Seasonal variation in biogas production in reinforced concrete dome biogas plants with buffalo dung in Pakistan

Kandhro, B., Sahito, A. R., Nixon, J., Uqaili, M. A., Mirjat, N. H., Harijan, K., Zaman, R. O. & Kumar, L

Original citation & hyperlink: Kandhro, B, Sahito, AR, Nixon, J, Uqaili, MA, Mirjat, NH, Harijan, K, Zaman , RO & Kumar, L 2022, 'Seasonal variation in biogas production in reinforced concrete dome biogas plants with buffalo dung in Pakistan', Biomass Conversion and Biorefinery, vol. (In-Press), pp. (In-Press). https://doi.org/10.1007/s13399-022-02654-3

DOI 10.1007/s13399-022-02654-3
ISSN 2190-6815
ESSN 2190-6823

Publisher: Springer

The final publication is available at Springer via http://dx.doi.org/10.1007/s13399-022-02654-3

Seasonal variation in biogas production in reinforced concrete dome biogas plants with buffalo dung in Pakistan

Barkatullah Kandhro[1], Abdul Razaque Sahito[1], Jonathan Daniel Nixon[2], Mohammad Aslam Uqaili[3], Nayyar Hussain Mirjat[3], Khanji Harijan[4*], Rafi O Zaman[1], Laveet Kumar[4]

[1]Institute of Environmental Engineering and Management, Mehran University of Engineering & Technology Jamshoro, Sindh, Pakistan

[2]School of Mechanical, Aerospace and Automotive Engineering, Coventry University, United Kingdom

[3]Department of Electrical Engineering, Mehran University of Engineering & Technology Jamshoro, Sindh, Pakistan

[4*]Department of Mechanical Engineering, Mehran University of Engineering & Technology Jamshoro, Sindh, Pakistan

*Corresponding Author: khanji.harijan@faculty.muet.edu.pk

Abstract

In this study, a reinforced concrete dome biogas plant processing buffalo dung was functioned to investigate the seasonal variations in biogas production, biogas composition, and loss of volatile solid and methane potential of digestate slurry. These analyses were undertaken from January to May 2019. The biogas quality was assessed using gas chromatography and biogas production was measured through the G4 VuGas diaphragm gas meter while methane potential was examined on Biochemical Methane Potential (BMP) assays under mesophilic conditions. In January, when the average digester temperature was 26.1 ºC, the minimum biogas production was 0.23±0.004m^3/kg VS_{added} with 67% CH_4 and 32.9% CO_2. In May, as the average digester temperature raised to 36.1ºC and the maximum biogas yield obtained increased to 0.384±0.006m^3/kg VS_{added}, comprising 71% CH_4 and 28.8% CO_2. In the cold season during January, the percentage losses of biogas production were recorded to 41% because of lower slurry temperature and accumulation of fatty acids. The average slurry temperatures within the digester during the cold season were 21.3℃ at 6 A.M and 21.9 ℃ at 3 P.M; increasing to 36 ℃ at 6 A.M and 36.2 ℃ at 3 P.M for the warm season. In addition, the methane potential of 115NmL/g VS_{loss} was observed from the digestate slurry through BMP test. The concrete dome biogas plant is favorable for its low cost and was shown to produce adequate amount of biogas to fulfill the domestic requirements during both warm and cold months in Pakistan.

Keywords: Anaerobic digestion AD; concrete dome biogas plant; temperature; seasonal variations; biogas

1 Introduction

Pakistan is powerless despite having many resources, and in order to meet its needs, Pakistan must rely heavily on foreign imports. Many rural areas have no electricity because they are too far from the grid station and do not have access to natural gas supply. The energy mix of Pakistan has a high proportion of oil and natural gas which are assumed to be depleted in next 10 years [1, 2]. The livestock potential of Pakistan is more than 90 million buffalos and the cattle population is estimated to be 70 million. As such, the biogas potential from these animals is predicted to be around 20 thousand million cubic meters per year [3]. Biomass from animal waste can, therefore, make a substantial contribution to the overall energy mix and help in addressing the on-going energy crises of Pakistan [4]. The most feasible way for energy generation is the production of biogas through the process of Anaerobic Digestion (AD) using animal manure [5, 6].

AD is a biochemical process in which several groups of microorganisms disintegrate biodegradable organic matter in an oxygen-free environment. The process generates biogas comprising of, carbon dioxide (CO_2), methane (CH_4), and minor traces of other gases [7, 8]. Biogas can also be a viable source of energy for areas where natural gas supply is limited or not available. Animal dung and other agricultural residues are widely available waste resources, which are easily digestible and used in AD processes. Biogas systems have the potential to increase incomes in poor rural areas, enhance ecology, reduce greenhouse gas emissions, and improve sanitation. Small domestic biogas units can be used for cooking and replace the use of traditional cookstoves, which are generally inefficinet and a major source of indoor air pollution [9]. The utilization of biogas has also supported in decreasing depletion of woody biomass through energy substitutions and enhancing efficiency of energy use. By-products from the AD process include liquid and solid digestate material, which can be used as a natural organic fertilizer [10, 11].

The use of biogas in Pakistan started in 1974 when the government commenced an inclusive biogas scheme leading to the installation of around 4,137 biogas units across the country by 1987. Pakistan domestic Biogas Program (PDBP) was started in Pakistan in 2009 to support biogas as an efficient replacement of dried animal manure and traditional wood fuel for domestic utilization of cooking and heating in rural areas [12]. The installed plants were typically large floating drum biogas plants with 5-15 cubic meters of gas production per day. Another 4016 biogas plants were installed until 2002-2012 with assistance from the Pakistan Centre for Renewable Energy Technologies (PCRET) [13]. In addition to these biogas plants, 14,500 biogas plants were installed till 2018 by the Rural Support Program Network [14]. However, the floating drum and biogas plant types are the most common technologies in Pakistan, but fixed dome plants have some benefits over floating drum type biogas plants as they are more simple, robust and low cost [15].

Fixed dome biogas plants have been constructed and functioned effectively in sub-tropical and tropical regions at ambient temperatures [16], but, their performance is highly dependent on various chemical and environmental factors such as the temperature, C/N ratio, pH, mixing, hydraulic retention time (HRT), volatile fatty acids (VFAs), total solid (TS) and volatile solid (VS) content of the feedstock. A neutral pH is suitable for the biogas production, as most methanogen increases at an optimal pH range of 6.8-7.2 [17]. The pH value can be increased to above optimum level by an increase in ammonia concentration which is produced during decomposition of proteins while the value of pH decreases with accumulation of VFA. Feedstock and equilibrium of carbon sources and supplementary nutrients such as sulfur, phosphorus, and nitrogen are also essential. The C/N ratio must be about 20-30. Excessive rise or decline in C/N ratio upsets production of biogas. The solid content in the digester should be maintained in between 7% and 9% [17]. The HRT must be sufficiently extended to ensure that the quantity of microbes removed with the digestate is not higher than the amount of reproduced microbes. The HRT and anaerobic digestion process temperature are directly relative to each other.

Temperature control is a key challenge as it significantly affects the physicochemical and biochemical processes in AD, hence influencing economic viability and energy recovery. Anaerobic digestion is usually characterized by four temperatures: psychrophilic <20 ^{o}C, psychotropic (20-30 ^{o}C), mesophilic (30-40 ^{o}C), and thermophilic (45-60 ^{o}C) [18]. These temperatures ranges affects the metabolic process in AD by various microbes such as hydrogenotrophic, acidogenic, acetogenic and methanogenesis. This means that temperature variations may rise or sort out the imbalance amongst metabolic processes [19]. We know that AD systems work best when temperatures are consistent, as most methanogenic bacteria grow under mesophilic conditions [20]. Digester conditions in tropical and subtropical areas, especially high altitudes, are psychotropic or psychrophilic in winter season and CH_4 production rate is therefore lower in winter season. Under low temperatures, in winter, the accumulation of VFAs, and digesters can be acidic thus reducing biogas production [21-23].

At present, 5350 biogas digesters of various size ranging from 3 to 15 m^3 are functioning in Pakistan [24]. Most of the plants are fixed-dome type and floating drum type operated on single substrate (poultry or cattle manure based). As there performance among other things depends heavily on ambient temperature because these plants are operating without any heating system for temperature control [25]. Climate of Pakistan is a continental type of climate containing various major seasons: a hot, dry spring from March through May; the summer rainy season, or southwest monsoon period, from June through September; and the retreating monsoon period of October and November; a cool, dry winter from December through February. The average temperature during June is above 30 ◦C [26], which is about optimal for production of biogas [27]. However, temperatures begin to decline from September to February (winter). In winter, the average temperature is below 15 ◦C [26], and low winter temperatures may affect anaerobic digestion performance. To date, many previous studies [28, 29] on the effect of seasonal temperature on anaerobic digestion have been performed on laboratory scales, and studies with domestic scale digestion are very rare. In addition, little information is available on how changes in ambient temperature affect the temperature of the full-scale anaerobic digestion process. Castano et al. [30] and Ihara et al. [31] found an improvement in biogas production through an increase in ambient temperature in the field-scale digester. Kalia et al. [32] examined the performance of the dome biogas plant under seasonal temperature fluctuations and found that declining temperatures from summer to winter results in lowering digester temperatures.

They observed that the digester temperature below 20°C produced less biogas and CH_4 content. On these temperatures the digester also showed signs of unstable performance with increased concentration of volatile fatty acids and decreases pH and alkalinity. These studies suggests the constant and lower organic loading rate for stable operation at lower temperature to achieve comparable gas production as those obtained at mesophilic temperatures [30]. Whilst the biogas production at mesophilic and thermophilic conditions have been well studied, knowledge of those in psychrophilic and psychotropic temperatures is limited in Pakistan.

To address this research gap, this study evaluated the performance of domestic biogas plants using lower organic loading rate under seasonal temperature variations in Pakistan conditions. For that experiments were conducted to monitor the effect of seasonal temperature variations inside the concrete dome biogas plant and its effect on biogas production, VS reduction, and an analytical parameters as domestic biogas plants could be better managed in various climatic conditions. The aim of this research is to evaluate the effect of seasonal temperature variations on a performance of domestic reinforced concrete dome biogas plant treating cattle dung installed at Khaskheli village, Hyderabad, Pakistan. The specific objective of this research included the assessment of the biogas quality and quantity, VS loss at various temperature variations, and CH_4 potential of digestate slurry through BMP. Section 2 provides the method and materials used in this study. The results are discussed in section 3, and the conclusions drawn from this research are summarized in section 4.

2 Materials and methods

In this study, concrete dome biogas plant processing buffalo dung was constructed at Khaskheli village at geographical position 25.456786° N, 68.365135° E in the Hyderabad district (Fig. 1). This location's economy is highly dependent on agricultural crop production and cattle farming. The site was selected by considering the unavailability of natural gas supply, sunlight, and there was sufficient animal manure and water available for the biogas plant operation.

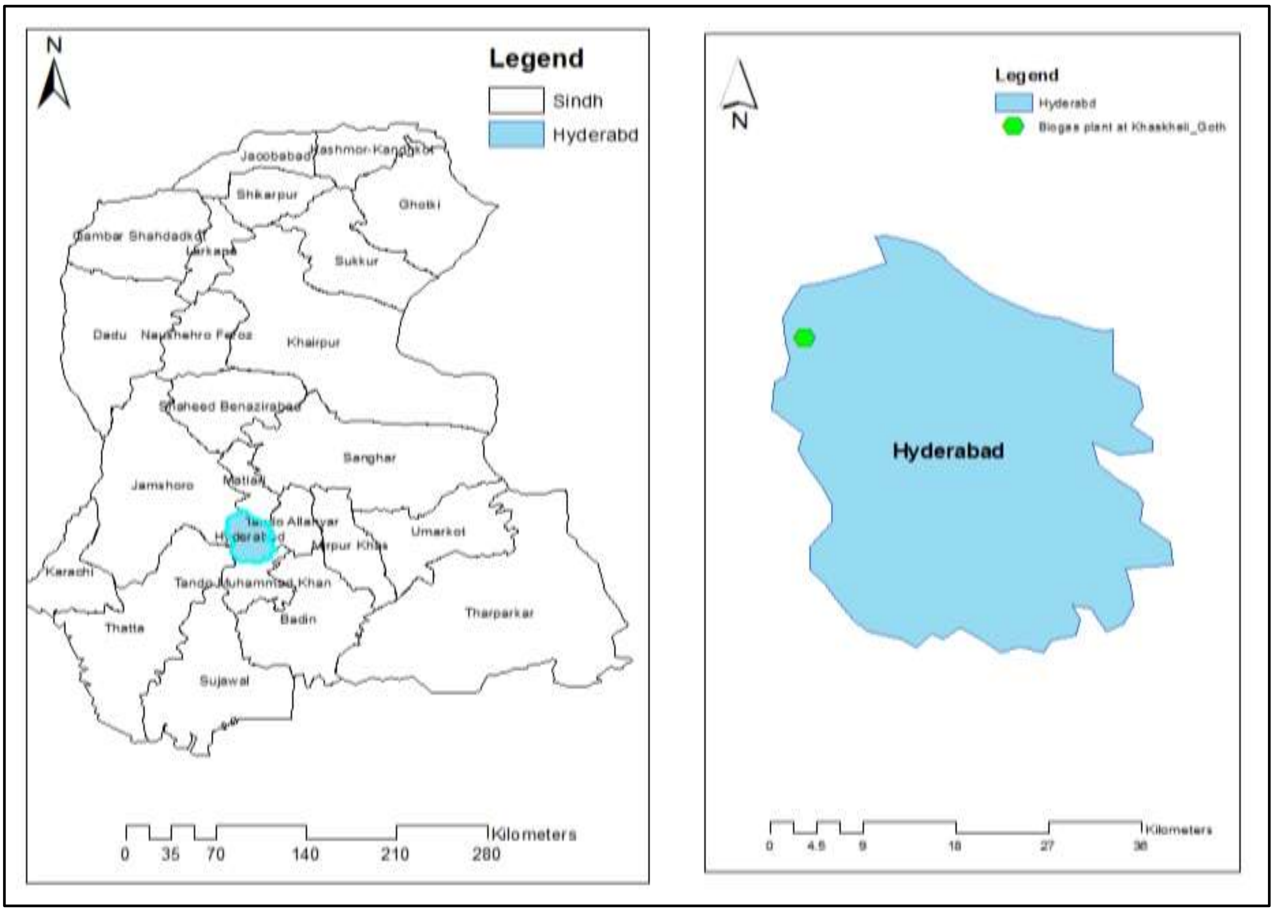

Fig. 1 Site selection of reinforced concrete dome biogas plant located at Khaskheli village in Hyderabad

The reinforced concrete dome biogas plant consists of inlet tank, digester pit, gas holder, outlet tank, and compensation pit. These digesters require specialized labor for construction and relatively low investment costs. The construction materials were acquired from the nearby towns. The dimensions of inlet tank was 1.5 ft. dia and 2 ft. height. The digester tank were 2.8 ft. depth and 8.8 ft. dia with total working volume of 4.4 m^3. The gas volume was 1.2 m^3 as gas holder were 8.8 ft. diameter and 2.1 ft. height. However, an opening of 1.9 ft.×1.9 ft. was placed for manhole to discharge the slurry into outlet tank (Fig. 2).The biogas generated from the plant was used for the domestic cooking purposes.

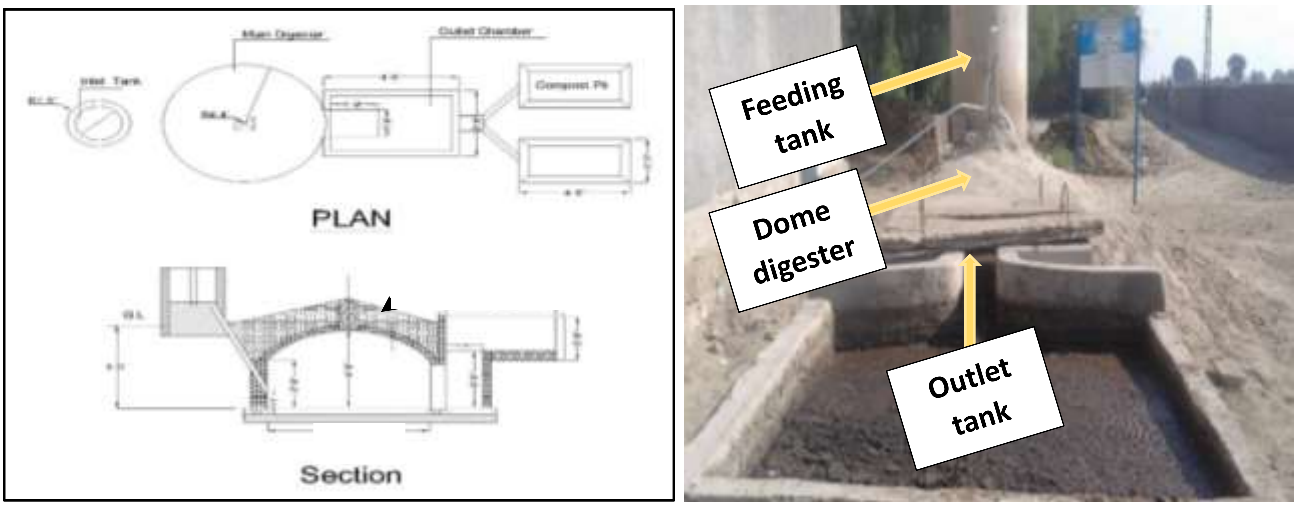

Fig. 2 Schematic diagram of concrete dome biogas plant with plan view and section view and Photograph of Dome biogas plant

Initially, the biogas plant was charged upto 75% of its volume with the homogeneous mixture of dung and water at the ratio of 1:1. After stabilization of plant, 45 kg of animal dung with 45 liters of water was fed daily. The sample of this mixture was weekly analyzed in the laboratory during the study period. The biogas yield was continuously monitored from the seventh week following the initial charging.

2.1 Measurement of biogas production

The volume of biogas produced from the anaerobic digestion process was monitored using a wet gas meter [33]. The wet type gas meters are based on the principal of liquid displacement and most common method for measurement of the biogas [34, 35]. In this study, a G4 VuGas diaphragm gas meter was used, which measures continues flow of gas through the meter. The VuGas meter has steel case design 110mm centers, Q_{max} 6 m^3/Hr, Q_{min} 0.04 m^3/Hr, 0.5 bar max pressure, 55 ^oC maximum temperature. It comprises of measurement chambers linked together to form a unit that is separated by a diaphragm wall. A rotating piston connects these diaphragms with each other and the quantity of gas passing through the diaphragm meter can be directly measured. The diaphragm meter was connected with a 1-inch galvanized iron pipe to the dome of the biogas plant. The amount of biogas produced in 24 hours was measured on a daily basis. The biogas generated from the plant was saturated with water vapour, as such, a water drain was used to condense and remove water vapours in the plant.

2.2 Estimation of methane by gas chromatography (GC)

The biogas sampling bags were used to collect the biogas samples from the biogas plant installed in khaskheli village. The biogas samples were analysed through the Gas Chromatograpgy (GC) to measure the composition (like CH_4 and CO_2 content) of biogas. The chromatograph (GC-2010 plus SHIMADZU) with thermal conductivity detector (TCD) and capillary column (Rt-Q-BOND 30m, 0.53mm ID, 20m df) were used. The GC was charged with a biogas sample of 500 µL with a gas-tight microsyringe (500 RGSG, SGE analytical science). The temperatures were adjusted at 250 ℃ for both the injection port and detector, and 60℃ for the column. The inject mode was set for gas chromatograph at a split ratio of 18.0. Gas samples were transported in a separation tube column. The detector was set at negative polarity to measure the quantity of the biogas components. Further, nitrogen gas with a flowrate of 8.60 mL.min^{-1} was used as a carrier gas [36].

2.3 Loss of volatile solids

The efficiency of the biogas plant was assessed by measuring the loss of volatile solid, the degree of degradation VS_{loss} can be calculated as shown in eq. (1).

$$VS_{loss} = 1 - \frac{VS_{output} \cdot (1 - VS_{input})}{VS_{input} \cdot (1 - VS_{output})} \qquad (1)$$

Where, VS_{loss} is the volatile solid's degree of degradation (%), VS_{output} is the volatile solids concentration of the output (% of TS), and VS_{input} is the volatile solids concentration (sometimes also termed as loss on ignition) of the input (% of TS). The degree of degradation in continuous concreted dome biogas plant can be calculated using equations found in [37].

2.4 Analysis and calculations

The moisture content (MC), total solids (TS), volatile solids (VS), and ash content (AC), VFA, total alkalinity (TA), and pH were analyzed by employing standard methods [38]. The samples were collected in culture glass bottles from the inlet and outlet tank of the biogas plant. The pH of feed slurry and effluent were measured off-site by using pen type pH meter (Lutron pH-223). A sample supernatant was used for analyzing the digestate alkalinity on titration method and VFA on distillation method. The slurry temperature and atmospheric temperature were measured using a digital thermometer (HTC-2). The MC was estimated by weight loss of substrates once evaporating the moisture content at 105 °C for 24 h till it stabilized. The difference between the initial weight before evaporation and final weight after evaporation gave the MC of the substrate. The TS, VS, and AC content were determined on gravimetric method by heating a sample at 105 ºC for 24 h for TS. The VS and AC were determined through ignition of the residue produced in TS analysis to constant weight in a muffle furnace at a temperature of 550 ºC for 2 h. The ultimate analysis including oxygen (O), carbon (C), nitrogen (N), hydrogen (H), and sulphur (S) were determined in animal dung by Flash EA 1112 Organic Elemental Analyzer.

2.5 Biochemical methane potential test

The (BMP) Biochemical methane potential test is the measure of volume of CH_4 that is produced as the decomposition of the volatile solids present in digested slurry. The digested slurry samples were used as inoculum and collected from outlet tank of concrete dome biogas plant processing buffalo dung. BMP comprises the incubation of a small amount of substrate along with the source of energetic CH_4 producing bacteria (methanogens) [39]. The batch experiments were conducted for three months (January, March, and April) to assess the methane potential in digested slurry that could still be produced in these months. The BMP assays were prepared in 500 mL borosilicate glass bottles, the borosilicate bottles were used as reactors and operated at 37 ± 1°C. The glass bottles were then joined to the CO_2 absorption jars, which were filled with the mixed solution of NaOH and Thymolphthalein. The reactor bottles were filled with 400mL of inoculum and were hermetically sealed [40]. The electric motors attached to the borosilicate glass bottles stirred the effluent at a speed of 70 rpm. The electric motors running time was set to 1 minute every 30 minutes. Before commencing the batch reactor process,anaerobic conditions were created in the bottles by purging the system with nitrogen gas for upto 5 minutes to remove any oxygen content [41, 42].

2.6 Statistical Data Analysis

Statistical data analysis for this study was performed using SPSS version 21 software. Most common and helpful statistical tools such as Pearson correlation and principal component analysis (PCA) were calculated. Correlation was measured for the parameters such as temperature, gas production, VFA, VS, TS and Alkalinity. PCA was performed by selecting principal component method with eigen value greater than 1. The rotation method used for PCA was equamax and variance was measured with parameters.

2.7 Economic assessment

Economic assessment involved cost of construction and installation that were mainly based on the local standard market prices of construction components. The components cost were used to estimate the construction cost of household fixed dome biogas plant. The economic comparison was also estimated by using the initial capital cost of biogas plant and operational costs.

3 Results and Discussion

3.1 Characteristics of feed and effluent slurry at seasonal temperature variations

The fresh buffalo dung was acquired from cattle farm and equal amount of water was added to make a (1:1) ratio feed slurry. The four (04) number of feed slurry and effluent slurry samples per month were collected on weekly basis for five (05) months. These samples were analysed for TS, VS, TA, pH, and VFAs on seasonal variations as presented in Table 1. However, the biogas production, ambient and slurry temperature were measured on daily basis and results were taken as average. In this study, a pH value ranging from 7.05-7.2, followed by TA and VFA which were 1517-1937 mg $CaCO_3$/L and 253-578 mg CH_3COOH/L, respectively, are also shown in Table 1. A low pH value in the digester can cause an accumulation of VFA, which results in the suppression of the anaerobic digestion process, while ammonia nitrogen increases at a high pH value, which can reduce methane production and it can inhibit methanogens due to toxic conditions [43]. The different pH ranges are required for anaerobic bacteria for their growth, e.g., a comprehensive pH range of 4.0–8.5 is essential by fermentative bacteria while a limiting range of 6.5–7.2 is favourable for methanogens' growth [44, 45]. As such, a pH value of 6.5-8.5 is essentially required for the AD process to be accomplished effectively [46]. It may also be noted from the Fig. 3, that the pH values are taken as monthly average for the 05 months (January-May) and the average values are nearly same therefore, the three values are close to 7. Moreover, TA and VFAs concentration were fluctuated because of seasonal variations. In January, the slurry temperature is close to 21-22 ºC whereas the slurry temperature is about 36 ºC during May. However, the TA of the plant had decreased in January and February due to the accumulation of volatile fatty acids and increased in April and May due to reduction in VFA concentration as shown in Fig. 3. These results are very similar to Fernandes [47], showing that as the alkalinity increases the VFA concentration reduces due to accumulation of ammonia. El-Fadel et al. [48] and Ossa-Arias et al. [49] observed that pH did not decrease when VFA concentration increased and TA decreased at digester temperature of 20 ºC. The VFAs which mainly include propionic acid, acetic acid, valeric acid, and butyric acid are the main intermediate products during AD of organic wastes [50, 51]. Usually, VFAs produced in the anaerobic process could be ultimately converted into CH_4 and CO_2 by methanogenic bacteria and syntrophic acetogens. Therefore, the VFA/TA ratios are in fact key parameters for monitoring the stability of the digester. The VFA/TA ratio of 0.5 or less indicates the safe working zone in the AD process [52, 53]. This study results illustrate that VFA/TA ratios were also less than 0.5 and recorded in the range of 0.13-0.36 (Table 1) during the study period. The outcomes indicated that the biogas plant was in a stable operation during the period from January to May 2019. In addition, the TS and VS represent the solid content of the digester. The quantity of biogas was measured in terms of OLR and loss of VS. The biogas production was obtained 0.23±0.004 m^3/Kg VS_{added} when digester was fed with OLR of 0.41±0.02 Kg VS/m^3/d and VS loss of 55.6%. Later on, it was observed that as the OLR increased from 0.41±0.02 to 0.51±0.029 Kg VS/m^3/d, the biogas production increased from 0.23±0.004 to 0.384±0.006m^3/Kg VS_{added} and VS loss of 68%. Besides, the TS_{in} content is maintained in the range of 6.5-8%. The biogas production is low at the higher TS concentration because of the accumulation of VFA as compared to lower TS concentration [54]. This study reveals that the highest biogas can be produced if water to dung ratio is kept as 1:1 beside higher destruction of VS. Therefore, the higher destruction of the VS produces more quantity of the biogas. The more production of biogas does not mean that more quantity of the methane has been produced. Sahito et al. [55] stated that the maximum methane can be produced if water to dung ratio is kept as 2.0. On the contrary, as the fixed dome biogas plants and floating drum type biogas plant cannot handle the dung to water ratio of 2.0 (high solids), thus for only floating drum type and fixed dome type biogas plants the water to dung ratio of 1:1 was found to be more suitable.

Table 1. Characteristics of feed slurry and effluent slurry with Mean ± STDEV (n), n = number of sample

Parameters	Unit	Range	January	February	March	April	May
pH	-	7.05-7.2	7.1±0.09(4)	7.05±0.05(4)	7.1±0.05(4)	7.1±0.05(4)	7.2±0.07(4)
TS_{in}	(%)	6.5-8	6.5±1.15(4)	6.8±0.5(4)	7.3±0.39(4)	7.5±0.61(4)	8±0.27(4)
TS_{out}	(%)	2.1-3.6	3.5±0.6(4)	3.25±0.95(4)	2.1±0.9(4)	3.6±1.1(4)	3.3±0.08(4)
VS_{in}	(%)	85.5-88.5	88±1.82(4)	85.5±0.86(4)	86±1.65(4)	88±1.25(4)	88.5±0.5(4)
VS_{out}	(%)	69-74.5	74.5±2.64(4)	69.7±1.92(4)	69±3.20(4)	72±1.79(4)	71±0.83(4)
TA	mg $CaCO_3$/L	1517-1937	1584±126(4)	1517±81(4)	1830±269(4)	1895±168(4)	1865±176(4)
VFA	mg CH_3COOH/L	253-578	578±45(4)	530±30(4)	406±11(4)	273±8(4)	253±15(4)
VFA/TA	-	0.13-0.36	0.36±0.012(4)	0.34±0.011(4)	0.22±0.008(4)	0.14±0.005(4)	0.13±0.007(4)
Biogas	m^3/Kg VS_{added}	0.23-0.384	0.23±0.004(4)	0.239±0.002(4)	0.272±0.008(4)	0.301±0.005(4)	0.384±0.006(4)

VS loss		%	55.6-68	55.6±2.09(4)	60.7±2.01(4)	62.7±1.04(4)	65±1.9(4)	68±1.7(4)
OLR		Kg *VS*./m^3/d	0.41-0.51	0.41±0.02(4)	0.42±0.022(4)	0.46±0.023(4)	0.48±0.021(4)	0.51±0.029(4)
T_{slurry}	6A.M	ºC	21.3-36	21.3±1.12(30)	22.9±2.18(28)	28±1.85(30)	32.5±1.35(30)	36±0.52(30)
	3P.M	ºC	21.9-36.2	21.9±0.92(30)	24.6±2.16(28)	28.7±1.81(30)	32.9±1.34(30)	36.2±0.55(30)
$T_{ambient}$	6A.M	ºC	10.2-27.2	10.2±1.95(30)	12.9±1.96(28)	17.3±2.76(30)	23±1.89(30)	27.2±0.89(30)
	3P.M	ºC	24-40	24±3.49(30)	30.6±3(28)	35.2±3.71(30)	39.2±2.31(30)	40±1.31(30)

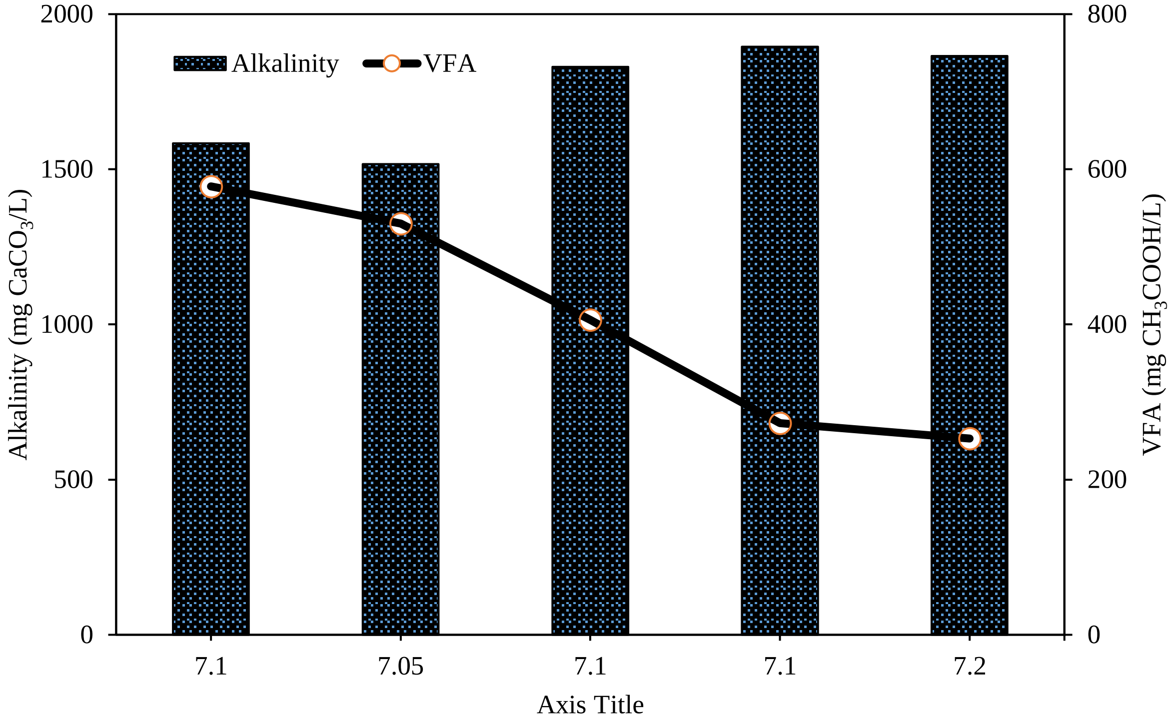

Fig.3 Relationship between pH, alkalinity, and VFAs in digester

3.2 Proximate and ultimate analysis of animal dung

Tables 2 represents the results of the proximate and ultimate analysis of animal dung. The MC of the animal dung was achieved to 81.73 % on wet basis. This indicated that the substrates had enough moisture content for AD. The TS, VS, and AC of animal dung were recorded to 18.27%, 78.51%, and 21.47% respectively. Proximate analysis results showed that the characteristics of the biomass were in the optimum range. The results indicated high percentage of MC, TS and VS which shows that animal dung are easily biodegradable and thus are feasible for anaerobic digestion to yield energy in terms of biogas. The ultimate analysis results of animal dung for C, H, N, and S content are represented based on the percentage by weights whereas, the % O content was determined as per difference basis. Therefore, the oxygen content by weight was not part of the nutrients analyzed because the anaerobic digestion system took place in the absence of oxygen. The C content of the animal dung was the dominated having 37.72 % on dry basis. Whereas, the H, N, S, and O content were detected to be 4.14, 1.67, 0.53, and 29.45 % respectively. The results of present study are in accordance to literature [56-58].

Table 2. Chemical composition represents proximate and ultimate analysis of animal dung

Proximate analysis				**Ultimate analysis**					
MC (%)	TS (%)	VS (%TS)	AC (%TS)	C (%)	H (%)	N (%)	S (%)	O (%)	C/N
81.73	18.27	78.51	21.47	37.72	4.14	1.67	0.53	34.45	22.5

Furthermore, the C/N ratio was a vital aspect in nutrients balance and bacteria strength in the AD process. The AD process requires an optimum C/N ratio. Most substrates were within the range of 15–30 which is optimum, except for bagasse, wood, and sawdust that revealed C/N ratio of 165.81, 200.64, and 230.89 respectively [59]. The current results demonstrated that the C/N ratio was estimated to 22.5 which is found to be in optimal range. However, the C / N ratio within 15-30 degrees promotes higher digestive stability because the higher carbon content provides the nutrients needed for bacterial growth and thus increases biomethane production. The high carbon content causes an increase in the formation of carbon dioxide, which ultimately lowers the pH due to the high C / N ratio that exceeds the optimum range. Biomethane production decreases with low pH because low pH creates an unfavorable environment for methanogenic microbes [59]. In contrast, a lower C / N ratio than the appropriate range indicates higher nitrogen to carbon content (faster use of nitrogen by methanogens). This will lead to the accumulation of ammonia in the digester which leads to an increase in pH above 8.5 which can inhibit the metabolism of methane-forming bacteria and lead to the production of low methane [59, 60].

3.3 Effect of slurry temperature on biogas production and composition

The average biogas production during January and February was comparable with 0.23-0.239m^3/kg VS_{added} with digester average temperatures of 21.6-23.7℃, respectivlty. In March, biogas production was 0.27m^3/kg VS_{added} when the average digester temperature was 28.3℃. The highest biogas production was obtained 0.384m^3/kg VS_{added} at the maximum slurry temperature of 36.1 ºC. In May, a 41% increase in biogas yield was observed when the digester average temperature increased to 36.1 ºC. The growth in biogas production was owing to rise in slurry temperature, more methanogenic bacteria, and increased bacterial activities [3]. The total amount of biogas required for the household was 1.5 m^3/d and the total biogas produced during the winter season was 0.23-0.239m^3/kg VS_{added} that contributes to 47% of home demand without heating system. While in the summer season it was 0.384m^3/kg VS_{added} that met to 75% of home demand without heating system. The biogas production could be enhanced by using heating systems in digester to maintain the favorable temperature range of 30–40 °C for optimum biogas production during winter. These systems are needed to reduce the temperature fluctuations in the digester and maintain the digester slurry temperature at optimum mesophilic conditions throughout the winter season. Hence, the installation of these systems in biogas digesters could increase the biogas yield by 41% during winter season. Therefore, the biogas plant would contribute to 75% to total energy needs of the home for cooking and heating during winter season with heating systems but without heating system the slurry temperature was 36.1 ºC during summer season in Pakistan. Fig. 4 shows the average biogas production at varying digester temperatures during winter and summer (January to May 2019).

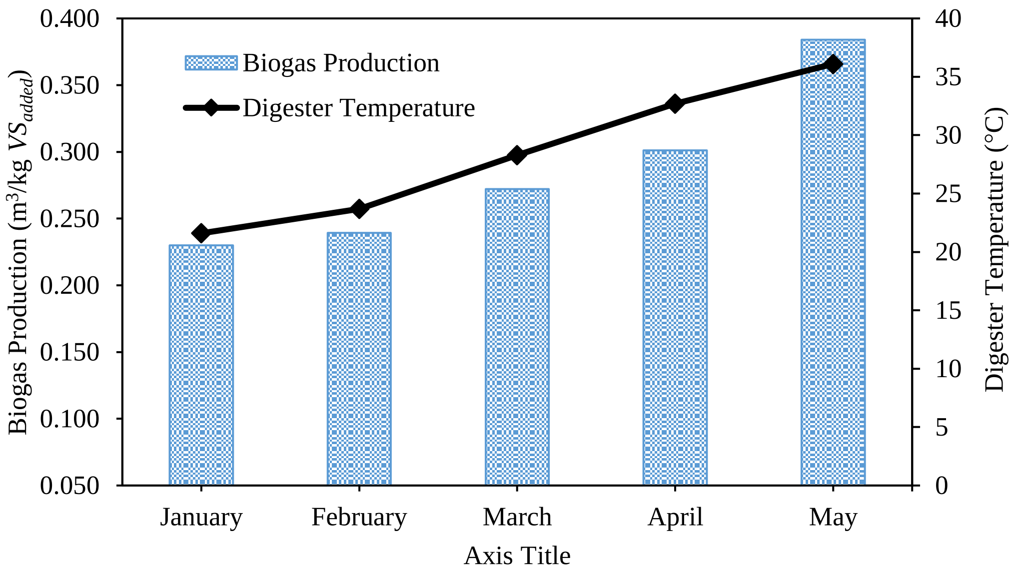

Fig. 4 Average biogas production at varying digester temperatures during winter and summer

The biogas quality during the first seven weeks (January and February) of the biogas plant revealed the concentration of CH_4 as 67-70%, CO_2 around 32.8- 32.9% and traces of other gases were between 0.1-0.2%, which is very minute and are not considered in this research study. The maximum averaged values for CH_4 content were 70-71%, for CO_2 were 28.8-28.9%, during the March to May 2019 as shown in Fig. 5. The CH_4 concentration was therefore relatively stable throughout the test, but around 3-4% lower during the winter due to lower temperatures of digester in winter season. The lower temperature of digester indicates that the conversion of organic material to CH_4 content was less because of slow degradation of organic material.

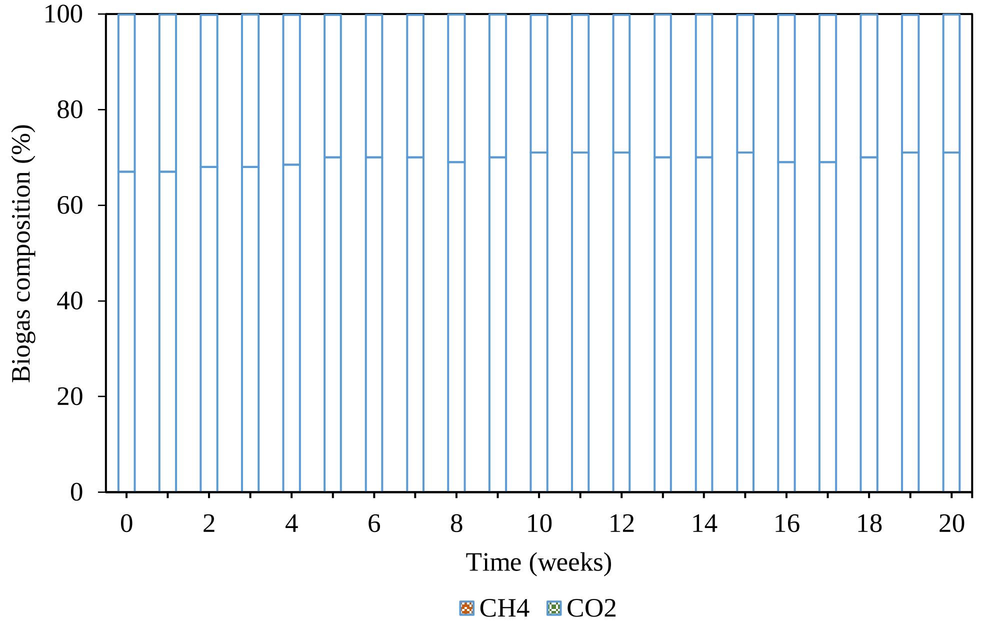

Fig. 5 Biogas composition of reinforced concrete dome biogas plant

3.4 Comparison of atmospheric temperature with slurry temperature

Insulating and burying the digester underground helps to maintain a more consistent tank temperature [61]. Fig. 6 shows the slurry temperature and atmospheric temperatures recorded at 6 A.M and 3 P.M on a daily basis for the study period to monitor the day and night fluctuations in digester temperature. In present study, the average slurry temperatures were recorded to be 21.3℃ at 6 A.M and 21.9 ℃ at 3 P.M during the month of January. Whereas the average slurry temperatures were 22.9, 28, 32.5, and 36 ℃ at 6 A.M and 24.6, 28.7, 32.9, and 36.2 ℃ at 3 P.M during the months of February, March, April, and May respectively. The average atmospheric temperature recorded was 10.2 ℃ at 6 A.M and 24 ℃ at 3 PM during the month of January while the average atmospheric temperatures were 12.9, 17.3, 23, and 27.2 ℃ at 6 A.M and 30.6, 35.2, 39.2, and 40 ℃ at 3 P.M during the months of February, March, April, and May respectively.

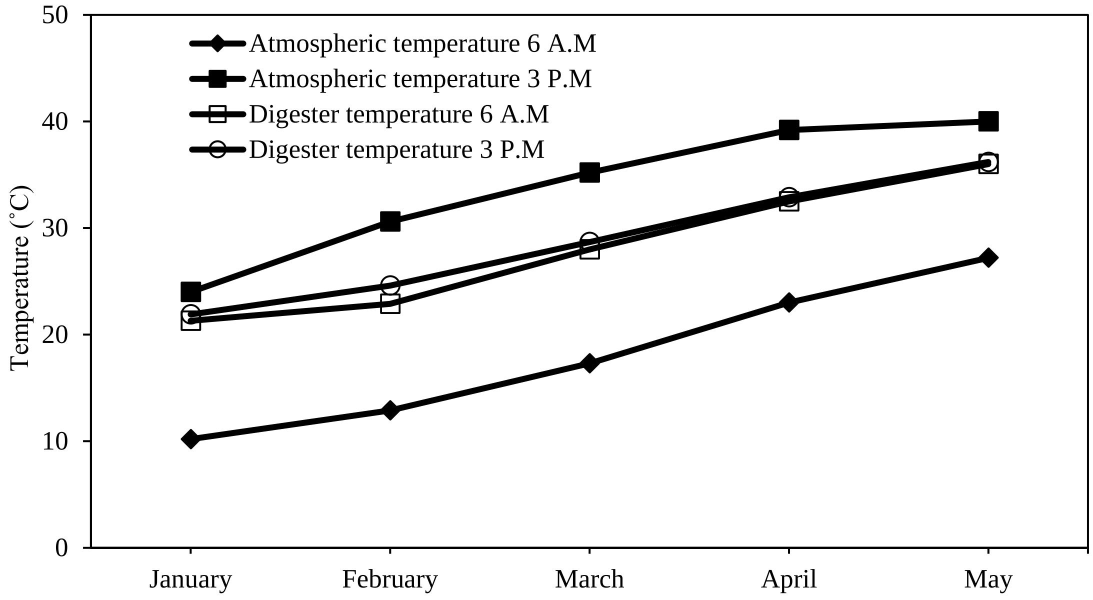

Fig. 6 Average monthly slurry temperature comparing with atmospheric temperature

The average slurry temperature within the digester was 21.3℃ at 6 A.M and 21.9 ℃ at 3 P.M during the month of January (cold season). The average slurry temperature of the digester remained stable during day and night except minor variations of +0.6℃. Whereas, the average atmospheric temperature was 10.2 ℃ at 6 A.M and 24 ℃ at 3 PM during the month of January. In addition, the average slurry temperature within the digester during the month of May (warm season) was 36 ℃ at 6 A.M and 36.2 ℃ at 3 P.M except with minor difference of 0.2℃. While average atmospheric temperature was 27.2 ℃ at 6 A.M and 40 ℃ at 3 P.M during May. However, the slurry temperature is stable during day and night whilst atmospheric temperature highly fluctuate. These results illustrate that the digester slurry temperatures were relatively stable from January to May 2019 in comparison to ambient temperatures. As the digester average temperatures remained above 20℃, which is sufficient to produce a viable amount of biogas, the results indicate that fixed-dome biogas plant can operate effectively throughout the year in Pakistan.

3.5 Effect of slurry temperature on VS loss

The VS loss represents the fraction of the organic material utilization during anaerobic digestion process. The effect of temperature on bacterial activity can be detected from VS degradation through anaerobic digestion process [45]. The loss of VS increased with the increase of temperature. In this study, an average VS loss of 55-60% were estimated for the first eight weeks (January and February) when digester slurry temperature was 22-24℃ respectively. Whereas, loss of VS was increased from 62-68% for the remaining period (March-May) and digester slurry temperature increased to 28-36 ℃ during the same period as shown in Fig. 7. The VS loss during first week of the study period i.e. during the month of January was 55% and peaked at 68% during month of May. It is noted from this data that VS loss had increased about 23.6% during the last month of the study period compared to the first month, it is indicating that microbial activity increased with the increase of temperature. Moreover, hydraulic retention time (HRT) is an important parameter which influence the substrate degradation. In this study, HRT was fixed to 45 days throughout the study period and hydraulic load of digester was 0.02 m^3/m^3.d. The lignin, cellulose, and hemicellulose in buffalo dung are hydrolyzed into glucose and xylose, respectively, which are able to be converted into biogas [62]. The efficiency in terms of VS loss of anaerobic digestion process is improved with increasing HRT. Shi et al. [63] stated that the VS loss increases with increase in HRT. Whereas, a short HRT may cause a washout, which means that the microbial numbers decrease because the microbial population does not have enough time to grow [63]. Furthermore, a short HRT can result in reduced efficiency of substrate degradation. The optimal HRT depends on the type of residue and the type of digester [64].

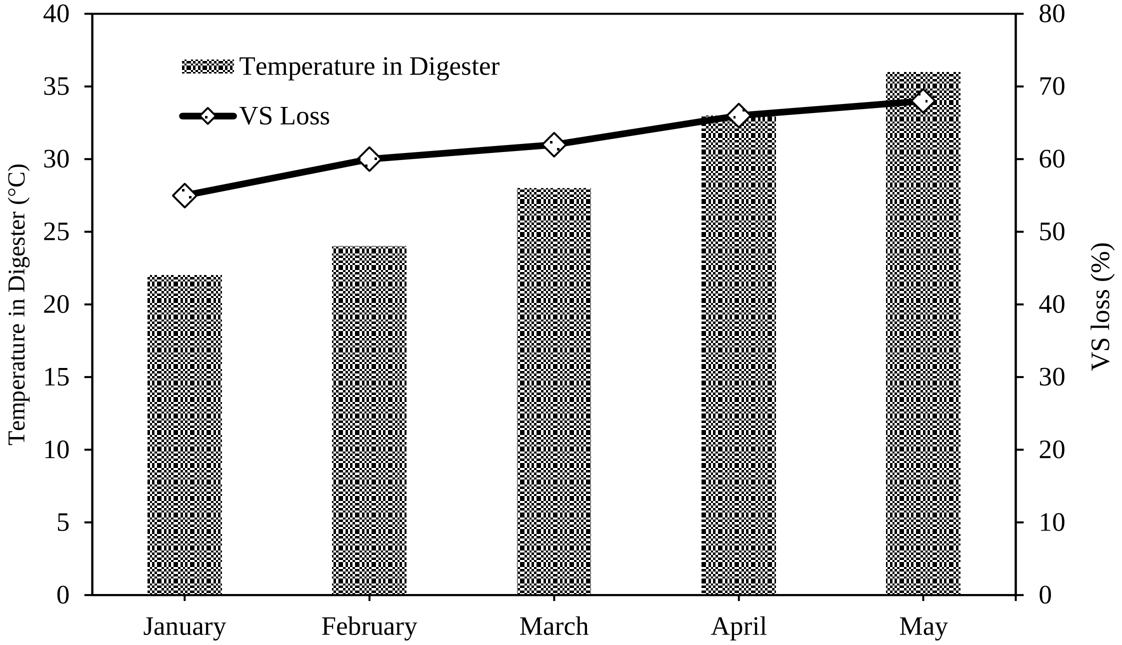

Fig. 7 Effect of monthly average slurry temperature on loss of volatile solids

3.6 Estimation of Biochemical Methane Potential (BMP)

In this study, a BMP test was used to analyze the effect of digested slurry on production of methane potential collected from outlet tank of concrete dome biogas plant. The BMP test waste terminated after incubating samples for 30 days during the month of January, March and April respectively. The batch experiments were conducted to measure the methane potential during these months. In the AD process, the substrate constitution is not only important, but at the same time the temperature, pH, and volatile fatty acids (VFAs) are also key working parameters. The pH, total alkalinity (TA) and VFA of each reactor bottle were analyzed at the start and the end of the 30 days' incubation period as per APHA standard methods [38]. The pH values were recorded in the range of 7-7.2 at the commencement of the batch reactor, and these were 7.2, 7.1, and 7.3 at the end of batch reactors during January, March, and April, respectively, as presented in Table 2. All the batch reactors were within the stable range of pH i.e. 6.8-7.2 [65], except the pH value 7.3 which was near the stability. However, the VFA/TA ratio were recorded in the range of 0.15-31 which indicated that the all reactor were stable. When the ratio of VFA/TA is less than 0.5 then AD system is reliable, but if the ratio exceeds the limit of 0.5 it considered the indication of instability of digester [66]. Table 3 shows the results of digestate slurry at the end of BMP test of (January, March, and April)

Table 3. The results of digestate slurry at the end of BMP test of (January, March, and April)

Sample	pH	Total Alkalinity (mg $CaCO_3$/L)	VFA (mg CH_3COOH/L)	VFA/ TA
January	7.2	1850	574	0.31
March	7.1	1910	401	0.21
April	7.3	1480	222	0.15

The weight of VS (at the start and end of batch reactors), percentage loss of VS, and the outcomes of the production of methane in terms of VS_{loss}, are given in Table 4. The maximum methane production of 115NmL/g VS_{loss} was observed at TS concentration of 3.5%, followed by 28 and 16NmL/g VS_{loss} at TS concentration of 2.5 and 3.0% respectively as presented in Table 3. These results reveal that the production of methane decreases with TS concentration of 2.5 %, while VS destruction was higher at the TS concentration of 3.5%. The outcomes of the present study is in correspondence to the literature as the mass of the solids decreases from 9.4-3.6%, the destruction of VS increases [55]. Moreover, in case of lower TS concentrations the level of microbial activity is also low because of the larger amount of the water [55]. On the contrary, as the mass of the TS increases from 3.6-9.4%, the specific methane potential also increases.

Table 4. The Results of methane potential for (January, March, and April)

Sample	TS (%)	CH_4 (NmL/g.VS_{loss})	VS_{in} (%)	VS_{out} (%)	VS_{loss} (%)
January	3.5	115	73.7	52	61.3
March	2.5	28	70.5	55	48.8
April	3.0	16	71.5	57	47

3.7 Statistical Analysis

Pearson Correlation and Principal component analysis (PCA) are analyzed statistically. Pearson correlation coefficient is fundamental statistical tool used by researchers to calculate linear relation between 2 Variables [67]. Correlation between the parameters such as atmospheric temperature, digester temperature, biogas production, VFA, VS, TS, and Alkalinity were calculated as presented in Table 5. Correlation results suggested that both temperature values at atmospheric (0.621) and digester (0.691) indicated highest correlation with gas production values at significant level of 0.01 than other parameters, highlighting the strongly dependent of biogas production with both temperatures. This relation of temperatures with gas production can also be justified by results indicated in fig 4 and table 1. Furthermore, the VFA showed strongly weak correlation with biogas with value of 0.299 and temperature values (-0.074 atmospheric and 0.25 digester temp), this is because both parameters biogas production and temperatures are strongly related with one another, hence are inversely related to VFA values. Alkalinity indicated negative correlation with VFA (-0.300) and VS (-0.255). VS and TS parameters also showed negative correlation (-0.290) with each other. Temperature also showed moderate correlation of 0.544 with alkalinity and negative correlation of -0.074 with VFA parameters, respectively.

Table 5. Pearson correlation results of different parameters studied for Biogas plant.

Parameters		Atmospheric temperature	Digester temperature	Biogas Production	VFA	VS	TS	Alkalinity
Atmospheric temperature	Pearson Correlation	1						
	Sig. (2-tailed)							
	N	21						
Digester temperature	Pearson Correlation	.973**	1					
	Sig. (2-tailed)	.000						
	N	21	21					
Biogas Production	Pearson Correlation	.621**	.691**	1				
	Sig. (2-tailed)	.003	.001					
	N	21	21	21				
VFA	Pearson Correlation	-.074	.025	.299	1			
	Sig. (2-tailed)	.750	.916	.187				
	N	21	21	21	21			
VS	Pearson Correlation	.371	.430	.156	-.020	1		

	Sig. (2-tailed)	.098	.052	.499	.933			
	N	21	21	21	21	21		
TS	Pearson Correlation	.213	.121	-.113	.050	-.290	1	
	Sig. (2-tailed)	.353	.601	.626	.830	.202		
	N	21	21	21	21	21	21	
Alkalinity	Pearson Correlation	.544*	.399	.221	-.300	-.255	.412	1
	Sig. (2-tailed)	.011	.073	.336	.186	.265	.064	
	N	21	21	21	21	21	21	21

**. Correlation is significant at the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed).

A principal component analysis (PCA) is a powerful statistical tool that is used to measure the variance of a dataset of inter correlated variables with a set of independent variables [68]. PCA results of this study are shown in Table 6. It was observed that PCA comprised three major components with Eigen values smaller than 1. The % variance measured for component 1 was 41.78, for component 2 it was 24.14 and component 3 was 16.93. The atmospheric temperature and digester temperature strongly correlated with component 1 with values of 0.997 and 0.969, whereas gas production indicated moderate correlation with component 1 with value of 0.746. Hence it can be concluded here that these 3 parameters lye within component 1 due to very close relation which is already indicated in correlation section. TS (0.715) and alkalinity (0.709) moderately correlated with component 2, whereas in component 3 only VFA correlated strongly with value of 0.884. Consequently, temperature atmospheric, digester and biogas production parameters are major components presented in this study.

Table 6. Principal component analysis results

Parameters	**Component**		
	1	**2**	**3**
Temperature atmosphere	.977	.041	-.093
Temperature digester	.969	-.118	-.030
Biogas Production	.746	-.282	.348
VFA	.006	-.369	.884
VS	.363	-.667	-.407
TS	.189	.715	.313
Alkalinity	.554	.709	-.100
Eigen Values	2.925	1.690	1.186
Variance %	41.789	24.142	16.938
Cumulative %	41.789	65.931	82.869

3.8 Economic analysis

The economic analysis for the fixed dome biogas plant was performed to estimate the total annual cost. The initial capital cost of biogas plant was 541 US$. Although, amortized capital cost of fixed dome biogas plant was estimated to 27.05 US$ /year. The most expensive part of the installation of the digester was the skilled labor, which founded almost 43% of the total investment cost. However, fixed dome biogas plant operations and maintenance procedures become easier after one becomes familiar to its handling. The total annual cost of plant was estimated to about 537.05 US$. The economic assessment including plant initial capital cost and maintenance cost of household fixed dome biogas plant were calculated as presented in Table 7. On the other hand, the cost comparison of fixed dome biogas plant and floating drum biogas plant indicated that the fixed dome biogas plant had low cost [69].Various studies had stated the similar economic facts and figures that fixed dome plant are comparatively more viable [9, 70 and 71].

Table 7. Economic assessment of household concrete fixed dome biogas plant

Fixed dome biogas plant		**Cost/value (**US$**)**
Plant initial capital cost	Construction materials (bricks, cement, gravel, sand, concrete ring, cover, iron rods)	280

	Plant fittings	
	Labor	26.5
		234.5
Expected life span	20 years	
Amortized capital cost per year		27.05
Operational and maintenance (O&M) cost per year	Maintenance and labor	510
Total annual cost		537.05

4 Conclusion and Future recommendation

This study was undertaken to investigate the seasonal variations in the performance of a reinforced concrete dome biogas plant; specifically, biogas production, biogas quality, VS loss and methane potential of digested slurry. The variation in the biogas production was recorded for both the winter and summer seasons owing to fluctuation of slurry temperatures. At lower digester temperatures during winter (January to February), average daily biogas production, methane concentration, and volatile solid loss were reduced in comparison to summer months (March-May). In January, minimum biogas production was obtained 0.23±0.004m^3/kg VS_{added} at an average slurry temperature of 28.3℃. The highest biogas production was obtained as 0.384±0.006m^3/kg VS_{added}. In May, a 41% increase in biogas yield was observed, in comparison to the month of January, when the average slurry temperature increased to 36.1 ºC and the highest VS loss was recorded. The concrete dome biogas plant contributes to 47% and 75% of household demand for cooking and heating during January and May respectively. The working parameters of the AD process demonstrated that the biogas plant was in stable operation and showed no signs of souring throughout the operation period. However, concrete dome biogas plant setup in rural areas of Pakistan is feasible for biogas production and produces enough methane gas to fulfill the domestic requirements. Conclusively, the average slurry temperature during cold and warm season were stable except the difference of 0.2-0.6 ºC whilst the ambient temperature highly fluctuates with cloudy and sunny day.

In the future, this work could be extended considering more research at varying temperatures by installing heating devices in the winter season as temperature is low and retention time is increased. As a future recommendation, it is also proposed to undertake a study using various cost-effective catalysts to decrease the retention time. Also, for commercial implementation and installation of a biogas plant, a subsidy may be provided so that more number of biogas plants can be installed.

Acknowledgment

The authors would like to acknowledge the Higher Education Commission, Government of Pakistan and the British Council for providing funding for this research under Knowledge Economy Partnership Project titled: "Biomass Resource Utilization for Clean Energy Production and Socio-economic Development in Rural Areas" (KEP-PK-046) and Mehran University of Engineering and Technology, Jamshoro, Sindh Pakistan for its support to carry out this research.

Declarations

Conflict of interest

The authors declare that they have no competing interests. The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Availability of data and materials

All data generated or analyzed during this study are included in this published article. Also, the datasets are available from the corresponding author on reasonable request.

Funding

Higher Education Commission, Government of Pakistan and the British Council Knowledge Economy Partnership Project titled: "Biomass Resource Utilization for Clean Energy Production and Socio-economic Development in Rural Areas" (KEP-PK-046)

Authors' contributions

Barkatullah Kandhro: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft.

Abdul Razaque Sahito: Conceptualization, Formal Analysis, Writing - review & editing, Supervision

Jonathan Daniel Nixon: Conceptualization, Formal Analysis, Writing - review & editing, Supervision

Mohammad Aslam Uqaili: Formal Analysis, Visualization, Writing - review & editing.

Nayyar H. Mirjat: Writing - Formal Analysis, Visualization, Writing - review & editing.

Khanji Harijan: Conceptualization, Formal Analysis, Writing - review & editing, Supervision

Rafi O Zaman: Writing - Formal Analysis, Review & editing.

Laveet Kumar: Writing - Formal Analysis, Review & editing.

References

1. Javed A (2016) Analysis of Energy Security, Environmental Emission and Fuel Import Costs Under Energy Import Reduction Targets: A Case of Pakistan. Renewable and Sustainable Energy Reviews 65 1065–1078.
2. Irfan M, Zhao ZY, Ahmad M, and Mukeshimana MC (2019) Solar Energy Development in Pakistan: Barriers and Policy Recommendations. Sustainability 11 (4) 1206
3. Abbas I, Liu J, Noor RS, Faheem M, Farhan M, Ameen M, and Shaikh SA (2020) Development and performance evaluation of small size household portable biogas plant for domestic use. Conversion and Biorefinery. https://doi.org/10.1007/s13399-020-00956-
4. Deepanraj B, Kumar NS, Ranjitha J, Jayaraj S, Chyuan H (2021) Biogas from food waste through anaerobic digestion: optimization with response surface methodology. Biomass Conversion and Biorefinery 11:227–239
5. Pandey B and Bajgain S (2007) Feasibility Study of Domestic Biogas in Pakistan. United nation development Programme (UNDP) Pakistan
6. Mirjat NH, Uqaili MA, Harijan K, Valasai GD, Shaikh F, and Waris M (2017) A review of energy and power planning and policies of Pakistan. Renewable and Sustainable Energy Reviews 79:110-127
7. Igoni AH, Ayotamuno MJ, Eze CL, Ogaji SOT, and Probert SD (2008) Designs of anaerobic digesters for producing biogas from municipal solid-waste. Applied Energy 85: 430-438
8. Nixon JD (2016) Designing and optimizing anaerobic digestion systems: A multiobjective non-linear goal programming approach. Energy 114: 814-822
9. Barnett A, Pyle L, and Subramanian SK, (1978) Biogas Technology in the Third World: Multidisciplinary Review Ottawa Ont International Development Research Centre (IDRC)
10. Green JM, Sibisi NT (2002) Domestic biogas digesters: a comparative study domestic use of energy. Conference Cape Town, South Africa.
11. Garfí M, Ferrer-Marti L, Velo E, Ferrer I (2012) Evaluating benefits of low-cost household digesters for rural Andean communities. Renew. Sustain. Energy Rev. 16: 575–81
12. Yaqoob H, Teoh YH, Din ZU, Sabah NU, Jamil MA, Mujtaba MA, Abid A (2021) The potential of sustainable biogas production from biomass waste for power generation in Pakistan, Journal of Cleaner Production 307 127250
13. Ministry of science and technology, Govt. of Pakistan. Pakistan Council of Renewable Energy Technologies (PCRET). Available online: http://www.pcret.gov.pk/. (Accessed 27.06.2014)
14. Sheikh MA (2010) Energy and renewable energy scenario of Pakistan. Renew Sust. Energy Rev. 14(1): 354–363
15. Surendra K (2014) Biogas as a sustainable energy source for developing countries: Opportunities and challenges. Renewable and Sustainable Energy Reviews 31:846-859.
16. An BX, Preston T (1999) Gas production from pig manure fed at different loading rates to polyethylene tubular biodigesters. Livest. Res. Rural Dev. 11
17. Rajendran K, Aslanzadeh S and Taherzadeh MJ (2012) Household Biogas Digesters: A Review. Energies 5: 2911-2942
18. Cuong HP, Jin MT, and Sven GS (2014) Predicting methane production in simple and unheated biogas digesters at low temperatures. Applied Energy 136 1-6
19. Mahmudul HM, Rasul MG, Akbar D, Narayanan R, and Mofijur M (2021) A comprehensive review of the recent devel
20. Kimberley EM, Esther G, Ben JS, and Sarah CD (2020) Pilot-scale biogas production in a temperate climate using variable food waste. Biomass and Bioenergy 138 105568

21. Lettinga G, Rebac S, Zeeman G (2001) Challenge of psychrophilic anaerobic wastewater treatment, Trends. Biotechnology 19: 363–370
22. McKeown RM, Scully C, Enright AM, Chinalia FA, Lee et al. (2009) Psychrophilic methanogenic community development during long-term cultivation of anaerobic granular biofilms. ISME J 3: 1231–1242.
23. Jiang X, Sommer SG, Christensen KV (2011) A review of the biogas industry in China. Energy Policy 39 6073–81.
24. Saghir M, Zafar S, Tahir A, Ouadi M, Siddique B and Hornung A (2019) Unlocking the Potential of Biomass Energy in Pakistan. Front. Energy Res https://doi.org/10.3389/fenrg.2019.00024
25. Nandi R, Saha CK, Huda MS, Alam MM (2017) Effect of Mixing on Biogas Production from Cowdung. Eco Friendly Agric. J. 10, 7–13.
26. Saifullah Khan1 ,Mahmood-Ul-Hasan2 Climate Classification of Pakistan Int. J. Econ. Environ. Geol. Vol. 10 (2) 60-71, 2019
27. Hubert, C.; Steiniger, B.; Schaum, C.; Michel, M.; Spallek, M. (2019) Variation of the Digester Temperature in the Annual Cycle–Using the Digester As Heat Storage. Water Pract. Technol. 14, 471–481.
28. Nandi, R.; Saha, C.K.; Sarker, S.; Huda, M.S.; Alam, M.M. (2020) Optimization of reactor temperature for continuous anaerobic digestion of cow manure: Bangladesh perspective. Sustainability 12, 8772.
29. Rahman, A.; Møller, H.B.; Saha, C.; Alam, M. (2019) The Effect of Temperature on the Anaerobic Co-Digestion of Poultry Droppings and Sugar Mill Press Mud. Biofuels
30. Castano, J.M.; Martin, J.F.; Ciotola, R. (2014) Performance of a small-scale, variable temperature fixed dome digester in a temperate climate. Energies 7, 5701–5716.
31. Ihara, I.; Yano, K.; Andriamanohiarisoamanana, F.J.; Yoshida, G.; Yuge, T.; Yuge, T.; Tangtaweewipat, S.; Umetsu, K. (2020) Field Testing of a Small-Scale Anaerobic Digester With Liquid Dairy Manure and Other Organic Wastes at an Urban Dairy Farm. J. Mater. Cycles Waste Manag. 22, 1382–1389.
32. Kalia, A.; Kanwar, S.(1998) Long-Term Evaluation of a Fixed Dome Janata Biogas Plant in Hilly Conditions. Bioresour. Technol. 65, 61–63.
33. Jung KK, Baek RO, Young, NC, and Si WK, (2006) Effects of Temperature and Hydraulic Retention Time on Anaerobic Digestion of Food Waste. Journal of bioscience and bioengineering Japan 102:328–332
34. Liu J, Olsson G, and Mattiasson B, (2004) A Volumetric Meter for Monitoring of Low Gas Flow Rate from Laboratory-Scale Biogas Reactors. Sensors and Actuators-B: Chemical 97:369-372
35. Walker M, Zhang Y, Heaven S, and Banks C, (2009) Potential Errors in the Quantitative Evaluation of Biogas Production in Anaerobic Digestion Processes. Bioresource Technology 100:6339-6346
36. Weiland P (2010) Biogas production: Current state and perspectives. Appl. Microbiol. Biotechnol. 85:849–860
37. Koch K (2015) Calculating the degree of degradation of the volatile solids in continuously operated bioreactors. b i o m a s s and b i o e n e r gy 74:79-83
38. APHA (1998) Standard methods for the examination of water and wastewater. American Public Health Association, 20th Ed., Washington, DC
39. Trine LH, Schmidt JE, Angelidaki I, Marca E, Jansen JLC, Mosbaek H, and Thomas HC (2004) Method for determination of methane potentials of solid organic waste. Waste Management 24:393-400
40. Sahito AR, Mahar RB, Brohi KM (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)
41. Abubakar IBSU, Ismail N (2012) Anaerobic digestion of cow dung for biogas production., Journal of Engineering & Applied Sciences 7(2):196-172
42. Zhao Q, Leonhard E, McConnell C, Frear C, Chen S (2010) Purification technologies for biogas generated by anaerobic digestion, CSANR Research Report
43. Lesteur MV, Maurel CB, Gonzalez E, Latrille JM, Roger et al., (2010) Alternative methods for determining anaerobic biodegradability: a review. Process Biochemistry 45:431-440.
44. Chen Y, Cheng JJ, Creamer KS (2008) Inhibition of anaerobic digestion process: a review. Bioresource Technology 99:4044-4064.
45. Appels L, Assche AV, Willems K, Degreve J, Impe JV, Dewil R (2011) Per acetic acid oxidation as an alternative pre-treatment for the anaerobic digestion of waste activated sludge. Bioresour Technol 102:4124–30
46. Elsayed M, Diab A, Soliman M (2021) Methane production from anaerobic co-digestion of sludge with fruit and vegetable wastes: effect of mixing ratio and inoculum type. Biomass Conversion and Biorefinery 11:989–998
47. Fernandes TV, Keesman KJ, Zeeman G, van Lier JB (2012) Effect of ammonia on the anaerobic hydrolysis of cellulose and tributyrin. Biomass Bioenergy 47:316–23
48. El-Fadel M, Saikaly P, and Ghanimeh S (2013) Startup and stability of thermophilic anaerobic digestion of OFMSW. Crit. Rev. Env. Sci. Technol. 43(24) 2685–2721 https://doi. org/10.1080/10643389.2012.694333
49. Ossa-Arias MDM and Martinez SG (2021) Methane Production from the organic fraction of municipal solid waste under psychrophilic, mesophilic, and thermophilic temperatures at different organic loading rates. Waste and Biomass Valorization 12:4859–4871 https://doi.org/10.1007/s12649-021-01354-9
50. Cysneiros D, Banks CJ, Heaven S, Karatzas KAG (2012)The effect of pH control and 'hydraulic flush on hydrolysis and Volatile Fatty Acids (VFA) production and profile in anaerobic leach bed reactors digesting a high solids content substrate. BioresourTechnol 123:263–71
51. Pham TN, Nam WJ, Jeon YJ, Yoon HH (2012) Volatile fatty acids production from marine macro algae by anaerobic fermentation. Bioresour Technol 124:500–3

52. Palacio BE, Robert PF, Boudenne JL, Coulomb B (2010) On-line analysis of volatile fatty acids in anaerobic treatment processes. Anal Chim Acta 668:74–9
53. Lin YQ, Wang DH, Wu SQ, and Wang CM (2009) Alkali Pretreatment Enhances Biogas Production in the Anaerobic Digestion of Pulp and Paper Sludge. Journal Haze. Mat. 170(1):366-373
54. Itodo IN and Awulu JO (1999) Effects of Total Solids Concentrations of Poultry, Cattle, and Piggery Waste Slurries on Biogas Yield. Transactions of the ASAE 42(6):1853-1855
55. Sahito AR, Mahar RB, and Ahmed F (2014) Effect of Buffalo Dung to the Water Ratio on Production of Methane through Anaerobic Digestion. Mehran University Research Journal of Engineering & Technology 33(2) ISSN 0254-7821
56. Isemina R, Klimova D, Larinaa O, Sytcheva G, Zaichenkoa V, and Milovanovb O (2019) Application of torrefaction for recycling bio-waste formed during anaerobic digestion. Fuel 243: 230–239
57. Sahito AR, Mahar RB and Brohi KB (2013) Anaerobic biodegradability and methane potential of crop residue co-digested with buffalo dung. Mehran University Research Journal of Engineering & Technology 32: 3 [ISSN 0254-7821]
58. Noonari AA, Mahar RB, Sahito AR, and Brohi KM (2020) Effects of isolated fungal pretreatment on bio-methane production through the co-digestion of rice straw and buffalo dung. Energy 206
59. Matheria AN, Ntulia F, Ngilab JC, Seodigengc T, Zvinowandab C, and Njengad CK (2018) Quantitative characterization of carbonaceous and lignocellulosic biomass for anaerobic digestion. Renewable and Sustainable Energy Reviews 92: 9–16
60. Matheri AN, Mbohwa C, Ntuli F, Belaid M, Seodigeng T, Ngila JC, and Njenga CK (2018) Waste to energy bio-digester selection and design model for the organic fraction of municipal solid waste. Renew Sustain Energy Rev 2018;82:1113–21.
61. Madan BB, Amrit B, Jagan N S, Sundar B (2004) Biogas as renewable source of energy in Nepal theory and development BSP - Nepal.
62. Sahito AR, Mahar RB, and Ahmed F (2016) Optimization of organic loading rate and hydraulic retention time for maximum production of methane through anaerobic codigestion of canola straw and buffalo dung. Journal of animal & plant sciences 26(2) 373-381
63. Shi XS, Dong JJ, Yu JH yin H Hu S, s huang SX, and Yuan XZ (2017) Effect of hydraulic retention time on anaerobic digestion of wheat straw in the semi-continuous continuous stirred-tank reactors. Biomed research international. https://doi.org/10.1155/2017/2457805
64. Arhoun B, MV, Mail R, Lahoz CG (2021) Anaerobic codigestion with fruit and vegetable wastes: An opportunity to enhance the sustainability and circular economy of the WWTP digesters. Clean Energy and Resources Recovery Biomass Waste Based Biorefineries 1 103-132
65. Gerardi MH (2003) The Microbiology of Anaerobic Digesters, Waste Water Microbiology Series Hoboken, John Wiley & Sons, Inc; New Jersey, 2003
66. Lin YQ, Wang DH, Wu SQ, and Wang CM, (2009) Alkali pretreatment enhances biogas production in the anaerobic digestion of pulp and papers sludge. Journal Haze. Mat 170(1):366-37
67. Temizhan E, Mirtagioglu H, Mendes M, (2022) Which correlation should be used for investigating relation between quantitative variables, American scientific journal for Engineering, Technology and Science, 85(1), 265-277
68. Khuhawar MY, Brohi ROZ, Jahangir TM, Lanjwani MF (2018) Water quality assessment of Ramser site, Indus Delta, Sindh, Pakistan. Environmental Monitoring& Assessment 190:492
69. Singh KJ and Sooch SS (2004) Comparative study of economics of different models of family size biogas plants for state of Punjab, India. Energy Conversion and Management 45 1329–1341
70. Siyal AW, Yasin M, Ali I, Hussain Z, Aslam M, and Khan M. (2015) Performance evaluation of fixed dome and floating type biogas digesters for tubewell operation with dual fuel approach in Pakistan. Int J Innov Appl Stud 10:4 1225.
71. Mishra S, Tenneti S and Mishra S (2005) Design of domestic scale bio-digester assembly, experimentation for biogas production and comparisons of results with conventional digester. J Teknol 11:75.