O_2 treated samples also showed the increased lag phase and longer digestion time. The acute inhibition in microbial growth was noted at 175 ℃ temperature despite the highest solubilisation yield. The biogas production was increased slightly (7 %) in the whole slurry after microwave treatment at 145 ℃. In a study of hydrothermal treatment (80-160 ℃) applied on OFMSW, the higher temperature >150 ℃ increased the lignin concentration while it was reduced at 100-150 ℃. The cellulose content was unaltered in the given temperature range. However, the hemicellulose was decreased after 140 ℃. Hydrothermal treatment can decrease lipid concentration and is more dependent on temperature instead of time. The biogas production was increased by 31.9 % after 140

°C treatment. Other treatments such as ultrasound (Rasapoor et al., 2016), high pressure extruding (Xu et al., 2016), aeration treatment (Xu et al., 2016), etc. were done to improve the biodegradability of OFMSW (Table 2.9).

An increase of 190 % in cumulative biogas production was achieved after the biological treatment (mature compost 2.5 % for 24 h) of OFMSW. The dissolved organic carbon (DOC) and volatile solid (VS) removal were also improved by 61.2 and 35.3 %, respectively (Fdez.-Güelfo et al., 2011a). In another study by the same authors, the mature compost, fungus (*A. awamori)* and waste activated sludge were employed for biological treatment with the varying concentration (2.5-10 %) of inoculation volume (Fdez.-Güelfo et al., 2011b). It was noted that 2.5 % was the best condition and solubilisation yield was decreased after increasing the inoculum volume. Thermo-chemical treatment was also carried out in the same study and it was found that temperature and pressure were the most important factors that can alter the efficiency of NaOH. The NaOH dose of 3 g/L at 180 °C and 5 bar pressure achieved the highest solubilisation yield in terms of DOC, Volatile fatty acid (VFA), COD and dissolved volatile solid.

2.5 Assessment of pretreatment

Evaluation of the pretreatment is necessary to determine the effect of treatment and to know if the biomass gained the desired properties so that it can effectively be used to produce biogas. The effect of pretreatment is done by evaluating the solid and liquid (hydrolysate) fraction of biomass after treatment.

2.5.1 Effect of the pretreatment on the structure of the substrate

The biomass was investigated for the compositional differences such as cellulose, hemicellulose and lignin content. Most of the researches are directed to estimate the compositional characteristics after the pretreatment of lignocellulosic biomass (Table

2.3). The pretreatments that remove lignin and store up the cellulose are said to be ideal. Pretreatments such as ammonia, urea, etc.had also directed to improve the C/N ratio of the biomass (Dongyan et al., 2014). Some of the researches were directed to calculate the VS removal (Dasgupta and Mondal, 2012, Fdez.-Güelfo et al., 2011a). The procedures employed to estimate the carbohydrates and lignin content were the method developed by New and Renewable Energy Laboratory (NREL) (Sluiter et al., 2008b) and Van Soest fiber analysis (Soest and Wine, 1968).

The evaluation of structure variation after treatment was also carried out by some researchers. Structure variation was studied by Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscope (SEM), X-ray diffraction (XRD), Nuclear magnetic resonance, etc. The FTIR spectrum was achieved by varying the wavenumber 700-4000 cm^{-1} (Fu et al., 2015). KBr is commonly mixed with biomass to form pallets for the FTIR study. FTIR can be carried out to get absorbance or transmittance peaks. FTIR analysis provides the idea of the presence of compounds such as lignin, hemicellulose and cellulose-based on the presence of some functional groups such as C-H, O-H, C-O, etc. The lignin peaks were compared after treatment that lied in the range of 1180-1300 and 1550-1700 cm^{-1} (Alexandropoulou et al., 2017). SEM analysis can be used to study the surface structure morphology after treatment. It is commonly done in the range of 500-5000 X. The cell wall structure was found to be distorted and disorganised after pretreatment as compared to untreated sawdust (Alexandropoulou et al., 2017). The structure study by XRD in terms of crystallinity index has been reported by many researchers. The cellulose is present in two forms of crystalline and amorphous, whereas lignin and hemicellulose are amorphous. The crystallinity index was decreased after the microaerobic pretreatment indicating that a higher amount of amorphous cellulose was present in corn straw (Fu et al., 2015).

However, in some study, the crystallinity index was increased after pretreatment indicating the removal of amorphous matter from biomass (Chen et al., 2014). The water retention value was also found out in a few studies to evaluate the porosity of biomass after treatment (Mancini et al., 2018).

2.5.2 Effect of pretreatment on the hydrolysate

Some studies were focussed on the variation of hydrolysate characteristics such as DOC, soluble chemical oxygen demand (sCOD), VFA, pH, phenolic content, total sugar, etc. after treatment (Table 2.9). The breakdown of organic matter into simpler compounds increased DOC, VFA and sCOD values after thermo-chemical and biological treatment of OFMSW (Fdez.-Güelfo et al., 2011b). The yield of solubilisation parameters is dependent on the chemical loading, temperature, and time of the treatment (Shetty et al., 2017; Fdez.-Güelfo et al., 2011b). The disorganisation of the cell wall and the removal of lignin led to the formation of phenolic by-products (Michalska et al., 2015). Therefore, measurement of phenolic content can indirectly indicate lignin degradation. The sCOD value was increased with respect to the concentration of NaOH in the alkali pretreatment of rice straw (Shetty et al., 2017). The pH reduction was observed in context to pretreatment evaluation because biomass structure variation leads to the release of sugars, amino acids, and fatty acids that convert into VFAand reduce the pH (Dasgupta and Mondal, 2012). The reduction in pH was also noted in the ammonia pretreatment of wheat straw (Dongyan et al., 2014).

2.6 Co-digestion to improve the biogas production from OFMSW

OFMSW is heterogeneous waste that contains high carbon and low nitrogen and turned out to be in a high C/N ratio. The low nitrogen of OFMSW can be balanced by adding a nitrogenous source to it. The main purpose of co-digestion is to improve biodegradability by providing an appropriate C/N ratio, essential nutrients and aiding to dilute the inhibitory compounds in the feedstock (Panigrahi and Dubey, 2019). The limitations associated with the mono-digestion of OFMSW are rapid acidification, long-chain VFA production, pH reduction, due to the presence of high organic matter that results in inhibition of methanogens (Panigrahi and Dubey, 2019).

The co-digestion of OFMSW with SS was widely studied because the low C/N ratio of SS and high C/N ratio of OFMSW can be effectively balanced by mixing them. The mono-digestion of SS resulted in less biogas (248.77 $NmLCH_4/gVS$) in comparison to the co-digestion with OFMSW (365.49 $NmLCH_4/gVS$) at a ratio of 2.09 gVS/gVS (Cabbai et al., 2013). The same authors studied the co-digestion of OFMSW with 50 % SS at the pilot plant level with different organic loading of 0.8-17 $kgVS/m^3d$ from phase 1-6. The increment of 192 % in biogas was noted in phase 6 as compared to phase 1 (Cabbai et al., 2016). The maximum VS removal and biogas yield achieved was 69.9 % and 0.49 $Nm^3/kgVS$, respectively. The phosphorus and heavy metals were found to be less in the co-digestion indicating the benefit of the process.

The co-digestion of OFMSW with thickened waste activated sludge (TWAS) and rice straw (RS) is also reported in the literature (Abudi et al., 2016). The thermal and thermo-chemical pretreatment on TWAS and RS increased the biogas production from co-digestion as compared to untreated samples. The maximum biogas yield of 558.5 L/kgVS was achieved by the mixture at ratio OFMSW: TWAS (thermochemical): RS (H_2O_2) of 3:0.5:0.5. The microbial diversity in SS makes it a more suitable co-substrate for OFMSW besides the available N_2 content (Ghosh et al., 2020). The 60% *SS* concentration was found to be effective to achieve the 586.2 mL/gVS biogas (Ghosh et al., 2020). The accumulation of VFA in the anaerobic digestion of OFMSW can be prevented by co-digested it with Fruit and vegetable waste (Pavi et al., 2017). The ratio

Table 2.10 Co-digestion of OFMSW

Co-substrate	Condition	DM	WV (L)	SL	T (°C)	t (d)	Findings	BP (mL/gVS)	IP (%)	Reference
Sewage sludge	SS: 20-80	Batch	-	-	-	30	Microbial diversity of sludge was found to be effective for OFMSW digestion, 60 % SS amount was effective	586.2	166	Ghosh et al., 2019
Fruit and vegetable waste (FVW)	OFMSW:FVW=1/0, 1/1,1/3,0/1	Batch	2	54.04 g	35	17	VS removal-54.6 % 1/3 was optimum	493.8	130	Pavi et al., 2017
Sewage sludge (SS)	OFMSW:SS-2.09 gVS/gVS	Batch	1.6	-	37	30	OFMSW as a monosubstrate produced 34.3 % more biogas than codigestion	365.5	*50	Cabbai et al., 2013
Sewage sludge	OFMSW: 29.3 % SS: 41.3 %	Contin-uous	-	17 gVS /L/d	37	20	VS reduction- 67.3 %	490	192.2	Cabbai et al., 2016
Thickened waste activated sludge (TWAS), rice straw (RS)	Pretreated and untreated used, OFMSW:TWAS:RS 1:1.5:1.5, 1:0.5:0.5, and 3:0.5:0.5 ratio	Batch	0.18	-	37	55	3:0.5:0.5 was best ratio with OFMSW: $\text{TWAS}_{\text{thermoalkaline}}$: RS (H_2O_2), VS removal-79.8	558.5	160.4	Abudi et al., 2016

*w.r.t sewage sludge (SS), DM=Digester mode, WV=Working volume, SL=substrate loading, T=Temperature, t=Time, BP=Biogas production, IP=Improvement in production of OFMSW to FVW ratio of 1:3 significantly enhanced the biogas production (130 %) by providing the stability to methanogenesis and resulted in the 493.8 mL/gVS (Pavi et al., 2017). Co-digestion approaches of OFMSW are depicted in Table 2.10.

2.7 Effect of operating process parameter on anaerobic digestion

The anaerobic digestion is greatly affected by the operational parameters such as temperature, pH, the substrate to inoculums (S/I) ratio, organic loading rate (OLR), and hydraulic retention time (HRT), Table 2.11. The temperature and pH significantly affect the process by influencing the growth of microorganisms. The mesophilic (30-40 °C) and thermophilic range (45-60 °C) of temperature are effective for biogas production. It is reported in the literature that a thermophilic temperature of less than 55 °C is more effective than the mesophilic temperature for the activity of methanogens and process stabilisation (Kim et al., 2006). The optimum temperature was 50 °C to achieve 78 % COD removal and 223 LCH_4/kg sCOD degraded biogas production in the 10 days of HRT from the anaerobic digestion of food waste. The lowest biogas production was achieved at 55 °C (Kim et al., 2006). A pH range of 6.5-8 is considered effective for biogas production. The effect of pH was found to be dependent on total solid concentration in feedstock (Mao et al., 2019). The adjustment of initial pH is very important when the feedstock contains a low solid concentration (4 %). Also, the pH of 7.4 was found to be efficient for microbial metabolism, buffering capacity and biogas production (457.8 mL/gVS) (Mao et al., 2019).

S/I ratio is the most important parameter to determine the biogas yield as an adequate amount of inoculum is essential to start the anaerobic digestion (Boulanger et al., 2012). A range of S/I ratio of 0.25 to 2 $gVS_{substrate}/gVS_{inoculum}$ is explored by various researchers on different feedstocks. The lag phase was increased by increasing the S/I

Table 2.11 Effect of operating parameters on biogas production

Substrate	Parameter Variation	DM	WV (L)	SL	T (°C)	t (d)	Findings	BP	Reference
Food waste	Temperature (30-55 °C) HRT-8,10,12	Batch and semi-continuous	8	-	30-55	*30	50 °C and 12 d HRT was optimum for sCOD removal and Biomethane production	223 $mLCH_4/g\ sCOD_{degraded}$	Kim et al., 2006
OFMSW	S/I ratio (0.25 to 66 $gVM_{waste}/gVM_{inoculum}$)	Batch	-	26.85 g	35	160	Optimum ratio: 0.5 $gVM_{waste}/gVM_{inoculum}$ Lag phage decreased when S/I ratio decreased	150 $NmLCH_4/$g dry matter	Boulanger et al., 2012
Food waste	Temperature (35, 55 °C) HRT- 30-200 d	CSTR	10	1.3-6.7 g COD/L.d	35, 55	30	35 °C was better in handling high organic loading (6.7 g COD/L.d, 30 HRT)	230 $mLCH_4$ /g COD_{added}	Kim et al., 2017
Corn straw	pH (6.5-8) TS (4-12 %)	Batch	0.7	29.2-87.6 g substrate	35	50	pH 7.5, TS 4 % were optimum	457.8 mL/gVS	Mao et al., 2019
Tannery fleshing	Organic loading rate (5-20 gVS/L)	Batch	0.07	5-20 gVS/L	32.5	30	Ammonia inhibition at high loading, 5gVS/L was optimum	440 $NmLCH_4/$gVS	Polizzi et al., 2018

*for batch mode. DM=Digester mode, WV= Working volume, SL= substrate loading, T= Temperature, t= time, BP= Biogas production ratio from 0.25 to 66.67 g VM_{waste}/g $VM_{inoculum}$ in the anaerobic digestion of OFMSW (Boulanger et al., 2012). The maximum biogas yield (150 NmL/g dry matter) and minimum latency were found at S/I ratio of 0.5 g VM_{waste}/g $VM_{inoculum}$. The increase in OLR can also increase biogas production (Cabbai et al., 2016). However, the VFA accumulation could be the problem associated with high loading. It was also associated with the ammonia accumulation when digestion of protein-rich feedstock was carried out (Polizzi et al., 2018).

2.8 Summary of literature review

The government of India has been taking great initiatives in the development of biogas technology and started various schemes to commercialise the process since 1951. Biogas production is highly dependent on the selection of feedstock. A feedstock that should be available enormously and having suitable properties such as moisture, C/N ratio and other nutrients is considered for biogas production. The wastewater has low total solid content that results in less biogas production. Also, it contains a high amount of nitrogen (leads to ammonia formation) and toxic metals that inhibit the anaerobic digestion process. Biogas production from different solid waste is successfully implemented by various researchers. The presence of cellulose and lignin makes the feedstock more complex and inaccessible to microorganisms. Therefore, a pretreatment step is required to reduce the rigidity of such wastes, so that microbial species can effectively utilise them. The biogas production increases with the lignin reduction of the substrate. Therefore, various pretreatment technologies directed to lignin removal were developed by researchers. The alkaline pretreatment was extensively and effectively used for lignin degradation. The temperature, time and chemical loadings are the influencing parameters of the pretreatment.

The OFMSW compositions and properties are variable from site to site according to the climatic condition and lifestyle of the community. Composting, vermicomposting and anaerobic digestion are used as an effective solution for waste treatment in India. The heterogeneity of waste present in OFMSW makes it rigid and complex for microbial consumption. Therefore, various pretreatment strategies were discovered to improve biogas production from OFMSW. The evaluation of pretreatment could be done by estimating the properties of the pretreated substrate and hydrolysate. The co-digestion of OFMSW with SS proved to be an effective method for biogas enhancement and conquer the limitations of mono-digestion. The parameters such as temperature, pH, S/I ratio, OLR, etc. can greatly affect anaerobic digestion and biogas production.

2.9 Research gap

Biogas production from different feedstock was reported in the literature. Lignocellulosic biogas production is still gaining attention due to its production in enormous amounts and the potential of biogas production. A variety of lignocellulosic wastes was employed to get the biogas. However, biogas production from sawdust was reported in a few studies. There was a lack of literature available on the pretreatment strategies to improve the sawdust hydrolysis and conversion to biogas. Also, the biogas production from OFMSW is still under development due to its heterogeneous nature. There is still a need for exploration of various pretreatment technologies for the solubilization of OFMSW. The optimisation of influencing factors of pretreatment can enhance biogas production. The co-digestion of SS with OFMSW is also an attractive method to enhance the yield and should be optimised for different regions as the variable properties of SS and OFMSW. There was also lack of the study directed to the optimisation of process parameters for the OFMSW digestion.

2.10 Objectives of the present work

Based on the available literature and research gap, the following objectives were decided to execute in the Ph.D. research work:

- To study the feasibility of sawdust for biogas production
- To determine the best pretreatment method for sawdust hydrolysis
- To study biogas production from OFMSW and its comparison with sawdust as feed material
- To observe biogas yield from OFMSW by pretreatment and co-digestion approaches
- To optimise the pretreatment process parameters using response surface methodology (RSM)
- To study the effect of process parameters on anaerobic digestion.
- To study the characteristics of the effluent of anaerobic digestion