

Characterization and Energy Analysis of Fruit Waste and Crop Residues for Sustainable Biogas Production

Prem Salhani*

Institute of Environmental Engineering and Management, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan

Email: premsalhani90@gmail.com

Muhammad Safar Korai

Institute of Environmental Engineering and Management, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan

Zohaib Ali

Department of Environmental Sciences, Aror University of Art, Architecture, Design & Heritage, Sukkur, Sindh, Pakistan.

Afsheen

Faculty of Engineering Science & Technology, Indus University, Karachi, Pakistan

Ashfaque Hussain Kaka

Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan

ABSTRACT

This study aims to determine the characteristics and theoretical BMP of fruit waste (FrW), crop residues (CR) and anaerobic digested sludge (ADS) used as inoculum at different mixing ratios. The FrW and CR were co-digested at different mixing ratios such as 60:40, 50:50, 40:60, and 30:70 for the theoretical biochemical methane and Energy potential. FrW co-digested with CR at a ratio of 30:70 and obtained the highest TBMP 766.27 NmL/g VS and energy potential of 10999.45 KJ/Kg, due to the highest percentages of VS and carbon content of CR. Based on ASTM standards, the laboratory analysis were carried out to calculate the proximate analysis (moisture content, total solids, volatile solids, volatile matter, ash content, and fixed carbon) as well as ultimate analysis (carbon content, hydrogen content, nitrogen content, oxygen content, and Sulphur content). In addition to this, pH, total alkalinity (TA), and volatile fatty acids (VFA) were also examined. The average moisture content and volatile solids range from 7-95% and 63 to 91% respectively. Furthermore, the pH values 4.8 and 5.9 showed that FrW and CR are in acidic nature.

KEYWORDS: Anaerobic Co-Digestion, Fruit Waste, Crop Residues, CSTR Sludge, Theoretical Biochemical Methane Potential, Energy Potential

INTRODUCTION

In the present era, both climate change and energy crises are significant issues throughout the world [1]. The fast depletion of non-renewable energy resources [2], increasing population growth, improvement of the living standard, and industrial and economic expansions [3], indicate that energy is a major issue for the next decades [4]. As a result of these issues, the world is paying attention to renewable energy sources instead of conventional resources because they are environmentally sustainable and offer new job openings in rural areas [2,5]. Throughout the world, overconsumption of fossil fuels due to the development of industries and growing population has led the environmental as well as public health issues and climate changes [6]. Consequently, extreme weather events such as increasing storms and cyclones, drought, flooding, and global warming may be influenced by global climate changes [7, 8].

As an agricultural country, Pakistan cultivates many crops and generates huge quantities of crop residues such as sugarcane trash, banana plant waste, wheat straw, rice straw, rice husk, sugarcane bagasse, cotton gin waste, and cotton stalks, and residues of these crops create disposal problems [9, 10]. Mostly, these crop residues are used both for cooking or heating and in brick kilns for backing the bricks or burning those in an open atmosphere and are wasted without getting any benefit from them. This open burning of biomass has adverse effects on the environment [11, 12].

In Pakistan, the generation rate of Municipal Solid waste (MSW) is increasing at an alarming rate due to the increase in population growth as well as urbanization. Around 25.420 Mt per year of MSW is generated and mostly composed of 64% organic and 36% inorganic waste [13]. In Pakistan, daily 225 Kt of crop residues and 1 million animal dung are generated. Annually, 8.8-17.2 billion cubic meters of gas are yielded as reported by [14]. Despite these energy resources, Pakistan is still facing energy crisis issues due to the lack of waste management infrastructures and has to rely on imports to fulfill its energy requirements [15].

Currently, biomass is widely used as a source of renewable energy with the highest potential to support the energy demands of emerging countries [16]. In Nepal, the majority of the rural population combusted biomass in traditional stoves for energy purposes, which causes environmental threats including emissions of greenhouse gases (GHGs) due to the formation of products by the incomplete combustion and smoke from these stoves causes public health issues [17,18]. Biomass provides about 10% of the energy needed within the global energy system and its contribution is slightly above 7% in Germany [19]. In Brazil, 597 million tons per year of crop residues are generated [20]. China generates 57.5% of waste agriculture biomass, 39.2% of fuel wood, and 3.2% of animal dung for bioenergy production [21]. In Zimbabwe, total annual residue yields for crops, fruits, and forestry plantations are 7.805 Mt, 378 Kt, and 3.05 Mt, respectively. The crops, fruits, and forestry residues have an energy potential of 81.5, 4.9, and 44.3 PJ per year, respectively, which represents about 44 % of the gross energy consumption of the country [22]. India generates 686 million tons of gross waste agriculture biomass per year and 34% of gross WAB is calculated as surplus for generation of bioenergy [3]. Several commercial and farm-scale biogas plants are operated with the feedstock of WAB and animal dung in developed countries [9].

AD is a biochemical process in which the organic waste is bacteriologically degraded into useful byproducts such as biogas and digestate in the absence of oxygen [23]. Digestate is a decomposed material that is rich in nutrients and is used as fertilizer to enhance the fertility of the soil [24]. AD is a proven and well-established technology for treating and managing wastes to generate renewable energy [25]. The advantages of AD include energy production (biogas), material recovery (fertilizers), and waste elimination (waste treatment) [24].

MATERIAL AND METHODS

Collection of samples and inoculum

Five samples of fruit waste (FrW) such as banana waste, orange peels, gray fruit peel, pomegranate waste, and papaya waste were obtained from the fruit shop and retailer market of Hyderabad [26]. Similarly, five samples of crop residues (CRs) such as wheat straw, rice straw, rice husk, canola straw, and sugar cane trash were collected from the fields of the Hyderabad division [27]. Whereas the effluent of a continuous stirring tank reactor (CSTRE) which is rich in microorganisms used as inoculum.

Preparation of substrates

Samples were dried in the oven at 105°C for 24 hours [28]. The larger pieces of FrW and CRs were cut and shredded by a hammer mill into smaller pieces [29]. Then, both samples were ground by coffee grinder to reduce their particle size by 1- 2mm [30]. After grinding, FrW and CRs were mixed in different ratios such as 60:40, 50:50, 40:60, and 30:70, respectively by quartering methodology as shown in Fig.1 and 2. Then, samples were stored at 4°C in plastic bags until use [31].

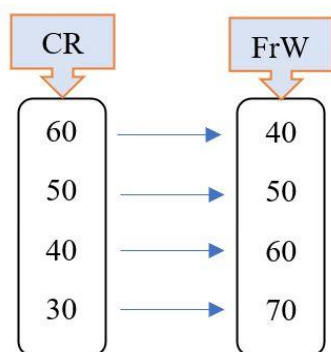


Figure.1 Preparation of sample

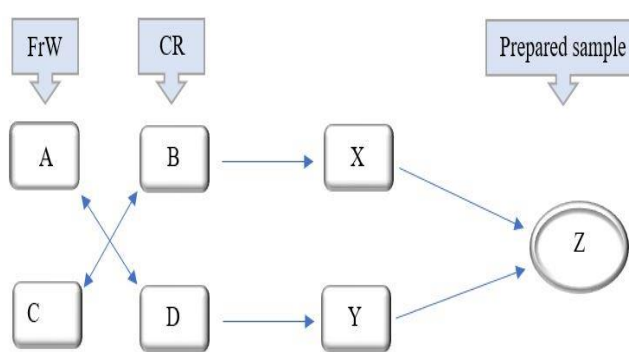


Figure.2 Block diagram of quartering method

Sample analysis

Proximate analysis

Moisture content (MC), total solids (TS), volatile solids (VS), Total alkalinity, pH, and VFA were determined by the standard methods as presented in Table.1 [32]. Moisture content was obtained by drying the sample in an oven at 105°C for 24 hours [33]. MC% was determined by using the eq.1.

$$MC = \frac{p-q}{p} \times 100 \quad (1)$$

Where, p represented the weight of the wet sample, and q denoted of dry sample. The total solids were obtained by the eq.2

$$TS = 100 - MC \% \quad (2)$$

Volatile solids were determined by heating the dried sample at 550°C for 2 hours in a muffle furnace to the constant weight [34]. Similarly, the volatile matter was calculated by combusting the dry sample in a covered crucible at 950°C for 7 minutes in a muffle furnace. The weight of the sample before and after the muffle furnace were recorded [35]. Both volatile solids and volatile matter were estimated by the given equations.

$$VS_{wb} \text{ or } VM_{wb} = \frac{q-r}{p} \times 100 \quad (3)$$

$$VS_{db} \text{ or } VM_{db} = \frac{q-r}{q} \times 100 \quad (4)$$

Where, VS_{wb} and VS_{db} stands for the volatile solids on the wet basis as well as the dry basis. Similarly, VM_{wb} and VM_{db} shows the volatile matter on a wet basis as well as a dry basis, “r” indicates the mass after the oven.

Ash content was obtained by putting the dried sample in a crucible at 750°C for an hour in a muffle furnace and the left material was called ash [36]. Both ash content and fixed carbon were enumerated by the given equations.

$$FC_{wb} \text{ or } AC_{wb} = \frac{r}{p} \times 100 \quad (5)$$

$$FC_{db} \text{ or } AC_{db} = \frac{r}{q} \times 100 \quad (6)$$

So, FC_{wb} and FC_{db} stands for fixed carbon on a wet as well as dry basis. Whilst AC_{wb} and AC_{db} for ash content on a wet as well dry basis.

Table 1: Methods used to find the characteristics of samples

Parameters	Methods	Equipment's
MC	ASTMD 3173	Oven
VM	ASTMD 3175	Muffle Furnace
AC	ASTMD 3174	Muffle Furnace
TA	Titration	Titration assembly
pH	Electrometric	pH meter (Hi 8424)
VFA	Distillation and titration	Distillation and titration assembly

Ultimate analysis

Statistical methods were used to calculate the ultimate analysis of the FrW and CRs. The percentages of carbon, hydrogen, nitrogen, and Sulphur was obtained by different mathematical correlations.

Percentage of Carbon, Hydrogen, and Oxygen present in solid waste

Based on the proximate analysis, equations 7 and 8 were used to calculate the carbon and hydrogen content of the solid waste, respectively [37, 38]. Oxygen content was estimated by subtracting the content of Carbon, Hydrogen, Nitrogen, Sulphur, and ash

from hundred [9].

$$C\% = 0.637FC\% + 0.455VM\% \quad (7)$$

$$H\% = 0.052FC\% + 0.062VM\% \quad (8)$$

$$O\% = 100 - (C\% + H\% + N\% + S\% + Ash\%) \quad (9)$$

Where,

FC: 4.7 to 38.4%, VM: 57.2 to 90.6%, Carbon: 36.2 to 53.1%, Hydrogen: 4.36 to 8.3%, and Oxygen: 31.37 to 49.5% in weight percent on a dry basis. Correlations with an average absolute error of 3.21% and 4.79%; and bias error of 0.21% and 0.15% regarding to measured values of carbon and hydrogen, respectively.

Percentage of Sulphur present in solid waste

It has been suggested by [39] that 25mg of sample were dissolved in 25ml of tape water and passed through the filter paper to remove the solid particles. Then, 50mg of BaCL₂ was added and allowed to stand for 30 seconds in order to get a homogeneous solution. The standard solution was put into a spectrophotometer at 420nm. The absorbance of the standard solution and the samples were read from the spectrophotometer at 420 nm. The graphs of absorbance against the concentration of standards were plotted and sample concentration was evaluated from the graph. The Sulphate and Sulphur content were calculated by equations 10 and 11, respectively.

$$A = \frac{B - 0.0408}{0.0126} \quad (10)$$

Where, A= Sulphate, mg/l

B= Absorbance

$$\text{The percentage of Sulphur} = \frac{AxRxDF}{\text{mass of sample}} \quad (11)$$

Where, A= Sulphate, mg/l

R= Total volume of sample, ml

DF= Dilution factor

Percentage of Nitrogen present in solid waste

The values of nitrogen content in solid waste were taken from the previous study of different researchers as described in Table 2.

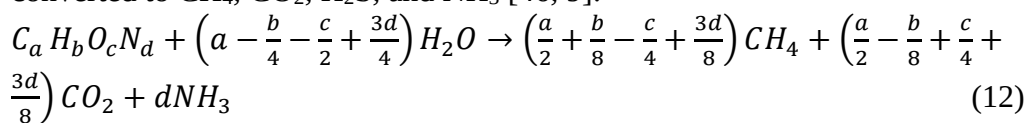
Table 2: Nitrogen percentage from previous studies

Waste	Waste component	References	N% from previous study	Components %	Nitrogen content by percent	Nitrogen content
CRs	Wheat straw	[40]	0.4	40	0.16	0.735
	Rice straw	[23]	0.73	20	0.146	
	Rice husk	[9]	1.7	20	0.34	
	Canola straw	[41]	0.44	10	0.044	
	Sugarcane trash	[41]	0.45	10	0.045	
FrW	Banana peels	[42]	0.69	40	0.276	0.54
	Pomegranate waste	[42]	0.02	20	0.004	

Papaya waste	[43]	0.6	20	0.12
Orange peels	[42]	0.85	10	0.085
Grapefruit peels	[42]	0.55	10	0.055

Theoretical biochemical methane potential

Theoretical biochemical methane potential of the FrW and CR was determined based on the Buswell reaction (12) and modified Dulong formula (13) [44, 45]. Equation (12) assumes that all the biodegradable organic materials present in the substrate were converted to CH₄, CO₂, H₂S, and NH₃ [46, 9].



Where,

a, b, c, d = Stoichiometric coefficients of biodegradable molecules

$$TBMP \text{ (Nml/g VS)} = \frac{930C + 2790H + 350 \times O - 600N - 175 \times S}{C + H + O + N + S} \quad (13)$$

$$E = 337C + 1420(H - 0.125O) + 93S + 23N \quad (14)$$

RESULTS AND DISCUSSION

Physical composition of samples

For present the study, fruit waste and crop residues were used as substrates. The composition of fruit waste and crop residues is depicted in Fig 2 (a) and Fig 2 (b), respectively. The fruit waste is composed of 40% banana peels and discarded followed by the 20% pomegranate waste, 20% papaya peels plus discarded, 10% orange peels and 10% grey fruit peels. Furthermore, crop residue consists of 40% wheat straw, 20% rice straw, 20% rice husk, 10% canola straw and 10% sugarcane trash.

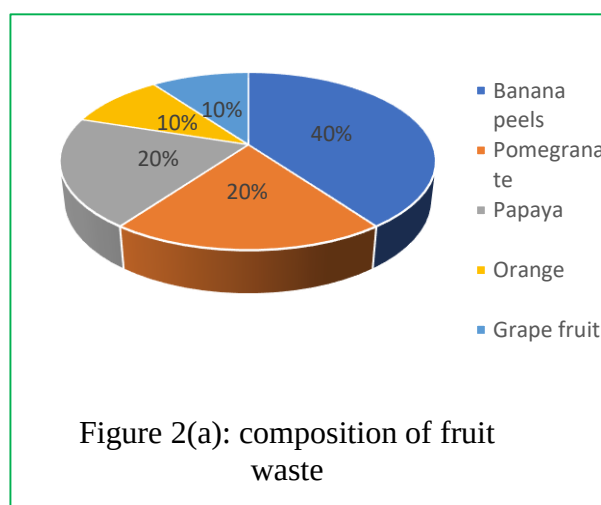


Figure 2(a): composition of fruit waste

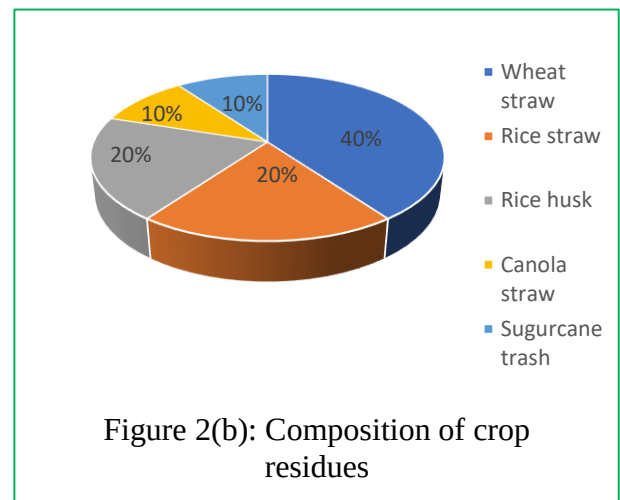


Figure 2(b): Composition of crop residues

Characteristics of feedstock

The characterization of the substrate plays a vital role in the successful AD, to ensure that it is balanced in carbon, nitrogen, TS, VS, and lignin content [29]. The characteristics of fruit waste, crop residues, and inoculum are presented in Table 3 (a) and (b). Table 3 (a) and (b) showed that CSTRE had the highest moisture content of 94.71% while the CRs had the lowest moisture content of 7.06%. Similarly, the moisture content of FrW was found to be 84.89%. These results are comparable to the study of [40, 41, and 47]. The comparative MC of FrW and CSTRE were indicated that they should be dried to achieve better control of the process variables for the purpose of acids or enzymatic hydrolysis in the laboratory [48].

On dry basis, the TS of the CRs, Frw, and CSTRE were determined 92.94%, 17.11%, and 5.29%, respectively. Similarly, the results of VM of the FrW, CRs, and CSTRE were 93.94%, 90.73%, and 67.98%, respectively. These results show that FrW had a VM higher of 93.94% while, CRs and CSTRE had VM values had 90.73% and 67.98%, respectively. The ranges of FC content were 6.06% to 32.02%. The highest FC content for the CSTRE, while the lowest value of FC content for FrW. The ash content of the Frw, CRs, and CSTRE were 6.94%, 12.47%, and 31.45%, respectively. On dry basis, it is predicted that CR was rich in carbon content and organics (VS) 46.44% and 80.07%, respectively. Similarly, FrW had carbon content and volatile solids of 46.4% and 17.11%, respectively, whereas low nitrogen content was 0.54%. The VS/TS ratio of Frw and CR were estimated 89.63% and 86.16%, respectively. High VS/TS ratios indicating high organic content that is desirable for anaerobic digestion [49]. The carbon-to-nitrogen ratio of FrW, CR, and CSTRE was found 85.92%, 35.8%, and 7.956%, respectively. The optimum C/N ratio for the running AD is considered in the ranges 20-30 [50].

pH measurement: The pH of the FrW, CR, and CSTRE measured by using a portable pH meter (Hi 8424) was 4.8, 5.9, and 7.1, respectively. The pH values indicated that FrW and CR are in acidic, whereas the CSTRE is in alkaline nature.

Total Alkalinity (TA) and Volatile fatty acids (VFA):

The TA of FrW, CR, and CSTRE calculated by the titration method was 1100 mg/l, 400 mg/l, and 1950 mg/l, respectively. The VFA was enumerated by the distillation and titration method. The VFA of FrW, CR, and CSTRE was 120, 240, and 120, respectively.

Table 3 (a): Characteristics of FrW, CRs and inoculum

Parameters		FrW	CR	Inoculum (CSTRE)
MC	Min:	82.51	5.81	93.92
	Max:	83.93	8.23	95.81
	Average	82.89	7.06	94.71
	STDeviation	0.78	0.97	0.63
	Percentage of STDeviation, %	0.94	13.73	0.67
TS	Min:	16.07	91.77	4.19
	Max:	18.15	94.19	6.08

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

	Average	17.11	92.94	5.29
	STDeviation	0.78	0.97	0.63
	Percentage of STDeviation, %	4.57	1.04	11.96
VS, wb	Min:	14.83	79.53	2.77
	Max:	15.84	80.62	3.38
	Average	15.33	80.08	3.07
	STDeviation	0.71	0.77	0.43
	Percentage of STDeviation, %	4.62	0.96	14.10
VS, db	Min:	90.78	86.58	55.59
	Max:	90.95	86.62	65.99
	Average	90.87	86.60	60.79
	STDeviation	0.12	0.03	7.35
	Percentage of STDeviation, %	0.13	0.04	12.10
VM, wb	Min:	15.15	81.01	3.72
	Max:	16.10	87.23	3.80
	Average	15.62	84.12	3.76
	STDeviation	0.67	4.40	0.06
	Percentage of STDeviation, %	4.30	5.23	1.63
VM, db	Min:	93.64	88.28	67.77
	Max:	94.23	93.18	68.20
	Average	93.94	90.73	67.98
	STDeviation	0.41	3.47	0.31
	Percentage of STDeviation, %	0.44	3.82	0.45
FC, wb	Min:	0.93	6.38	1.77
	Max:	1.09	10.76	1.77
	Average	1.01	8.57	1.77
	STDeviation	0.12	3.09	0.00
	Percentage of STDeviation, %	11.56	36.11	0.22
FC, db	Min:	5.77	6.82	31.80
	Max:	6.36	11.72	32.23
	Average	6.06	9.27	32.02
	STDeviation	0.41	3.47	0.31
	Percentage of STDeviation, %	6.84	37.42	0.95

Table 3 (b): Characteristics of FrW, CRs and inoculum

Parameters		FrW	CR	Inoculum (CSTRE)
AC, wb	Min:	1.23	11.63	1.59
	Max:	1.24	11.72	1.69
	Average	1.24	11.68	1.64
	STDeviation	0.00	0.07	0.07

	Percentage of STDeviation, %	0.26	0.58	4.29
AC, db	Min:	6.83	12.35	31.37
	Max:	7.06	12.59	31.52
	Average	6.94	12.47	31.45
	STDeviation	0.16	0.17	0.11
	Percentage of STDeviation, %	2.36	1.40	0.34
C, %		46.60	47.19	23.79*
H, %		6.14	6.11	3.46*
O, %		39.68	33.37	34.92*
N, %		0.54	0.74	2.99*
S, %		0.09	0.13	3.39*
C/N Ratio		14.32	58.00	7.956*
pH		4.87	5.98	7.10
TA, mg/L		1100	400	1950
VFA, mg/L		120	240	120

* = Values taken from the study of Li et al., 2018

Theoretical BMP and Energy Potential

Based on elemental composition, theoretical biochemical methane potential (TBMP) and energy potential of the different substrates and their mixing ratio was calculated by the equations 12 and 13, described in Table 6. The FrW and CRs are blended as Sample-A (60:40), Sample-B (50:50), Sample-C (40:60), and Sample-D (30:70). Maximum theoretical BMP and energy potential of R10 of sample-D was estimated 766.27 NmL/g VS and 10999.45 KJ/Kg, respectively. Whereas low theoretical BMP as well as energy potential of other ratios such as R1, R2, R3, R4, R5, R6, R7, R8, R9, R11, and R12 was estimated as shown in Table 6. Moreover, the highest theoretical BMP and energy potential of R10 was calculated as compared to other ratios because CRs have a high percentage of VS as well as carbon content.

Table 4 (a): Characteristics of substrate mixing at different ratios R1-R6

Parameters		Sample-A (60:40)			Sample-B (50:50)		
		a	b	c	d	e	f
MC	Min:	56.04	60.25	64.46	49.14	54.11	59.09
	Max:	57.87	62.08	66.30	51.05	56.02	61.00
	Average	56.78	60.99	65.20	49.95	54.92	59.90
	STDeviation	0.83	0.81	0.79	0.85	0.83	0.80
	Percentage of STDeviation, %	1.47	1.33	1.21	1.70	1.51	1.34

TS	Min:	42.13	37.92	33.70	48.95	43.98	39.00
	Max:	44.32	40.07	35.82	51.16	46.15	41.14
	Average	43.22	39.01	34.80	50.05	45.08	40.10
	STDeviation	0.83	0.81	0.79	0.85	0.83	0.80
	Percentage of STDeviation, %	1.93	2.08	2.27	1.70	1.84	2.00
VS, wb	Min:	36.92	33.12	29.33	42.74	38.30	33.86
	Max:	37.91	34.08	30.24	43.75	39.26	34.77
	Average	37.42	33.60	29.78	43.24	38.78	34.32
	STDeviation	0.70	0.67	0.64	0.71	0.68	0.65
	Percentage of STDeviation, %	1.88	2.01	2.16	1.64	1.75	1.89
VS, db	Min:	85.75	82.40	79.05	85.37	82.06	78.75
	Max:	86.90	84.57	82.25	86.51	84.23	81.95
	Average	86.32	83.49	80.65	85.94	83.15	80.35
	STDeviation	0.81	1.54	2.27	0.80	1.53	2.26
	Percentage of STDeviation, %	0.94	1.84	2.81	0.93	1.84	2.81
VM, wb	Min:	37.72	33.94	30.16	43.64	39.21	34.77
	Max:	40.48	36.40	32.33	46.88	42.09	37.31
	Average	39.10	35.17	31.24	45.26	40.65	36.04
	STDeviation	1.95	1.74	1.53	2.29	2.04	1.79
	Percentage of STDeviation, %	4.99	4.95	4.90	5.05	5.02	4.98

where, a= R1(90:10), b= R2(80:20), c= R3(70:30), d= R4(90:10), e= R5(80:20), and f= R6(70:30)

Table 4 (b): Characteristics of substrate mixing at different ratios R1-R6

Parameters		Sample-A (60:40)			Sample-B (50:50)		
		a	b	c	d	e	f
VM, db	Min:	89.12	86.75	84.38	88.64	86.32	84.00
	Max:	91.25	88.69	86.13	91.16	88.60	86.05
	Average	90.19	87.72	85.25	89.90	87.46	85.03
	STDeviation	1.50	1.37	1.24	1.78	1.61	1.45
	Percentage of STDeviation, %	1.67	1.56	1.45	1.98	1.85	1.71
FC, wb	Min:	2.98	2.84	2.71	3.47	3.28	3.09
	Max:	4.64	4.32	4.00	5.51	5.10	4.68

	Average	3.81	3.58	3.36	4.49	4.19	3.88
	STDeviation	1.18	1.05	0.92	1.45	1.29	1.13
	Percentage of STDeviation, %	30.92	29.24	27.32	32.21	30.70	28.97
FC, db	Min:	8.75	11.31	13.87	8.84	11.40	13.95
	Max:	10.88	13.25	15.62	11.36	13.68	16.00
	Average	9.81	12.28	14.75	10.10	12.54	14.97
	STDeviation	1.50	1.37	1.24	1.78	1.61	1.45
	Percentage of STDeviation, %	15.32	11.16	8.39	17.60	12.88	9.69
AC, wb	Min:	5.01	4.63	4.25	5.95	5.46	4.98
	Max:	5.06	4.68	4.31	6.00	5.52	5.04
	Average	5.04	4.66	4.28	5.97	5.49	5.01
	STDeviation	0.03	0.04	0.04	0.04	0.04	0.05
	Percentage of STDeviation, %	0.66	0.80	0.97	0.65	0.77	0.92
AC, db	Min:	11.27	13.50	15.74	11.77	13.94	16.12
	Max:	11.50	13.72	15.95	12.00	14.16	16.33
	Average	11.38	13.61	15.84	11.88	14.05	16.23
	STDeviation	0.16	0.16	0.15	0.16	0.16	0.15
	Percentage of STDeviation, %	1.42	1.14	0.94	1.37	1.11	0.92
C, %		44.53	42.23	39.92	44.58	42.27	39.96
H, %		5.86	5.59	5.33	5.85	5.59	5.32
O, %		36.95	36.72	36.50	36.38	36.22	36.06
N, %		0.86	1.09	1.33	0.87	1.11	1.34
S, %		0.42	0.75	1.08	0.42	0.75	1.08
C/N Ratio		29.40	27.02	24.63	33.34	30.51	27.7
pH		5.49	5.67	5.85	5.59	5.76	5.93
TA, mg/L		933	1046	1159	870	990	1110
VFA, mg/L		163	158	154	174	168	162
where, a= R1(90:10), b= R2(80:20), c= R3(70:30), d= R4(90:10), e= R5(80:20), and f= R6(70:30)							

Table 5 (a): Characteristics of substrate mixing at different ratios R7-R12

Parameters		Sample-C (40:60)			Sample-D (30:70)		
		g	h	i	j	k	l
MC	Min:	42.24	47.98	53.72	35.33	41.84	48.35
	Max:	44.24	49.97	55.70	37.43	43.91	50.40
	Average	43.13	48.86	54.59	36.30	42.79	49.28
	STDeviation	0.87	0.84	0.82	0.89	0.86	1
	Percentage of STDeviation, %	2.01	1.72	1.49	2.44	2.00	0.00
TS	Min:	55.76	50.03	44.30	62.57	56.09	49.60

	Max:	58.00	52.23	46.46	64.85	58.32	51.79
	Average	56.87	51.14	45.41	63.70	57.21	50.72
	STDeviation	0.87	0.84	0.82	0.89	0.86	0.83
	Percentage of STDeviation, %	1.53	1.65	1.80	1.39	1.50	1.64
VS, wb	Min:	48.56	43.48	38.39	54.39	48.65	42.92
	Max:	49.58	44.44	39.31	55.41	49.63	43.85
	Average	49.07	43.96	38.85	54.90	49.14	43.38
	STDeviation	0.72	0.68	0.65	0.72	0.69	0.66
	Percentage of STDeviation, %	1.46	1.56	1.68	1.31	1.40	1.52
VS, db	Min:	84.99	81.73	78.46	84.61	81.39	78.16
	Max:	86.12	83.88	81.65	85.73	83.54	81.34
	Average	85.56	82.80	80.05	85.17	82.46	79.75
	STDeviation	0.80	1.52	2.25	0.79	1.52	2.25
	Percentage of STDeviation, %	0.93	1.84	2.81	0.93	1.84	2.82
VM, wb	Min:	49.57	44.48	39.38	55.50	49.75	43.99
	Max:	53.28	47.78	42.29	59.68	53.47	47.27
	Average	51.43	46.13	40.83	57.59	51.61	45.63
	STDeviation	2.62	2.34	2.05	2.96	2.64	2.31
	Percentage of STDeviation, %	5.10	5.07	5.03	5.14	5.11	5.07
VM, db	Min:	88.16	85.89	83.63	87.67	85.46	83.25
	Max:	91.06	88.52	85.98	90.97	88.44	85.91
	Average	89.61	87.21	84.80	89.32	86.95	84.58
	STDeviation	2.05	1.86	1.66	2.33	2.10	1.88
	Percentage of STDeviation, %	2.29	2.13	1.96	2.61	2.42	2.22
FC, wb	Min:	3.96	3.71	3.47	4.45	4.15	3.85
	Max:	6.38	5.87	5.36	7.25	6.64	6.03
	Average	5.17	4.79	4.41	5.85	5.40	4.94
	STDeviation	1.71	1.52	1.33	1.98	1.76	1.54
	Percentage of STDeviation, %	33.15	31.80	30.22	33.88	32.65	31.20
where, g= R7(90:10), h= R8(80:20), i= R9(70:30), j= R10(90:10), k= R11(80:20), and l= R12(70:30)							

Table 5 (b): Characteristics of substrate mixing at different ratios R7-R12

Parameters		Sample-C (40:60)			Sample-D (30:70)		
		g	h	i	j	k	l
FC, db	Min:	8.94	11.48	14.02	9.03	11.56	14.09
	Max:	11.84	14.11	16.37	12.33	14.54	16.75
	Average	10.39	12.79	15.20	10.68	13.05	15.42

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

	STDeviation	2.05	1.86	1.66	2.33	2.10	1.88
	Percentage of STDeviation, %	19.76	14.53	10.96	21.80	16.12	12.18
AC, wb	Min:	6.88	6.29	5.71	7.82	7.13	6.43
	Max:	6.95	6.36	5.78	7.89	7.20	6.51
	Average	6.91	6.33	5.74	7.85	7.16	6.47
	STDeviation	0.04	0.05	0.05	0.05	0.05	0.06
	Percentage of STDeviation, %	0.65	0.75	0.88	0.65	0.74	0.85
AC, db	Min:	12.26	14.39	16.51	12.76	14.83	16.89
	Max:	12.49	14.61	16.72	12.99	15.05	17.11
	Average	12.38	14.50	16.62	12.87	14.94	17.00
	STDeviation	0.16	0.16	0.15	0.16	0.16	0.15
	Percentage of STDeviation, %	1.32	1.09	0.91	1.28	1.06	0.89
C, %		44.64	42.32	40.00	44.69	42.37	40.05
H, %		5.85	5.59	5.32	5.85	5.59	5.32
O, %		35.76	35.67	35.57	35.19	35.16	35.13
N, %		0.89	1.12	1.36	0.91	1.14	1.37
S, %		0.48	0.80	1.13	0.49	0.81	1.13
C/N Ratio		37.26	34.00	30.75	41.20	37.50	33.80
pH		5.69	5.85	6.01	5.79	5.94	6.08
TA, mg/L		807	934	1061	744	878	1012
VFA, mg/L		185	178	170	196	187	179
where, g= R7(90:10), h= R8(80:20), i= R9(70:30), j= R10(90:10), k= R11(80:20), and l= R12(70:30)							

Table 6: Formula, theoretical BMP and energy potential of substrate and inoculum ratio

S. No	Mixed ratio of FrW & CR	Substate & Inoculum ratio	Empirical Formula		Theoretical BMP, NmL/g VS	Energy potential, KJ/Kg
			S= 1	S= 0, N=1		
1	FrW	Frw	C ₁₀₆₉ H ₁₆₃₆₁ O ₈₁₀₃ N ₁₀ S	C ₁₀₃ H ₁₅₈₃ O ₇₈₄ N	496.91	2969.58
2	CR	CR	C ₉₈₂ H ₁₇₆₉ O ₆₂₇ N ₁₃ S	C ₇₅ H ₁₃₅ O ₄₈ N	557.30	17590.83

3	CSTRE	CSTRE	C ₁₉ H ₁₈₈₈ O ₉₅₈ N ₂ S	C ₉ H ₉₂₈ O ₄₇₁ N	250.46	363.84
4	Sample-A (60:40)	R1(90:10)	C ₂₈₆ H ₁₅₅₉ O ₇₄₀ N ₅ S	C ₆₁ H ₃₃₂ O ₁₅₈ N	747.37	7266.84
		R2(80:20)	C ₁₅₂ H ₉₈₃ O ₄₇₄ N ₃ S	C ₄₅ H ₂₉₀ O ₁₄₀ N	727.81	6171.62
		R3(70:30)	C ₉₈ H ₇₆₀ O ₃₇₃ N ₃ S	C ₃₅ H ₂₇₄ O ₁₃₅ N	704.71	5096.84
5	Sample-B (50:50)	R4(90:10)	C ₂₈₄ H ₁₂₈₅ O ₅₉₈ N ₅ S	C ₅₉ H ₂₆₈ O ₁₂₅ N	755.15	8502.95
		R5(80:20)	C ₁₅₀ H ₈₀₅ O ₃₈₄ N ₃ S	C ₄₅ H ₂₃₉ O ₁₁₄ N	732.62	7141.75
		R6(70:30)	C ₁₀₀ H ₆₅₀ O ₃₁₆ N ₃ S	C ₃₅ H ₂₂₆ O ₁₁₀ N	708.92	5900.40
6	Sample-C (40:60)	R7(90:10)	C ₂₅₁ H ₉₅₅ O ₄₃₆ N ₄ S	C ₅₈ H ₂₂₁ O ₁₀₁ N	760.74	9706.59
		R8(80:20)	C ₁₄₁ H ₆₄₂ O ₃₀₂ N ₃ S	C ₄₄ H ₂₀₂ O ₉₅ N	737.59	8161.90
		R9(70:30)	C ₉₅ H ₅₂₉ O ₂₅₄ N ₃ S	C ₃₄ H ₁₉₀ O ₉₁ N	713.27	6760.81
7	Sample-D (30:70)	R10(90:10)	C ₂₄₅ H ₇₉₉ O ₃₅₄ N ₄ S	C ₅₇ H ₁₈₇ O ₈₃ N	766.27	10999.45
		R11(80:20)	C ₁₄₁ H ₅₅₂ O ₂₅₃ N ₃ S	C ₄₄ H ₁₇₁ O ₇₈ N	742.51	9260.38
		R12(70:30)	C ₉₅ H ₄₅₇ O ₂₁₇ N ₃ S	C ₃₄ H ₁₆₃ O ₇₇ N	717.57	7617.96

Conclusion

The waste samples were collected according to waste sampling methodology and then characterized by using ASTM standards. FrW and CRs were co-digested by mixing at different ratios such as R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11 and R12. The highest Theoretical BMP was 766.27 NmL/g VS for R10 followed by 760.74 NmL/g VS, 755.15 NmL/g VS, 747.37 NmL/g VS, 742.51 NmL/g VS, 737.59 NmL/g VS, 732.62 NmL/g VS, 727.81 NmL/g VS, 717.57 NmL/g VS, 713.27 NmL/g VS, 708.92 NmL/g VS and 704.71 NmL/g VS for R7, R4, R1, R11, R8, R5, R2, R12, R9, R6, and R3, respectively. The highest EP was calculated as 10999.45 KJ/Kg of R10. It was concluded from the results of the present study that, the R10 is considered the optimal ratio for TBMP. Furthermore, it was observed that the co-digestion of FrW and wasted CRs are renewable and feasible energy sources.

References

- [1] Al Mamun, M.R. and Torii, S., 2014. Production of Biomethane from Cafeteria, Vegetable and Fruit Wastes by Anaerobic Co digestion Process. *Journal of Advanced Agricultural Technologies Vol, 1*(2).
- [2] Kumar, J.S., Subbaiah, K.V. and PVV, P.R., 2010. Waste to Energy—A case study of Eluru city, Andhra Pradesh. *International Journal of Environmental Sciences, 1*(2), pp.151-162.
- [3] Hiloidhari, M., Das, D. and Baruah, D.C., 2014. Bioenergy potential from crop residue biomass in India. *Renewable and sustainable energy reviews, 32*, pp.504-512.

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- [4] Abbas, T., Ali, G., Adil, S.A., Bashir, M.K. and Kamran, M.A., 2017. Economic analysis of biogas adoption technology by rural farmers: The case of Faisalabad district in Pakistan. *Renewable energy*, 107, pp.431-439.
- [5] Isci, A. and Demirer, G.N., 2007. Biogas production potential from cotton wastes. *Renewable energy*, 32(5), pp.750-757.
- [6] Budiyo, B., Widiyasa, I.N., Johari, S. and Sunarso, S., 2014. Increasing biogas production rate from cattle manure using rumen fluid as inoculums. *International Journal of Science and Engineering*, 6(1), pp.31-38.
- [7] Sen, Z., 2009. Global warming threat on water resources and environment: a review. *Environmental geology*, 57(2), pp.321-329.
- [8] Mills, D.M., 2009. Climate change, extreme weather events, and US health impacts: what can we say?. *Journal of Occupational and Environmental Medicine*, 51(1), pp.26-32.
- [9] Mahar, R.B., Sahito, A.R. and Uqaili, M.A., 2012. Biomethanization potential of waste agricultural Biomass in Pakistan: a case study. *International Journal of Biomass & Renewables*, 1, pp.32-37.
- [10] Sahito, A.R., Mahar, R.B. and Brohi, K.M., 2014. Anaerobic co-digestion of canola straw and buffalo dung: optimization of methane production in batch experiments. *Mehran University Research Journal of Engineering & Technology*, 33(1).
- [11] Guoliang, C.A.O., ZHANG, X., Sunling, G.O.N.G. and ZHENG, F., 2008. Investigation on emission factors of particulate matter and gaseous pollutants from crop residue burning. *Journal of Environmental Sciences*, 20(1), pp.50-55.
- [12] Yang, S., He, H., Lu, S., Chen, D. and Zhu, J., 2008. Quantification of crop residue burning in the field and its influence on ambient air quality in Suqian, China. *Atmospheric Environment*, 42(9), pp.1961-1969.
- [13] Korai, M. S., R. B. Mahar, M. A. Uqaili, and K. M. Brohi. "Assessment of municipal solid waste management practices and Energy recovery potential in Pakistan." In *Proceedings of the 14th International Conference on Environmental Science and Technology Rhodes*, pp. 3-5. 2015.
- [14] Khan, S.I., Aftab, S., Chaudhry, T.A. and Younis, M.N., 2018. Production of biogas by the co-digestion of cow dung and crop residue at the University of the Punjab, Lahore, Pakistan. *African Journal of Environmental Science and Technology*, 12(2), pp.91-95.
- [15] Korai, M.S., Mahar, R.B. and Uqaili, M.A., 2014. Assessment of power generation potential from municipal solid wastes: a case study of Hyderabad City, Sindh, Pakistan. *Pakistan Journal of Analytical & Environmental Chemistry*, 15(1), p.10.
- [16] Demirbas, M.F., Balat, M. and Balat, H., 2009. The potential contribution of biomass to the sustainable energy development. *Energy Conversion and Management*, 50(7), pp.1746-1760.
- [17] Surendra, K.C., Khanal, S.K., Shrestha, P. and Lamsal, B., 2011. Current status of renewable energy in Nepal: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, 15(8), pp.4107-4117.

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- [18] Bhattacharya, S.C. and Salam, P.A., 2002. Low greenhouse gas biomass options for cooking in the developing countries. *Biomass and Bioenergy*, 22(4), pp.305-317.
- [19] Kaltschmitt, M., 2011. Biomass for energy in Germany-status, perspectives and lessons learned. *Journal of Sustainable Energy & Environment. Special Issue*, pp.1-10.
- [20] Ferreira-Leitao, V., Gottschalk, L.M.F., Ferrara, M.A., Nepomuceno, A.L., Molinari, H.B.C. and Bon, E.P., 2010. Biomass residues in Brazil: availability and potential uses. *Waste and Biomass Valorization*, 1(1), pp.65-76.
- [21] Qingyu, J., Yuan-bin, H., Bhattacharya, S.C., Sharma, M. and Amur, G.Q., 2007. A study of biomass as a source of energy in China. *International Energy Journal*, 21(1).
- [22] Jingura, R.M. and Matengaifa, R., 2008. The potential for energy production from crop residues in Zimbabwe. *Biomass and Bioenergy*, 32(12), pp.1287-1292.
- [23] Kainthola, J., Shariq, M., Kalamdhad, A.S. and Goud, V.V., 2019. Enhanced methane potential of rice straw with microwave assisted pretreatment and its kinetic analysis. *Journal of environmental management*, 232, pp.188-196.
- [24] Achinas, S. and Euverink, G.J.W., 2016. Theoretical analysis of biogas potential prediction from agricultural waste. *Resource-Efficient Technologies*, 2(3), pp.143-147.
- [25] Darwin, D., Cheng, J.J., Liu, Z., Gontupil, J. and Kwon, O.S., 2014. Anaerobic co-digestion of rice straw and digested swine manure with different total solid concentration for methane production. *International Journal of Agricultural and Biological Engineering*, 7(6), pp.79-90.
- [26] Fonoll, X., Astals, S., Dosta, J. and Mata-Alvarez, J., 2015. Anaerobic co-digestion of sewage sludge and fruit wastes: evaluation of the transitory states when the co-substrate is changed. *Chemical Engineering Journal*, 262, pp.1268-1274.
- [27] Kainthola, J., Kalamdhad, A.S. and Goud, V.V., 2019. Optimization of methane production during anaerobic co-digestion of rice straw and hydrilla verticillata using response surface methodology. *Fuel*, 235, pp.92-99.
- [28] Wu, X., Yao, W. and Zhu, J., 2010. Biogas and CH₄ productivity by co-digesting swine manure with three crop residues as an external carbon source. In *2010 Pittsburgh, Pennsylvania, June 20-June 23, 2010* (p. 1). American Society of Agricultural and Biological Engineers.
- [29] Elsayed, M., Andres, Y., Blel, W. and Gad, A., 2015. Methane Production By Anaerobic Co-Digestion Of Sewage Sludge And Wheat Straw Under Mesophilic Conditions. *International Journal of Scientific Engineering and Technology*.
- [30] Esposito, G., Frunzo, L., Panico, A. and Pirozzi, F., 2012. Enhanced bio-methane production from co-digestion of different organic wastes. *Environmental technology*, 33(24), pp.2733-2740.
- [31] Fonoll, X., Astals, S., Dosta, J. and Mata-Alvarez, J., 2015. Anaerobic co-digestion of sewage sludge and fruit wastes: evaluation of the transitory states

- when the co-substrate is changed. *Chemical Engineering Journal*, 262, pp.1268-1274.
- [32] APHA, 2012. Standard Methods for Examination of Water and Wastewater, 22 ed. American Public Health Association Washington, DC.
- [33] Mou, Z., Scheutz, C. and Kjeldsen, P., 2014. Evaluating the biochemical methane potential (BMP) of low-organic waste at Danish landfills. *Waste management*, 34(11), pp.2251-2259.
- [34] Parralejo, A.I., Royano, L., González, J. and González, J.F., 2019. Small scale biogas production with animal excrement and agricultural residues. *Industrial Crops and Products*, 131, pp.307-314.
- [35] Kalanatarifard, A. and Yang, G.S., 2012. Identification of the municipal solid waste characteristics and potential of plastic recovery at Bakri Landfill, Muar, Malaysia. *Journal of Sustainable Development*, 5(7), p.11.
- [36] Kalantarifard, A. and Yang, G.S., 2011. Energy potential from municipal solid waste in Tanjung Langsat landfill, Johor, Malaysia. *International Journal of Engineering Science and Technology (IJEST)*, 3(12), pp.8560-8568.
- [37] Parikh, J., Channiwalla, S.A. and Ghosal, G.K., 2007. A correlation for calculating elemental composition from proximate analysis of biomass materials. *Fuel*, 86(12-13), pp.1710-1719.
- [38] Hasan, M., Haseli, Y. and Karadogan, E., 2018. Correlations to predict elemental compositions and heating value of torrefied biomass. *Energies*, 11(9), p.2443.
- [39] Rominiyi, O.L., Olaniyi, T.K., Azeez, T.M., Eiche, J.F. and Akinola, S.A., 2017. Synergetic Effect of Proximate and Ultimate Analysis on the Heating Value of Municipal Solid Waste of Ado-Ekiti, Metropolis, Southwest Nigeria. *Current Journal of Applied Science and Technology*, 22(1), pp.1-12.
- [40] Li, Y., Zhang, R., Liu, G., Chen, C., He, Y. and Liu, X., 2013. Comparison of methane production potential, biodegradability, and kinetics of different organic substrates. *Bioresource technology*, 149, pp.565-569.
- [41] Sahito, A.R., Mahar, R.B. and Brohi, K.M., 2013. Anaerobic biodegradability and methane potential of crop residue co-digested with buffalo dung. *Mehran University Research Journal of Engineering and Technology*, 32(3), pp.509-518.
- [42] Safar, K.M., Bux, M.R., Aslam, U.M., Ahmed, M.S. and Ahmed, L.I., 2016. Energy recovery from organic fractions of municipal solid waste: A case study of Hyderabad city, Pakistan. *Waste Management & Research*, 34(4), pp.327-336.
- [43] Shruthivihahshini, N.D., 2009. Composting of papaya wastes: An anaerobic composting trial using different amendments.
- [44] Buswell, A.M. and Mueller, H.F., 1952. Mechanism of methane fermentation. *Industrial & Engineering Chemistry*, 44(3), pp.550-552.
- [45] Safar, K.M., Bux, M.R., Aslam, U.M., Muhammad, B.K. and Ahmed, M.S., 2018. Analysis of the feasibility of fruit and vegetable wastes for methane yield using different substrate-to-inoculum ratios at Hyderabad, Sindh, Pakistan. *Journal of Material Cycles and Waste Management*, pp.1-10Korai 2018

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- [46] Feng, L., Li, Y., Chen, C., Liu, X., Xiao, X., Ma, X., Zhang, R., He, Y. and Liu, G., 2013. Biochemical methane potential (BMP) of vinegar residue and the influence of feed-to-inoculum ratios on biogas production. *Bioresources*, 8(2), pp.2487-2498.
- [47] Vats, N., Khan, A.A. and Ahmad, K., 2019. Effect of substrate ratio on biogas yield for anaerobic co-digestion of fruit vegetable waste & sugarcane bagasse. *Environmental Technology & Innovation*, 13, pp.331-339.
- [48] Orozco, R.S., Hernández, P.B., Morales, G.R., Núñez, F.U., Villafuerte, J.O., Lugo, V.L., Ramírez, N.F., Díaz, C.E.B. and Vázquez, P.C., 2014. Characterization of lignocellulosic fruit waste as an alternative feedstock for bioethanol production. *BioResources*, 9(2), pp.1873-1885.
- [49] Zhao, C., Yan, H., Liu, Y., Huang, Y., Zhang, R., Chen, C. and Liu, G., 2016. Bio-energy conversion performance, biodegradability, and kinetic analysis of different fruit residues during discontinuous anaerobic digestion. *Waste management*, 52, pp.295-301.
- [50] Li, Y., Park, S.Y. and Zhu, J., 2011. Solid-state anaerobic digestion for methane production from organic waste. *Renewable and sustainable energy reviews*, 15(1), pp.821-826.