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A SHORT REVIEW ON FEEDSTOCK CHARACTERISTICS IN METHANE PRODUCTION FROM MUNICIPAL SOLID WASTE

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Abstract
The increase in population and industrialization leads to an increase in the solid waste year by year. The limited availability, increasing cost and adverse effect of climate change on fossil fuel leads to encouraging the research in the field of finding alternatives for energy sources. The organic fraction of municipal solid waste (OFMSW) can be utilized as a bio-energy source, which reduces the environmental impact and the requirement of landfill areas to dispose of municipal solid waste. Anaerobic digestion is the widely used sustainable approach to treat OFMSW. In recent years, the generation of methane from municipal solid waste has received increasing attention in research. This paper reviews literature published in recent years considering various characteristics of input feedstock parameters like pH, total solids, volatile solids, and water content which affect the digestion quality of the OFMSW and increase the production of methane. A regression model is developed to identify the relationship between methane production and various feedstock parameters. When the chemical compositions of feedstock were used as independent variables, the percentage variation accounted for by the model is low (r^2 = 0.63) and also the important observation from the analysis is that the pH of the feedstock influences majorly methane production.

Keywords: **Bioenergy; Climate change; Fossil fuel; Organic fraction; Regression model.**

1. INTRODUCTION

Worldwide, the various sources of waste generated are Municipal Solid Waste (MSW), Industrial waste and Bio-medical waste; out of which a large quantity is contributed by MSW which is dumped in the open landfill. In the year 2016, MSW generation is about 2.01 billion metric tons per year out of whole waste produced across the world and it is estimated to increase by 3.4 billion tons by 2020 [1–3]. In India, approximately 1,43,449 tons of MSW per day is generated, of which approximately 70% of waste is disposed in an open landfill without being sorted and treated [4].

Normally, the composition of MSW consists of approximately 40-60% biodegradable and the remaining is non-biodegradable. If this putrescible waste is not properly managed at landfill sites then it causes a potential threat to the environment such as greenhouse gas emission (GHG), soil, air and water pollution [5–9]. These landfill gases (LFG) consist of 55% methane (CH_4), 40% carbon – dioxide (CO_2) and numerous chemical compounds like aromatics, chlorinated organic and sulfur compounds in traceable quantity [10]. In India, CH_4 emission is estimated as 29% of total GHG from MSW landfill sites which are higher than the average production of 15% CH_4 worldwide [11].

The reason for an increase in CH_4 emission has increased tremendously due to population growth and improper disposal of waste in landfills [9].

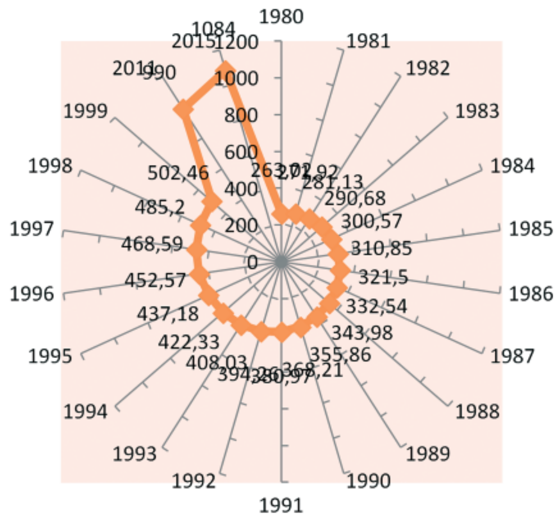

Figure 1.
Methane production from landfills in India

Figure 1 shows the details of estimated methane generation from landfills since the years 1980 to 2015 (through various models such as the Default method – DM, Modified triangular method – MTM and First-order decay method – FOD, [12]) in various research work.

Many studies focused on the aspect of utilising CH_4 as a renewable energy source [13]. Hence developing countries took an initiative to adopt the WtE (Waste -to- Energy) techniques to manage waste from landfill sites effectively and increase the degree of recovery and then recycle the waste. As per the report given by the Ministry of New and Renewable energy (2014) of a developing country, the energy obtained from MSW is 1460 MW [14–16]. WtE technology includes incineration, anaerobic digestion (AD), pyrolysis and gasification to manage MSW effectively [1, 17]. Out of the above-mentioned techniques, AD is the best suitable WtE option for the management of MSW due to the presence of higher organic fraction and water content [14, 17–20].

The organic fraction present in MSW is decomposed by microbial action through four stages 1. Convert complex organic molecules to soluble monomers 2. Acidogenesis 3. Acetogenesis 4. Methanogenesis in an oxygen-free environment (Fig. 2) [21, 22]. Hence, the organic substrate is converted into bioenergy and digestate, which is commonly used as manure or soil improver; as it has a predominant proportion of Nitrogen [23]. Many researchers and Government agencies have chosen AD to recover bioenergy from OFMSW and also worked to find the solution to increasing the digestion process of AD [1, 24–27]. The CH_4 production from AD is properly utilized as fuel so that it does not cause any effect on the surrounding environment [25, 26, 28].

Certain factors that influence the performance of AD are temperature, organic loading rate (OLR) and total solids. Temperature is the main important parameter to control the selection of microorganisms and the growth rate of organisms in AD. Maximum research works are focused to analyze the estimation of CH_4 production at different temperatures, OLR and total solids [29–32]. The production rate of CH_4 depends on the composition, age of the waste, total solids, moisture content, temperature and pH [33–35].

This study aims to review the composition of MSW and input feedstock characteristics which affect the quality of end product (digestate and CH_4) in AD.

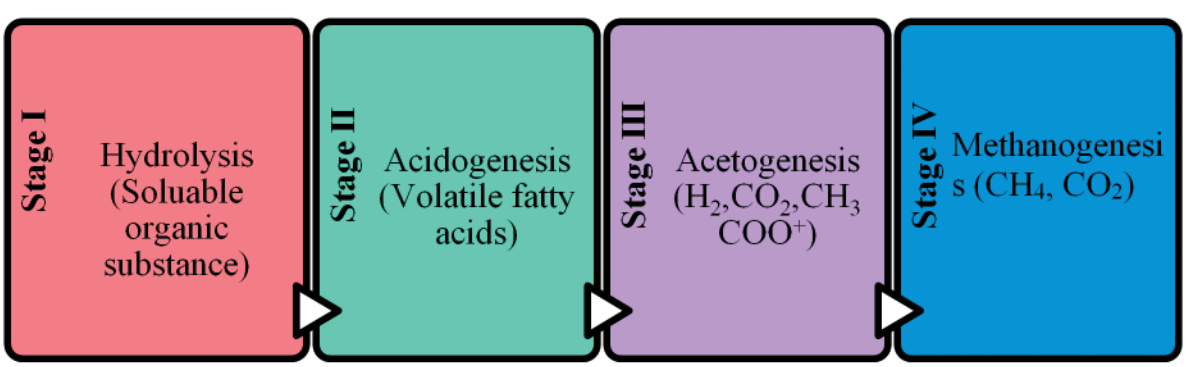

Figure 2.
Various stages of AD

As there is a limited study on considering input feedstock parameters rather than operational parameters in the production of CH_4, a model is developed between the CH_4 production and input feedstock parameters such as pH, total solids(TS), volatile solids (VS) and moisture/ water content (WC) using the regression analysis.

2. DATA COLLECTION AND REGRESSION ANALYSIS

2.1. Influencing parameters in Methane production

The performance of AD is affected by various biotic and abiotic factors. The main outcome of the AD process is biogas which includes CH_4 production, depending on the substrate composition, characteristics of feedstock (such as moisture content, TS, VS, particle size, pH, COD, BOD, carbon and nitrogen content) and process parameters (such as temperature, pH, hydraulic retention time, organic loading rate and optimum amount of nutrient level) [36, 37]. In this study, the substrate composition and five parameters of input feedstock characteristics are given importance.

2.1.1. Composition of the substrate

MSW normally consists of 46% organic fraction, 17% paper, 10% plastics,5% glass, 4% metal and 18% others (Fig. 3) [1]. Out of total MSW generated, the organic fraction is greatly varied between 50–70% for low and middle-income communities and 20 - 40% for high-income communities in developing and developed countries respectively [38, 39].

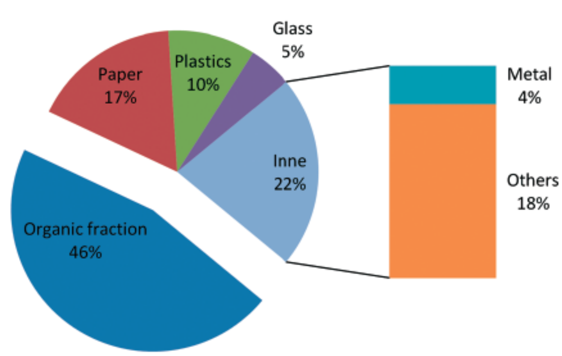

Figure 3.
Typical Composition of MSW

When organic fraction present in MSW is more it
When organic fraction present in MSW is more it
results in a larger volume of CH_4 production due to bacterial decomposition[9]. The undesirable substances such as plastics, metals etc., affect the process of digestion because of its non – biodegradable nature and finally, it increases the budget of the AD process. Hence, on-site segregation of MSW or mechanically sorted MSW is required to improve the digestion process as well as CH_4 production [39, 40].

2.1.2. Characteristics of feed-stock

There are a variety of factors that influence OFMSW behaviour during the AD process. The general characteristics of OFMSW that significantly contribute to AD are Physical, Chemical and Elemental composition.

The OFMSW substrate includes the physical composition of particle size and density. The impact of the surface area of OFMSW on digestion rate has not been properly examined and the high density of substrate indicates the exclusion of non-biodegradable from the feedstock [1]. The elemental composition of the OFMSW substrate consists of carbon (C), hydrogen (H), nitrogen (N), Oxygen (O) and sulphur (S). These elements are considered important sources of energy and new cell formation for anaerobic bacteria [41].

The main properties of the chemical composition of the substrate are pH, WC, TS, VS, chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) [42]. These directly influence the microbial activity of the AD process [1]. Hence, the characteristic study of feedstock is needed to obtain a better quality of biogas and digestate [42].

The published studies mainly focus on the physical, chemical and elemental composition of feedstock in the generation of methane as renewable energy. Figure 4 shows the importance given by the researchers in terms of feedstock characteristics.

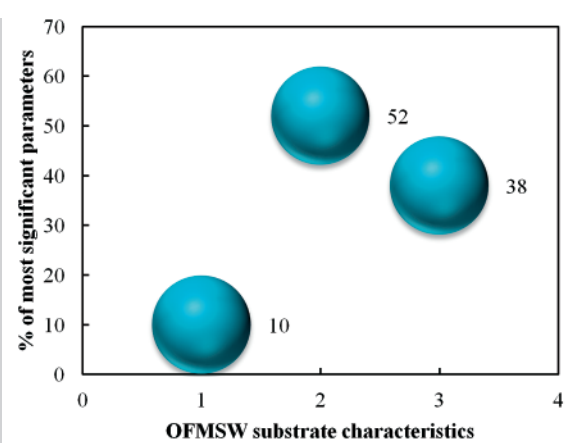

Figure 4.
Percentage of more significant factors considered in substrate OFMSW

As chemical composition contributes more to methane production, the key chemical characteristics of OFMSW substrate are considered for regression and the same is explained below.

Water Content

The generation of MSW in a developing nation like India consists of high moisture content (40%–60%) and low calorific value (800–1100 kcal/kg) [14]. The high water content present in MSW is helpful for bacterial decomposition under oxygen-free conditions and supports the chemical reactions that produce methane gases[1], [9]. A higher moisture content (90%) yield leads to producing a higher amount of biogas from MSW[43]. Hence it is required to increase the water content of the substrate to produce a high amount of biogas; as this parameter is also important to determine the other chemical characteristics of MSW like TS and VS[1]. The process of AD is also classified into dry AD (60–75%) and wet AD (85–90%) based on the water content of MSW [42] making it an important parameter to be considered.

Total Solids and Volatile Solids

Total solids (TS) content of the feedstock is commonly used to classify AD into two types: i. namely low-solids or wet digestion for TS < 15% and ii. high-solids or dry digestion for TS >15 to 20% [34, 44, 45]. Many research studies reported that the performance of AD is influenced by initial substrate concentration (TS >30%) which results in reducing the methane yield. At 30% of TS content, the CH_4 production reduces by 17% compared to 20 % solid content; this is mainly due to the accumulation of volatile fatty acids (VFAs) [26, 44, 46, 47].

The degradable solid organic matter is represented as volatile solids(VS) and non-degradable besides with some non-digestible VS – called fixed solids. OLR is an operational parameter that is represented by the concentration of VS in the substrate. Higher OLR in the digestion process produces higher biogas and CH_4 yield. But the higher amount of VS fed into the digester influences the pH and alkalinity of the digester due to the formation and accumulation of volatile acids [37, 48].

pH

The process and performance of AD are affected by pH as it is a basic and vital parameter that influences the growth of microorganisms in various stages of AD [37, 49]. A lower pH value affects methanogens and higher pH leads to producing toxic ammonia. The variation of pH in AD is occurred due to three main factors such as volatile fatty acids (VFA's), bicarbonates and alkalinity of the system. The alkaline reagents such as NaOH, $NaHCO_3$, Na_2CO_3 and $Ca(OH)_2$ are used for controlling pH to improve the performance of biomethanation [50]. Based on the type of substrate and digester, the optimal pH is maintained to increase the rate of reaction in AD [42]. The pH value near neutral is suitable for methanogenesis activity and it produces higher CH_4 at high moisture content. Any material can be added to the feedstock to maintain the value of pH and to ensure the continued existence of an active biological population in AD [1].

Temperature

Temperature is the main environmental factor when considering the release of CH_4 from landfill sites as well as the digestion of OFMSW in AD. The variation in temperature influences the activity of methane-forming bacteria in the fermentation process [37, 49, 51–53]. Many researchers commonly used two kinds of AD processes; such as mesophilic AD (30–40°C) and thermophilic AD (50–60°C) for the generation of biogas and methane[14, 21, 38, 54]. Hence, the optimal temperature is considered for constant and effective fermentation. The biogas generation from OFMSW at thermophilic AD is higher than that at mesophilic AD, which is mainly due to the increased temperature [47].

2.2. Regression analysis

Statistical analysis is made on collected data by considering the input feedstock characteristics and the significant level was fixed at 0.05.

2.2.1. Generation of Methane from various feedstock

Many authors carried out the experiments at mesophilic (30–40°C) and thermophilic(50–60°C) conditions in the AD process. The bio-degradable waste used as feedstock is vegetables, fruit wastes, fish wastes, food wastes, supermarket wastes and OFMSW to determine the production of CH_4 at varying operation conditions [1, 21, 38, 46, 47, 55–58].

The characteristics of OFMSW are generally classified into physical, chemical and bromatological analysis[46, 59–62]. Several authors studied the impact and developed the model on methane production by considering the various process parameters such as pH, Temperature, C/N ratio, TS, OLR, Hydraulic retention time (HRT)[1, 12, 24, 29, 63].

The key literature considered in understanding methane production in the last two decades is listed in Table 1.

The selection criteria for the source of feedstock are: (i) Source-separated OFMSW (ii) Mechanically separated OFMSW (without considering non-biodegradable) (iii) Supermarket food waste – MSW (iv) Single substrate feedstock are considered for this study as they contribute a large amount to MSW.

Table 1.
Using various feedstock, the operation conditions of AD studied by various authors

Substrate	AD condition	CH_4 yield ($L CH_4/kgVS$)	Contributor
OFMSW (Karaj, Iran)	Digester capacity: 100mL Operating Temperature: 37°C Digestion period: 25 days TS = 6% Pretreatment: Ultrasonic	478	[42]
MSW (UK)	Digester capacity: 5L Operating Temperature: 36°C Inoculum: substrate ratio: 4.5:1	300	[64]
SSFW	Digester capacity: 5L Operating Temperature: 37°C Digestion period: 30 days	467-529	[46]
SSFW	Digester capacity: 3974L Operating Temperature: 35°C OLR = 8gVS/L/d TS = 30.9%	347	[65]
KW	Digester capacity: 1.5L Operating Temperature: 35°C HRT = 30 days TS = 22.17% wet basis	620	[25]
FVW	Digester capacity: 1.5L Operating Temperature: 35°C HRT = 30 days TS = 7.94%	693	[25]
MS-OFMSW	Digester capacity: 5L Operating Temperature: 55°C OLR = 2.26 Kg VS/m^3/d TS = 24.7%	176	[29]
OFMSW	Operating Temperature: 35°C HRT = 21 days Inoculum: substrate ratio: 4 TS = 29.7%	545	[59]
OFMSW Synthetic	Digester capacity: 4.5L Operating Temperature: 55°C HRT = 20 days OLR = 8.862 g VS/L/d TS = 0.90 (g/g sample)	131.4	[30]
SMW	Operating Temperature: 55°C HRT = 14 days pH = 7.5 TS = 273 (g/Kg)	678	[63]

SSFW – Source separated food waste; KW – Kitchen waste; FVW – Food and vegetable waste; MS-OFMSW – Mechanically separated OFMSW; SMW – Separated municipal waste.

2.2.2. Data for Multiple Linear Regression (MLR)

Data regarding the input characteristics of feedstock and CH_4 production are taken from various research articles for the regression model and the units for each parameter considered are homogenised to make an easier comparison. Data used in this work include 56 samples published between the period 2000–2020.

In this study, influencing feedstock parameters such as pH, TS, VS and WC are considered for regression analysis. From the literature, most of the authors report TS and VS range between 5–50% of wet weight with high moisture content, whereas pH ranges from 3.7- 8.1 and CH_4 production between 61–859 L/Kg of VS. The original data value of pH, TS and VS are transformed into natural logarithmic form to get a better fit in the model and the value of WC is not changed. The transformed value of the parameters is listed in Table 2.

MLR is a statistical tool that uses several independent variables to predict the output of a dependent variable. The objective of MLR is to develop a model between the dependent and independent variables. The key variables used for regression are mentioned in table 2 and the regression model was developed using excel software 2010. In this study, the amount of methane produced is considered a dependent variable and pH, VS, TS and WC are considered independent variables. Based on the literature, the temperature parameter taken for the regression analysis is not significantly contributing to methane production. Hence, the temperature is not considered for this study.

The co-efficient of R square between the methane production and other variables such as pH, VS, TS and WC are studied. Regression equation (1) was developed to predict the methane production for the given data and that is compared with the actual methane production mentioned in Table 2.

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$$Y(CH_4) = 3.419 + (-1.52) \times \ln(pH) + (1.258) \times \ln(VS) + (-0.522) \times \ln(TS) + 0.038 \times (WC)\ldots \quad (1)$$

In the above eq (1), Y is the methane generation rate (L/ kg of VS) and natural logarithmic transformation is applied to the independent variables except for water content for regression analysis. The independent variables such as VS, TS and WC are considered in percentage. The regression analysis for the given data is carried out and found regression coefficients

Table 2.
Input feedstock characteristics from references

S.No.	Ln(CH_4)	Ln(pH)	Ln(VS)	Ln(TS)	Water content (WC),%	References
1	5.765191	1.938742	3.178054	3.238678	74.50	[66]
2	6.142037	1.547563	2.980619	3.054001	78.80	[67]
3	5.749393	1.667707	2.424803	2.912351	81.60	[28]
4	6.152733	1.435085	3.044522	3.139833	75.00	[3]
5	4.70048	1.783391	3.139833	3.48124	67.50	[68]
6	6.214608	1.536867	3.194583	3.332205	72.00	[69]
7	6.244167	1.536867	3.178054	3.401197	70.00	[70]
8	6.350886	1.536867	3.273364	3.496508	67.00	[63]
9	6.184149	1.536867	3.226844	3.380995	70.00	[71]
10	4.110874	2.067	2.001	2.845	82.80	[72]
11	5.921578	1.536867	3.424263	3.572346	64.40	[73]
12	5.438079	1.871802	2.520113	3.002708	75.01	[74]
13	6.063785	1.526056	3.194583	3.401197	70.00	[31]
14	6.269096	1.629241	3.113515	3.238678	74.50	[75]
15	5.966147	1.435085	2.587764	2.70805	74.50	[75]
16	5.768321	1.629241	2.587764	2.70805	85.00	[76]
17	6.270988	1.410987	3.332205	3.380995	70.60	[46]
18	6.194405	1.704748	3.33577	3.417727	69.50	[77]
19	5.192957	2.091864	3.015535	3.091042	78.00	[72]
20	5.899897	1.526056	3.314186	3.401197	70.00	[78]
21	6.016157	1.477049	3.100092	3.186353	75.80	[79]
22	6.519147	2.014903	3.194583	3.306887	81.40	[63]
23	6.515039	1.386294	3.740048	3.809326	65.00	[63]
24	6.2186	1.360977	2.85647	3.049273	78.90	[80]
25	4.382027	2.066863	2.00148	2.844909	82.80	[72]
26	5.966147	1.446919	2.235376	2.379546	75.00	[25]
27	5.17615	1.686399	3.586293	3.916015	49.80	[58]
28	6.075346	1.547563	3.273364	3.430756	69.10	[81]
29	6.131226	1.629241	3.00072	3.126761	74.80	[82]
30	5.505332	1.871802	3.71113	3.951244	80.00	[70]
31	5.749393	1.749094	3.025291	3.325036	75.00	[21]
32	6.115892	2.00148	3.139833	3.280911	80.00	[63]
33	6.109248	1.545433	2.772589	2.995732	80.00	[38]
34	6.429719	1.960095	3.113515	3.38439	81.50	[63]
35	5.733341	1.987874	3.60522	3.79369	54.00	[83]
36	6.214608	1.629241	2.547881	2.778819	85.00	[38]
37	6.464588	1.629241	3.194583	3.321432	79.00	[62]
38	6.216606	1.545433	3.135059	3.208825	75.12	[80]
39	5.560682	1.969906	2.988708	2.998229	79.95	[80]
40	6.040255	1.818077	3.161247	3.313095	76.00	[80]
41	6.755769	1.435085	3.099642	3.143721	76.76	[84]
42	6.152733	1.871802	2.839078	2.895912	80.00	[67]
43	6.55108	1.625311	2.883123	3.09874	85.00	[80]
44	3.912023	2.054124	2.644755	3.015535	79.60	[72]
45	5.749393	1.506297	3.254629	3.317453	72.30	[80]
46	5.849325	1.648659	2.833213	2.917771	81.37	[80]
47	6.086775	1.321756	1.658228	1.704748	94.49	[80]

48	6.040255	1.61343	3.178054	3.253857	75.00	[80]
49	5.950643	1.591274	3.138966	3.367296	69.49	[85]
50	6.104793	1.477049	3.100092	3.186353	75.80	[85]
51	6.166006	1.386294	3.077773	3.097837	77.40	[83]
52	6.086775	1.675226	3.215269	3.296577	75.00	[86]
53	5.966147	1.663926	2.235376	2.379546	92.06	[87]
54	5.278115	1.644805	3.293612	3.706228	52.28	[85]
55	5.834811	1.660131	3.162517	3.468856	64.89	[85]
56	5.463832	1.813195	3.220475	3.688879	70.00	[85]

for the model. Analysis of variance (ANOVA) is used to determine the statistical significance between dependent and independent variables with a threshold p-value is 0.05.

The regression curve was plotted using Eq.1 shown in Figure 5 and the percentage variation accounted for by the model is low i.e R squared value = 0.636. These results revealed that 64% of the variation is explained by input feedstock characteristics. ANOVA results revealed a significant difference by the functional group in all measure feedstock characteristics ($p < 0.05$ in all parameters) except for TS content.

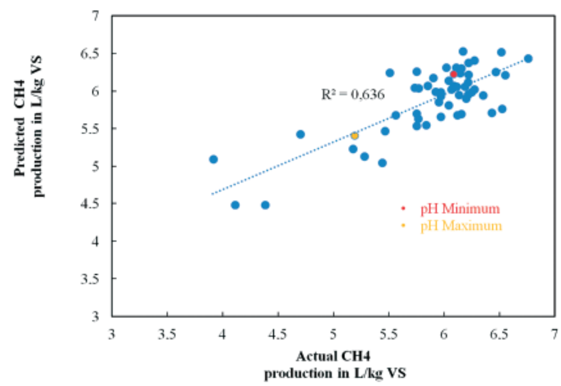

Figure 3.
Typical Composition of MSW

2.2.3. Influencing parameter in the regression plot

The pH is the most significant parameter that directly influences the digestion progress and end product. In the digestion process, a pH of 4–8.5 is required by the hydrolytic bacteria and acidogens while a narrow range of pH of 6.5–7.2 is required by methanogens. Hence, the microbial activities in AD are significantly affected under too high pH or too low pH. The optimal pH for overall AD was reported to be in the range of 6–8.

The pH is relatively correlated with methane production compared with other input feedstock factors and the tendency of correlation is negative. Figure 5 shows the minimum and maximum pH values that are taken from the data. The maximum pH value almost fits on the trendline of the generated Eq. (1).

From the generated equation, methane production is suitable for a pH value of 8.1, with corresponding TS and VS ranges between 20-22% with higher water content.

2.2.4. Limitations

Previous literature mainly focused on the AD process of landfill waste to a maximum extent and developed a model through their experimental or field data. Hence, our attempt is limited to the chemical composition of the substrate in understanding the feedstock characteristic in CH_4 generation. Out of all chemical compositions of the substrate, few parameters were considered due to the availability of a limited data source.

The input feedstock parameters considered in the regression are pH, VS, TS and WC. However, many parameters influence the model generated to a larger extent such as COD, bromatological factors etc. in the MSW effect the methane production. The data collected from the literature is ensured that they have the considered input values to analyse the relationship the methane production and feedstock parameters.

3. CONCLUSION

In developing countries, the MSW is dumped in open landfill sites without proper cover and lining. This leads to environmental and health risks to the animals, birds, humans and soil in that location. However, the governments of the nations lay stringent regulations in disposing of the waste, it is always a mixture of solid, biomedical and demolished material waste in addition to plastic wastes. The waste in the landfill decompose over time and starts producing methane gas – a greenhouse gas. The produced methane gas from the decomposition of MSW largely contributed to altering the pattern of global temperature, so it can be converted into renewable energy by various methodologies.

The factors affecting the generation of methane from the feedstock are pH, VS, TS and WC. Understanding the relationship between these parameters with the CH_4 production from the regression model generated; helps in identifying the feedstock quality and helps in the pretreatment of feedstock to enhance the production of CH_4. This can be later converted into renewable energy. From the regression model generated, the most influencing parameter of the feedstock is pH and the variations explained by the input parameters as 64%. The ideal pH value suitable for this model of the feedstock is basic (8.1), as most of the materials in the feedstock are moisturised. With the increase in VS and TS, the generation of methane production increases and decreases respectively. As the varied source of feedstock is considered, the total solids and volatile solids correlation are not significantly contributing to methane production; which can be rectified by considering a single feedstock as an input.

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