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Bioenergy recovery analysis from various waste substrates by employing a novel industrial scale AD plant

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ABSTRACT

In this novel industrial scale case study, the bioenergy recovery based on sole and mixed cow-buffalo (CBM) and potato waste (PW) substrates has been analyzed in real time, i.e., on-site on a full-scale operational anaerobic digestion (AD) plant. The plant employed in this study is a novel design, consisting of tri-digesters connected via an underground UASB type lagoon allowing it to function as a continuous-flow reactor. The system has been further equipped with CSTR, microwave heating, gas scrubbers, compression, and storage systems. The highest energy recovery readings were 123.9 m^3/1,000 kg, 77 m^3/1,000 kg, and 151.6 kWh/1,000 kg in terms of biogas, bio-methane, and electricity generated, respectively, with 75:25 ratio of CBM:PW. Operating with 100% CBM, yields of 79.9 m^3/1,000 kg, 47 m^3/1,000 kg, and 95 kWh/1,000 kg were obtained. The percentage of recovery in bio-methane production increased on using the mixed substrates, but it was the lowest with a 25:75 ratio of CBM:PW. The electrical power generation efficiency was found to be significantly increased, but not distinctively with the plant aggregate power rating that was probably associated with the variable quality of biogas which was fed to the power generator. A linear regression analysis had shown a significant and positive correlation between the rate of VS removal and biogas yield.

KEYWORDS

Anaerobic digestion (AD); bioenergy; Pakistan; sustainable energy; waste-to-energy recovery

Introduction

Anaerobic digestion (AD) has been proven to be an efficient and profitable technique for the treatment and conversion of organic wastes into energy; likewise, many lab-scale experiments have shown that co-digested organic substrates give more efficient comparative outputs of bioenergy (Esposito et al. 2012). However, the transition from laboratory experiments to pilot and industrial scale in the alternate energy sector is tedious and costly. The extrapolation of lab-scale results to a pilot scale and commercially operable AD plant often leads to deceiving results (Weiland 2010). The reasons for such failures are mostly the different operating conditions and the use of synthetic feedstock (Hosseini and Wahid 2013). These problems lead the authors to invest in a sophisticated medium industrial scale AD plant, which is more practical, convenient, and realistic R&D so to validate the results and advance more readily toward the commercial–industrial scale bioenergy generation (Song et al. 2014). In such a novel pilot scale, realistic operational conditions can be corrected on a daily basis (Hosseini et al. 2013), using online monitoring measurements (too expensive for labscale) and using real quantities and qualities of

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feedstock substrates, by providing realistic design parameters (Budzianowski 2012). As far as the performance and energy recovery from various feedstock substrates for an AD bioenergy system are concerned, it had been observed that many substrates such as fruit–vegetable wastes were digested rapidly and easily, whereas animal manure takes a longer time. In fruit/vegetable feedstock substrates, the lower TS, higher VS, and richer carbohydrate amounts present undergo a faster stage of hydrolysis which leads to an acidification stage, causing the inhibition of biogas generation (Baeyens et al. 2016; Gunaseelan 2004). Animal manures on the contrary, such as cow-buffalo dung, are abundant and easily and economically accessible. Moreover, they also provide other complementary advantages in terms of efficiency and effectiveness through their Supply chain, waste and odor management, etc. (Yang and Chen 2014). Many lab-scale studies had shown more efficiencies in terms of methane when animal manure was co-digested with other substrates such as food waste (Cuetos et al. 2011; Wang et al. 2013a, 2013b; Zhang et al. 2013; Kothari et al. 2014; Fitamo et al. 2016). In experimental studies, several tests were performed on various ratios of cattle manure (CM) to food waste (FW) so to verify the increased amount of methane with respect to various ratios, particle size, and rate of organics load. Where these had been evident that with a ratio of 2:1 of CM to FW, decreasing the FW particle size and controlling loading rate at 3 g VS/L/d, respectively; the methane recovery had been increased sufficiently (Agyeman and Tao 2014; Zhang et al. 2013a). Few other studies (Abouelenien et al. 2014; Sawasdee and Pisutpaisal 2014; Sittijunda 2015) described that agricultural wastes such as Napier grass, cassava waste, coconut waste, coffee been grounds with semi-solid chicken manure, and Napier grass with slaughterhouse waste, respectively, were co-digested at thermophilic and mesophilic temperatures, while utilization of fresh chicken manure enhanced the bioenergy recovery efficiency up to 93% compared to the control, whereas in second process the treated chicken manure was used that increased the amount of methane production up to 42% than the control. Several studies have highlighted that there are many contributing factors for an effective yield of commercialindustrial scale bioenergy recovery efficiency and enrichment such as suitable and available feedstock, effective co-digestion, and hydraulic retention time. Whereas pretreatment of substrates, their composition, and operational conditions such as temperature, pH, and design and size of the digester employed also play a vital role in enhanced recovery of biogas (Alatriste-Mondragón et al. 2006; Astals, Nolla-Ardèvol, and Mata-Alvarez 2012; Callaghan et al. 2002; Cavinato et al. 2010; Comino, Riggio, and Rosso 2012; Hinken et al. 2008; Nkemka and Murto 2010; Park and Li 2012; Pobeheim et al. 2010; Shah et al. 2015). Apart from these some researches, Akbulut (2012) and Gebrezgabher et al. (2010) also highlighted that the power proficiency of a bioenergy plant could be variable and reliant upon the power rating of the generation set. Walla and Schneeberger (2008) also showed similar facts based on their study of various 25–2,500 kW bioenergy plants; larger-scale bioenergy plants showed an increase in their relevant electrical-power efficiency. However, the major aspect that seems missing in all such earlier studies is the determination of energy productivity on a full-scale industrial plant in real time, i.e., on commercial–industrial scale plant, according to realistic operational conditions. Therefore, the objective of the current research was to monitor and investigate the energy recovery in terms of biogas and electric power based on a 150kVA generator from a medium–large-scale bioenergy plant (Figure 1) designed and installed at an industrial area near Lahore, Pakistan. Various mass ratios of feedstock substrates, i.e., cow and buffalo manure (CBM) versus potato waste (PW), were employed for this particular study.

Methodology

Determination of substrates and energy recovery

The ultimate aim of a bioenergy plant design is to maximize the methane yield based on the feedstock and the size of the plant. At this specific medium–large-scale bioenergy plant, the typical

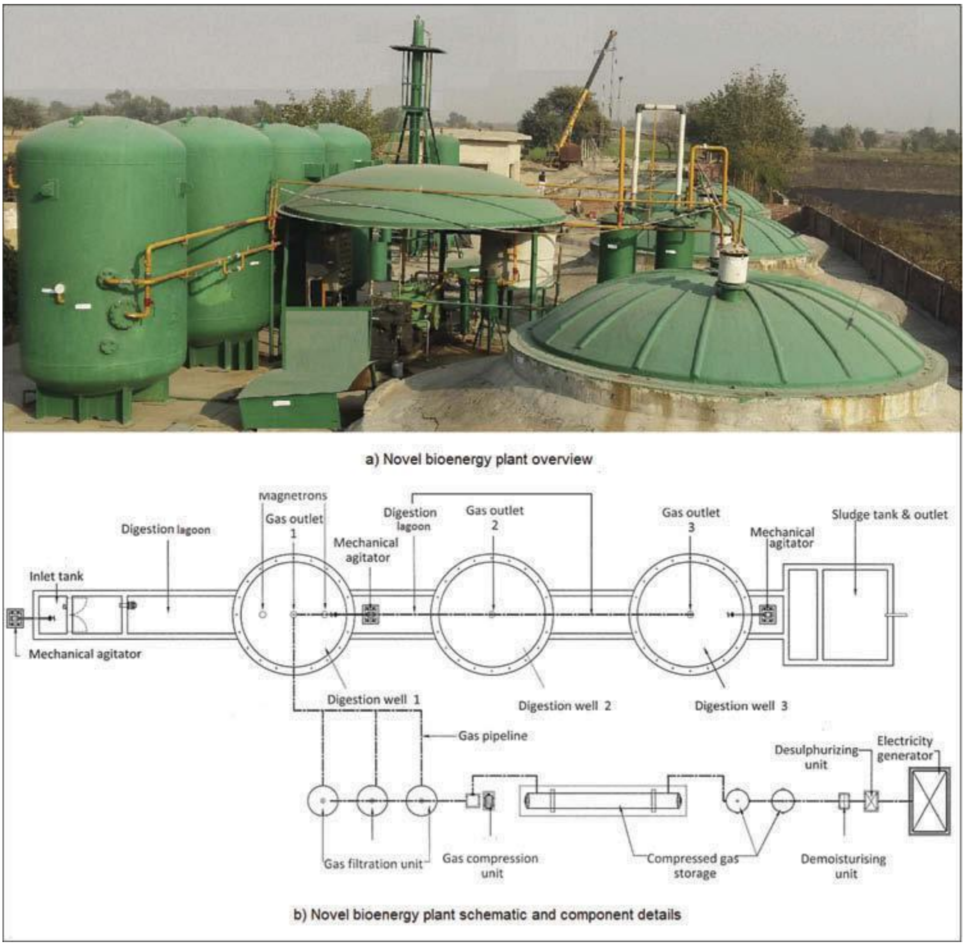

Figure 1. Novel industrial bioenergy plant installed at an industrial area near Lahore, Pakistan.

experiments for bioenergy recovery analysis have been performed for about a year with conveniently and economically available substrates, i.e., CBM and its mixture with PW in various ratios.

Substrate characterization

The AD process energy analysis experiments at the plant were performed with five substrate ratios of CBM and PW i.e., 100:00; 50:50; 75:25; 25:75, and 00:100. To attain the best bioenergy productivity and recovery, the effective operational parameters such as pH, temperature, water content, and continuous stirring were monitored and maintained within the optimum ranges. The subsequent substrate slurry samples were collected and analyzed by the lab at SDSC, GC University Lahore for determining the TS, VS, and C/N ratio as per standard methodology (Apha 1998; ECOFYS 2005). Table 1 presents all the parameters of the experiments and analysis, as also presented in references (Deublein and Steinhauser 2011; Moody et al. 2011). The COD of the relevant substrate slurries was also determined at the beginning and end of each month as per standard method-8000 using a spectrometer.

Monitoring of energy output

The capability of the plant for feedstock substrate handling was recorded as 24,000 kg. Firstly 20,000 kg of 100% CBM substrate was employed and fed to the plant that was left for 30 days to acclimatize the system. Subsequently, a further feedstock at the rate of 4,000 kg/day has been applied. To assure anaerobic

Table 1. Feedstocksubstrates' characteristics in various mixtures of cow-buffalo manure (CBM) and potato waste (PW) used in the experiments at a novel industrial scale bioenergy plant.

CBM:PW (ratios)	Wet weight (kg:kg)	TS wet basis (% avg.)	VS dry basis. (% avg.)	C/N Ratio	Temperature (°C avg.)	pH (avg.)
100:00	24,000:00	12	84	11.80	35.2	7.3
75:25	18,000:6000	11.25	86.75	15.54	35.8	6.9
50:50	12,000:12,000	10.5	89.5	19.27	36.1	6.6
25:75	6000:18,000	9.75	92.25	23.01	36.9	6.5
00:100	00:24,000	9	95	26.75	35.3	6.9

conditions at an optimal mesophilic temperature condition (35–37°C) and pH, microwave irradiations were employed in digestion well 1 for about 5–10 min intervals, i.e., after the induction of each 1,000 kg of fresh substrate against a total of 4,000 kg of substrate that was introduced daily into the reactor. To control the quality and stability of the AD reactor, the pH level of each treatment was measured after every 3 days by the installed pH probes. Similar practices were observed for all feedstock substrate ratios experimented. The cumulative energy output monitoring was performed over a period of 10 months from July 2015 till April 2016. The energy outputs have been examined and recorded in terms of mean biogas yields in m^3/ month and then further converted to electrical power (kWh/month). Identical biogas bioenergy amounts had been generated by employing dairy manure, as previously used (Kryvoruchko et al. 2009; Li et al. 2015). The monitored results are tabulated in Table 2.

Analysis of bioenergy yield

The generated biogas was stored in the biogas storage tanks. The gas volumes and pressures were measured daily with the help of installed gauges at these storage tanks. The biogas amount generated

Table 2. Energy outputrecovery of the novel bioenergy plant (mean energy amounts between July 2016 and April 2017).

Monitoring months	Feedstock-substrate used (x1000kgs)	Mean biogas recovery (m^3/1000 kg wet mass)	Mean biogas recovery (m^3/ 1000 kg of VS)	Total biogas output (m^3/ month)	Bioenergy content (kJ/ Nm^3)*	Electrical energy efficiency (kWh/ month)**
July 2016	100% CBM 120@4day	80.53	95.86	9,663	21,329.4	11,493
August 2016	100% CBM 120 @4/ day	79.33	94.44	9,520	21,329.5	11,322
September2016	75%CBM:25%PW 90:30 @1 + 3 each/ day respectively	122.97	141.75	14,756	21,951.8	18,060
October 2016	75%CBM:25%PW 90:30 @1 + 3 each/ day respectively	124.82	143.90	14,978	21,951.8	18,334
November 2016	50%CBM:50%PW 60:60 @2 + 2 each/ day respectively	112.24	125.41	13,469	20,418.8	15,334
December 2016	50%CBM:50%PW 60:60 @2 + 2 each/ day respectively	110.39	123.34	13,247	20,418.8	15,082
January 2017	25%CBM:75%PW 30:90 @1 + 3 each/ day respectively	94.28	102.33	11,328	20,535.7	12,954
February 2017	25%CBM:75%PW 30:90 @1 + 3 each/ day respectively	95.73	103.77	11,488	20,535.7	13,154
March 2017	100%PW 120 @4/day	92.81	97.70	11,138	20,303.2	13,154
April 2017	100%PW 120 @4/day	91.08	95.87	10,930	20,303.2	12,908

*The average energy content of the biogas generated was calculated relatively to 60%Vol. methane having a calorific value of 21,521.4 kJ/Nm^3.
**Based on a 150-kW power generator with 38% (avg.) efficiency.

Table 3. Recovery of specific biogas and bioenergy determined from the experimental results for various substrate ratios (all data are based on mean duplicates from two months each).

Feedstock description CBM:PW (% Ratio)	Biogas recovery (m^3/ 1000 kg wet mass)	Methane recovery % Content	Methane recovery m^3/1000 kg wet mass	% increase in Methane amount against 100% CBM	Electrical energy determined (kWh/1000 kg wet mass)
100:00	79.9*	59.1	47*	-	95.0
75:25	123.9*	62.0	77*	61.5	151.6
50:50	111.3*	54.6	61*	29.8	126.7
25:75	95.0	55.2	52	10.7	108.8
00:100	91.9	58.4	53	12.8	108.6

*Mean values which were found to be significantly different, i.e., $P < 0.05$; Tukey's HSD test.

was measured in m^3 per 1,000 kg of wet mass (Table 2). The percentage composition of the produced biogas and its CH_4 content was measured twice a week before and after the scrubbing process by using a gas analyzer GA 2000 (Geo Tech Incorporation, England). The gas analyzer had been calibrated before every reading as per standard procedure. Table 3 depicts this analysis statistically.

Statistical analysis of bioenergy recovery

Statistical analysis was performed by using the software package PASW Statistics 18. Firstly, the descriptive statistics had been executed to determine the mean values of data, standard deviations, and frequency distributions. The variances in the efficiencies of bioenergy based on various feedstock substrate compositions were tested relatively on a bimonthly pairwise data appraisal methodology. The t-test' and Tukey's HSD test were then employed by fixing the significance level, i.e., P= 0.05. MS Excel 2010 was further used for sifting and sorting of data and generating tables and charts.

Results and discussion

Bioenergy recovery from pure CBM

Bioenergy recovery in terms of biogas and methane yields against 100% CBM is shown in Figs. 2 and 3, respectively. Mean biogas, bio-methane, and electricity yields were calculated as 79.9 m^3/1,000 kg, 47 m^3/1,000 kg, and 95.0 kWh/1,000 kg (wet mass basis) respectively, during July and August 2015, i.e., months of fermentation in the continuous flow multistage digestion system. The statistical analysis demonstrated that the productivity of biogas and bio-methane generation were significantly different from other feedstock substrates experimented at the plant. The mean biogas productivity/ day (m^3/1,000 kg wet mass) against 100% CBM is shown in Figure 2. On the 17th day of digestion, the peak biogas production rate was observed against 100% CBM, and this highest biogas recovery rate was 95 m^3/1,000 kg wet mass.

Bioenergy recovery from mixed ratios of CBM and PW

Three sorts of mixed ratios of CBM and PW were applied: (i) 75% CBM+ 25% PW, (ii) 50% CBMS+ 50% PW, and (iii) 25% CBM+ 75% PW. The respective bioenergy productivities against these three mixed ratios are also portrayed in Figs. 2 and 3. After 2 months of continuous fermentation against each sort of these mixed ratios, i.e., during September–October 2016, November–December 2016, and January–February 2017, the respective mean yields of biogas were calculated as 123.9, 111.3, and 95.0 m^3/1,000 kg wet mass. Whereas the bio-methane generation recovery had been obtained as 77, 61, and 52 m^3/1,000 kg wet mass, respectively, and these calculated values significantly exceed the 100% CBM results. Within 28 days of the digestion process, about 98.9, 96.7, and 91.5% of the final biogas efficiencies, respectively, had been generated. The mean electrical energy produced against all

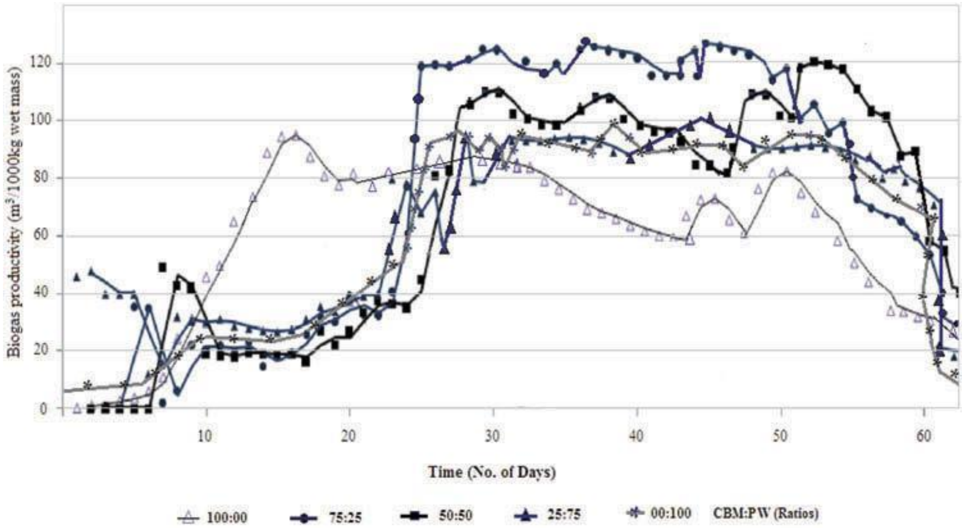

Figure 2. Biogas recovery against various experimented substrate ratios on a novel industrial scale plant.

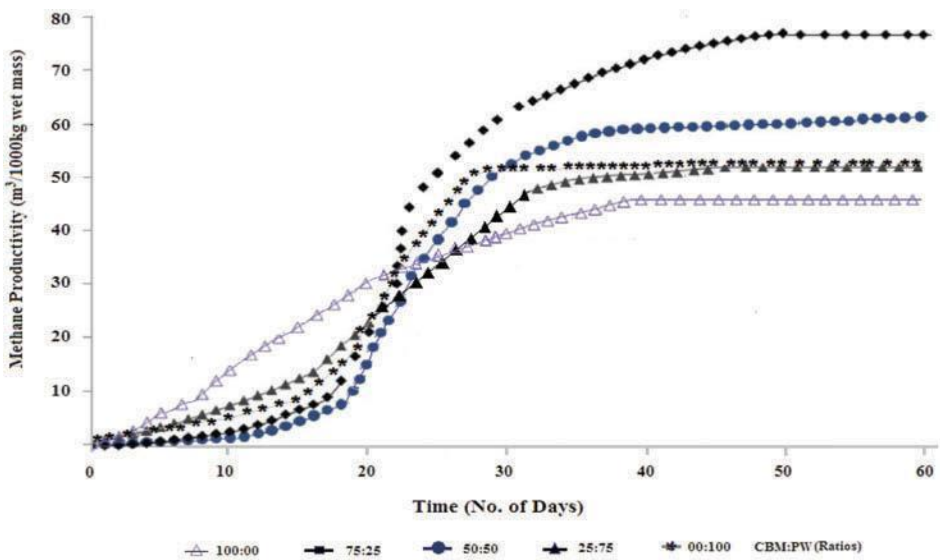

Figure 3. Cumulative bio-methane recovery against various digestion ratios of CBM and PW (on a novel industrial scale plant).

three substrate mixes recorded during the stated months was 151.6, 126.7, and 108.8 kWh/1,000 kg wet mass, respectively.

Furthermore, there was also a significant difference determined among biogas yields of all three substrates mix ratios of CBM+ PW. On the other hand, no significant difference was found among the biogas yields of 100% PW and the third mixed ratio of 25% CBM+ 75% PW. The biogas recovery/day against these three mixed substrates is depicted in Figure 2, where it was evident that 155 biogas production procedures were similar at all three mixed ratios. However, these went on at a lower rate until the 17th day. It was because of low bacterial concentration, and hence later the subsequent biogas production rates have risen with increased bacterial population and their meta-bolism progression. Between days 28 and 37 of digestion, several peaks of biogas generation rates can be seen which are quite unsimilar to the digestion of CBM alone. Hence, it could be derived that co-digestion of CBM with PW may diminish the accrual of intermediaries. It leads to a stable performance of the continuous digestion reactor, and as a result better bioenergy generation rates and productivity could be achieved (El-Mashad and Zhang 2010; Rasheed et al. 2016a, 2016b). The results of statistical analysis are also tabulated in Table 3. There was considerably steady and highest biogas energy recovery for the substrate ratio of 75% CBM and 25% PW among all feedstock – substrates mixtures. Generally, there are larger amounts of bacteria in CBM that caused progressive impacts toward the digestion and infer the higher amounts of bioenergy. Lower CBM:PW ratios lead to lower recovery. It was, hence, established that a greater fraction of CBM substrate in combination with PW caused a synergetic performance with higher and stable yields of bioenergy (Figure 2). Figure 3 depicts that in all feedstock ratios there is complete substrate degradation. The energy system was continuous. With the daily addition of 4,000 kg of relevant substrates in the reactor, the energy recovery rate gradually stabilized and then remained consistent later on the 28th day of digestion. It was evident against almost all type of feedstock substrates, indicating that the process is reliable. These bioenergy efficiencies are analogous with the results reported earlier (Parawira et al. 2005), where PWs were digested via an acidogenic reactor. Comparable results of a raised energy recovery were obtained by co-digestion of sugar-beet and PW in the initial 10 days, and average digestion period and output results are quite consistent with present study (Kryvoruchko et al. 2009). In the present study, the best results were obtained with 75:25 respective ratio and having C/N = 15.5 (Table 3). These findings are correlated with other literature deliberations (Misi and Forster 2001a, 2001b), whereas the digestion synergism when employing more than one substrate was also confirmed previously (Callaghan et al. 2002).

The corresponding amounts of electrical energy generated in the ratios 100% CBM, 100% PW, 25% CBM:75%, 50% CBM:50% PW, and 75% CBM:25% PW were calculated as 95.0, 108.6, 108.8, 126.7, and 151.6 kWh/1,000 kg wet mass, respectively. It depicts the realization potential of the system based on the best available and accessible feedstock. Likewise, their ratios can be adjusted and managed keeping in view the best energy yielding and economically optimal conditions. Similar energy yields with a two-stage AD system for various ratios of sugar beet and PW as feedstock were demonstrated (Parawira et al. 2005).

Bioenergy recovery from pure PW

The bioenergy efficiencies (m^3/1,000 kg wet mass) against 100% PW are presented in Figs. 2 and 3. Bioenergy generation from this substrate was also deliberated for a period of 2 months, i.e., MarchApril 2017. A mean biogas, bio-methane, and electricity yields of 91.9 m^3/1,000 kg wet mass, 53 m^3/1,000 kg wet mass, and 108.6 kWh/m^3/1,000 kg wet mass per month, respectively, were determined during this period. Two peak biogas generation rates were observed as 98.5 m^3 and 100 m^3 per 1,000 kg wet mass at 28th and 38th days of digestion, respectively, whereas 94.5% of the bioenergy recovery had been achieved within 28 days of initial fermentation, against this typical feedstock substrate. Moreover, as compared to 100% CBM, 75% CBM:25% PW, and 50% CBM:50% PW, significant differences were found in respect of both biogas and methane generation recovery against 100% PW (Table 3). However, no significant difference was calculated in biogas and methane yields relative to the substrate mix of 25% CBM:75% PW. Liu et al. (2009), Sanaei-Moghadam et al. (2014), and Zhang et al. (2014) also deliberated the similar bioenergy yields based on the AD of various food waste substrates.

Analytics of COD and VS reduction

The efficiency of an AD bioenergy reactor can be ascertained via COD and VS measurements, and these were also measured for all the feedstock substrates experimented and employed at this mediumlarge industrial bioenergy plant. These were observed and analyzed twice, i.e., at the commencement and at the culmination points during each 2-month period of utilization of each type of feedstock substrate as per Table 1 and Figure 4. As such the calculated aggregates of COD reduction ranged from 56.9%, i.e., the lowest value measured for 25% CBM:75% PW, to 70.6% as the highest value for 100% CBM. The average COD reduction against all feedstock substrates was about 60.3% although this percentage decreased with the decreased addition of co-substrate, i.e., potato waste. The highest COD reduction occurred for the 75% CBM:25% PW mix, where also the highest energy yield and energy productivity were obtained. Similar COD removal efficiencies of 53–70% were reported (Sanaei-Moghadam et al. 2014) for the co-digestion of press water and food waste. Other studies (Borui, Sun, and Wang 2013; Safari et al. 2011) regarding AD treatment of MSW leachate reported COD reductions in the range of 32–96% and the lower COD reductions were correlated to low organic matter loading rates. The average volatile solids eradication was deliberated as 53 and 55.6% for the substrates of 100% CBM and 100% PW, respectively. Whereas the average VS eradications in other feedstock mixtures having co-substrates were found increasing as 56.4, 62.6, and 69.5% against 25% CBM:75%, 50% CBM:50% PW, and 75% CBM:25% PW, respectively (Figure 4).

Error and regression analysis

Table 4 portrays the error analysis of the presented, i.e., bioenergy recovery efficiency versus the rate of eradication of VS on this typical industrial scale AD plant, where MAD was found as 1.12 which referred to be an adequate error value for such energy efficiency forecasts. Likewise, MSE was the calculated average of the squared forecast error and its value here, i.e., 1.5, shows that expected and predicted values have been quite close, as such data are reliable. Moreover, MAPE value, 0.02 as represented in Table 4, further strengthens the argument, as this value is easier to interpret and a smaller MAPE value indicates that the data depictions and analysis regarding bioenergy productivity have been accurate. Lay, Lee, and Noike (1999), Akkaya et al (2015), and Rahman et al. (2017) also presented similar data error analysis for their studies on hydrogen production from organic fraction of MSW; biogas generation from a UASB reactor via multiple regression model; and optimal ratio for anaerobic co-digestion of poultry droppings and lignocellulosic-rich substrates, respectively.

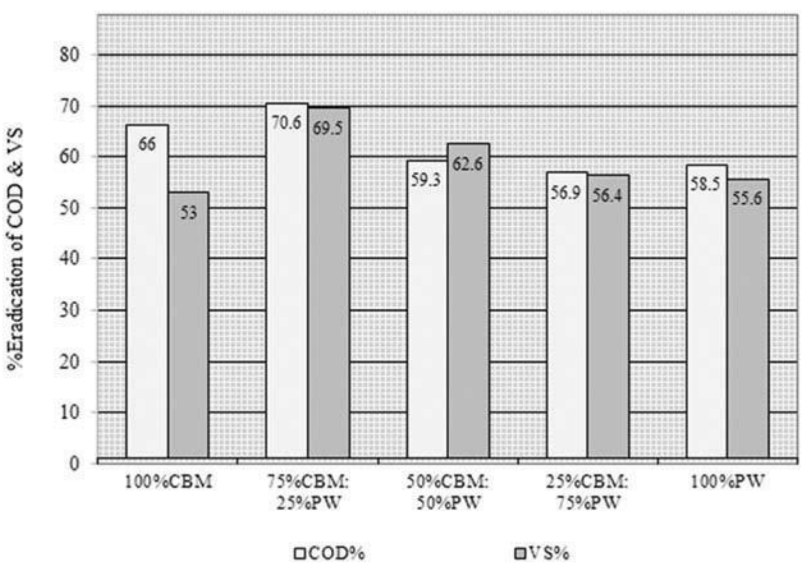

Figure 4. Destruction rates of COD and VS against various digestion ratios of CBM and PW (on a novel industrial scale plant).

Table 4. Error Analysis: Bioenergy recovery v/s eradication of VS on industrial scale plant.

Month	Biogas recovery (m^3/1000 kg VS)	% VS eradication	Forecast	Error	ABS (Error)	Squared Error	Percent Error
July 2016	94.4	54.0	53.52	0.58	0.58	0.33	0.01
Aug. 2016	96.0	52.0	54.05	−2.05	2.05	4.21	0.04
Sept. 2016	96.0	55.0	54.05	0.95	0.95	0.90	0.02
Oct. 2016	98.0	56.0	54.71	1.29	1.29	1.66	0.02
Nov. 2016	102.0	55.0	56.03	−1.43	1.43	2.05	0.03
Dec. 2016	104.0	58.0	56.69	1.31	1.31	1.71	0.02
Jan. 2017	123,0	61.0	62.97	−1.57	1.57	2.45	0.03
Feb. 2017	125.0	64.0	63.63	0.37	0.37	0.14	0.01
March 2017	142,0	69.0	69.24	−0.54	0.54	0.29	0.01
April 2017	144.0	71.0	69.90	1.10	1.10	1.21	0.02
					1.12 MAD*	1.50 MSE*	0.02 MAPE*

*MAD = mean absolute deviation; MSE = mean squared error and MAPE = mean absolute percent error.

The correlation of VS eradication and biogas yield was established using ‘linear regression analysis’ and had been plotted as shown in Figure 5. Subsequent linear regression equation and the enormous value of R^2, correlation coefficient, directed about a significant and positive correlation among the rate of VS eradication and biogas yield (Figure 5), which established that higher biogas efficiencies were dependent upon higher OM degradation and VS eradication rates. In an identical investigation by Li, Chen, and Li (2010), authors also established a linear regression correlation among rates of biogas productivity, total solids, and volatile solids. In a similar regression analysis by Akkaya et al (2015), the best correlation coefficients had been established and the relevant study, therefore, could predict accurate biogas productivity.

Conclusion

This article presented and reviewed the consistent functioning of a novel medium industrial scale bioenergy plant, in terms of energy recovery and productivity. Biogas yield and subsequent electricity

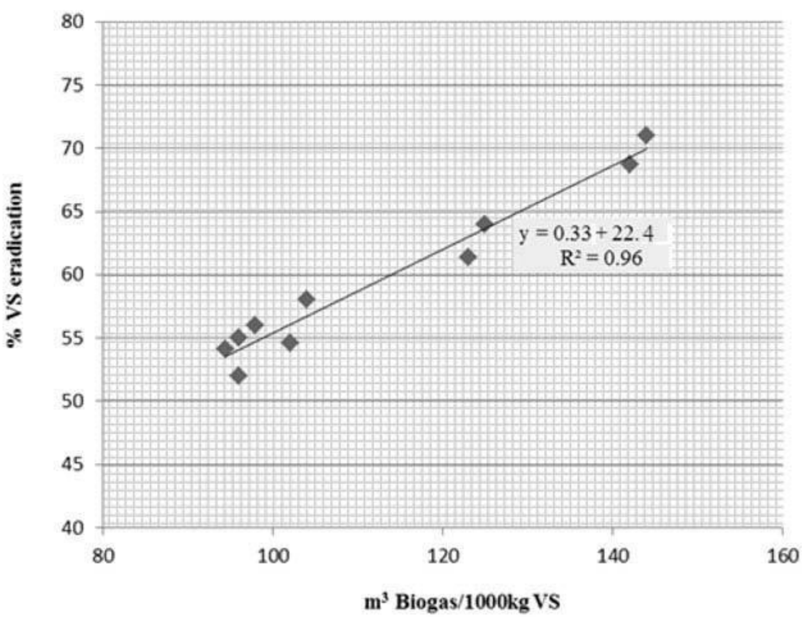

Figure 5. Correlation among bioenergy recovery and eradication of VS on an industrial scale plant.

efficiency could be optimally managed and enhanced based on available substrates in a typical regional scenario. The long-duration experimental results revealed that feedstock substrate consisting of 75% CBM plus 25% PW produced the best energy yields, i.e., 124 m^3 biogas, 77 m^3 biomethane, and 152 kWh electricity per 1,000 kg of wet mass, respectively. The system performance and recovery can be further enhanced by a more direct corrective action if a rapid high-tech online quantitative monitoring system could be used.

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