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Kinetic study and optimization of total solids for anaerobic digestion of kitchen waste: Bangladesh perspective

Thamina Nasrin[a], Chayan Kumer Saha[a,*], Rajesh Nandi[a], Md. Sanaul Huda[b] and Md. Monjurul Alam[a]
[a] Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh
[b] Department of Agricultural and Biosystems Engineering, North Dakota State University, Fargo, ND 58108, USA
*Corresponding author. E-mail: cksaha@bau.edu.bd
Thamina Nasrin, Chayan Kumer Saha and Rajesh Nandi contributed to this work equally and should be regarded as co-first authors.

ABSTRACT

Kitchen waste from hotels and homes is one of the major problems for urban and rural environment and could be one of the best sources of renewable energy by producing biogas through anaerobic digestion. A research work was undertaken to assess the methane potential of kitchen waste at different total solids (TS) content. Kitchen wastes such as spoiled rice, brinjal, potato, papaya, tomato, fish and poultry parts etc., which are easily decomposed, were selected for this study. Batch experiments were set up under ambient temperature. Kitchen waste was added to the batch digester at different TS content (5, 7, 10, 12 and 15%) and sealed for 146 days until the gas production stopped. Substrate characteristics were analyzed before and after the anaerobic digestion. The highest methane yield was 78.12 L/kg VS at 15% TS content followed by 12, 10, 7 and 5%. Different kinetic parameters were determined using a logistic model and the model showed a good fit with the experimental results. After modelling using Minitab®, the optimum TS content for kitchen waste was found to be 14.90%.

Key words: anaerobic digestion, biogas, kitchen waste, optimization, total solids

HIGHLIGHTS

- Performance of anaerobic digestion at different solid concentrations of kitchen waste were investigated.
- The total solids content was optimized to maximize yield.
- Significant variation in methane yield was observed at different total solids.
- The optimum total solids was found to be 14.90% with methane yield of 78.23 L/kg VS.

INTRODUCTION

In Bangladesh, energy production is mainly based on natural fossil fuel and the contribution of energy from renewable resources is almost negligible in the country. Nevertheless, with increasing prices of oil, energy from renewable resources has become necessary to maintain the economic growth of the country. Currently, the power generation capacity of the country is ~20,000 MWe, only 1.37% of which comes from renewable sources (Nandi *et al.* 2020). It is estimated that the country would require circa 34,000 MWe by the year 2030 to fulfil its demand (Nandi *et al.* 2020). Conversely, the daily production of waste in the country is around 30,000 tons (Joshi 2020) of which kitchen waste (KW) comprises about 50–60% in urban areas (Mahmud *et al.* 2016). Kitchen waste includes food waste, vegetables waste, garbage, broken material that are found in homes and these are discarded into open areas and generate harmful gases (such as CO_2, CO, H_2S etc.). To reduce such emissions, controlled biodegradation of these wastes through anaerobic digestion (AD) is necessary. As KW makes up a significant part of biodegradable waste and thus it can be utilized to produce biogas for cooking and power generation. Biogas produced from organic waste could play a vital role in solving energy crisis and environmental problems of the country.

Several factors influence the AD of organic matter, such as temperature, C/N ratio, volatile fatty acids (VFA), pH, TS content, etc. Yi *et al.* (2014) observed an increase in biogas production with high solid content while examining the biogas potential of food waste. Liu & Lv (2016) examined the effect of TS content on biogas production from dairy manure and

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found the best performance at 8% of TS while Deepanraj *et al.* (2019) found the best performance at 20% TS content for rapeseed oil cake. Many researchers examined the biogas potential of KW (Agrahari & Tiwari 2013; Bo & Pin-jing 2013; Anwar *et al.* 2016). Bo & Pin-jing (2013) investigated the effect of organic loading rate (OLR) on the two-phase AD of KW and suggested that an increase in OLR improves the performance of AD. Anwar *et al.* (2016) examined the effect of sodium salt on the AD of KW and suggested to keep the salt concentration below 8 g/L to avoid any inhibition. In Bangladesh, rice is the main food, two-thirds of the daily diet is composed of rice, some vegetables, small quantities of fish and meat (Kabir *et al.* 2018). Rice and vegetables are rich in carbohydrates, while meat and fish are rich in proteins and lipids. So, due to different food habits, the characteristics of KW generated in Bangladesh might be different from other countries. So, the biogas potential of KW generated in Bangladesh needs to be examined. The effect of TS content on AD of KW in Bangladesh also needs to be investigated for optimization of biogas production. Moreover, previous studies only examined the effect of TS content on biogas production from different substrates (Liu & Lv 2016; Paramaguru *et al.* 2017; Deepanraj *et al.* 2019) but attempts to optimize the TS content have been rarely focused. In this regard, this study aims (i) to examine the methane production potential from KW in Bangladesh context at different TS contents through experiments and kinetic study and (ii) to optimize the TS content for methane production from KW using a best-fit regression model.

MATERIALS AND METHODS

Feedstock and inoculum preparation

The experiment was conducted in the laboratory of the Green Energy Knowledge Hub, Department of Farm Power & Machinery, Bangladesh Agricultural University, Mymensingh. For this experiment, KW was selected according to its availability in the hotels situated nearby the experimental site. The KW comprised of spoiled rice, fish parts, poultry parts and vegetables (brinjal, potato, papaya and tomato). Pretreatment of substrates was necessary to avoid hazardous circumstances during the experiment. The KW was chopped into small pieces and then the chopped particles were crushed with the help of manual crusher. No large particles were left after crushing. After crushing, particle size was reduced and accessible surface area was increased. Therefore, it was easy for the microorganisms to dissolve the substrates to produce biogas. The fermented slurry of dairy manure from a biogas plant was selected as inoculum for this experiment. The inoculum was stored for 2 weeks in an incubator at 35 °C to ensure minimum biogas production from the inoculum during the experiment.

Experimental set-up

A laboratory-scale batch AD system was prepared using batch bottles. Pretreated KW was added to the batch digester (500 mL batch bottles) with different TS contents (5, 7, 10, 12 and 15%). An appropriate amount of water was added to the digester to obtain the designed TS contents according to Equation (1) (Rahman *et al.* 2019):

$$\frac{kg}{kg} = \frac{TS_{raw}}{TS_{req}} - 1 \tag{1}$$

where, TS_{req} denotes the required percentage of TS content to make slurry and TS_{raw} represents the TS content of the raw feedstock.

Each digester was gently homogenized and closed carefully with butyl rubber bungs. The headspace of all reactors was flushed with nitrogen gas for 2 minutes to ensure anaerobic conditions. Each substrate sample and a control containing only inoculum were repeated in triplicate. Mesophilic batch digestion was conducted for 146 days under ambient conditions as most of the digesters used in Bangladesh use ambient conditions for biogas production. Ambient temperature was recorded daily using a data logger (ACR TRH-1000) in 5-second intervals.

Analytical methods

The biogas production was measured by volume displacement of glass syringe (SGE, Australia, capacity: 500 mL) and gas composition was analyzed using a gas analyzer (BIOGAS 5,000, Geotechnical Instruments Ltd, Coventry, UK) with the help of gas sampling bags according to the manufacturer procedure. The TS content and VS content were measured following standard procedures (APHA 2017). For the measurement of total solids, around 100 g of sample was transferred into a previously weighed tray and was dried at 105 °C for 24 h in a heating oven (UN30, Memmert, Schwabach, Germany). The increase in weight over that of the empty tray represents the total solid. The dried sample obtained after TS estimation was ignited in a muffle furnace (LE 14/11/B 150, Nabertherm, Lilienthal, Germany) at 550 °C for 5 h. The weight lost on ignition represents the volatile solids. The remaining weight represents the ash content of the sample. The pH was measured using a calibrated pH/Conductometer (914 pH/Conductometer, Metrohm, Herisau, Switzerland). The VFA was measured using a Titrator (848 Titrino plus, Metrohm, Switzerland) following a model developed by Møller & Ward (2011). Total ammonium nitrogen (TAN) was measured using photometric kits (Spectroquant kit, Merck, MA, USA) and photometer (NOVA 60, Memmert, Germany). Total nitrogen (TN) was measured using a thermo-reactor (TR 420, Merck, Darmstadt, Germany) and the photometer.

Calculation

The C/N ratio was determined using Equation (2) (Nandi *et al.* 2020):

$$\frac{C}{N} = \frac{VS(\%)/1.76}{TN\ (\%)} \tag{2}$$

Triplicates were carried out for this experiment including a control, which indicated the productivity of the inoculum. In order to obtain the production of the sole substrate, methane produced from each sample was corrected by subtracting the volume of methane produced from the inoculum acting as control. The specific methane yield was calculated using Equation (3):

$$BMP_{observed} = \frac{V_{(ino+feedstock)} - V_{ino}}{mVS_{feedstock}} \tag{3}$$

where, $BMP_{observed}$ represents the observed biochemical methane potential (L CH_4 kg^{-1} VS^{-1}), $V_{(ino+feedstock)}$ represents the volume of methane produced by inoculum and substrate (L CH_4), V_{ino} represents the volume of methane produced by inoculum alone (L CH_4), and $mVS_{\mathrm{feedstock}}$ represents the mass of volatile solids in substrate (kg VS).

Kinetic study

Kinetic modelling is used to describe specific parameters of the system performance. Several models are available to describe the kinetics of methane generation. These models are useful in determining maximum methane production potential, maximum methane production rate, lag phase duration, etc. In this study, experimental data were verified for fit using a logistic model (Equation (4)) (Donoso-Bravo *et al.* 2010):

$$M(t) = \frac{M_o}{1 + \exp\left[\frac{4 \times R_m}{M_o}(\lambda - t) + 2\right]} \tag{4}$$

where, *M(t)* is the cumulative methane yield at digestion time *t* days (L/kg VS added), M_o represents the methane potential of the substrate (L/kg VS added), λ is the duration of lag phase (days), R_m is the maximum methane production rate (L/kg VS.day), t is the duration of the assay at which cumulative methane production *M(t)* is calculated (days). All the parameters of the model were calculated using the nonlinear curve fitting toolbox of MATLAB (R2014a).

Optimization

Optimum input settings are required to maximize the methane yield and volatile solid degradation. Best-fit regression equations and standard forms of regression models were analyzed for optimization of TS content using Minitab®-19 (State College, PA, USA).

RESULTS AND DISCUSSION

Characteristics of selected kitchen waste and inoculum

Different characteristics of KW and inoculum were determined and are presented in Table 1. The TS content of the KW was 21.10% and the VS content was 19.92%. The TS and VS contents of the inoculum were 6.04% and 4.40%, respectively. The C/N ratio of KW was 38.96 which is similar to 37.74 obtained by Das & Panda (2020). Too high or too low a value for the

Table 1 | Characteristics of selected kitchen waste and inoculum used in the batch study before starting the experiment and after the digestion

	Kitchen waste	Inoculum
TS (%)	21.10	6.04
VS [wb] (%)	19.92	4.40
Ash (%)	1.18	1.63
NH4-N (g/L)	2.4	1.10
TN (g/L)	2.9	2.44
C/N	38.96	nd

nd, Not determined.

C/N ratio results in low gas production. Rahman *et al.* (2017) determined that the optimum C/N ratio for biogas production lies between 25 and 30, other researchers such as Guarino *et al.* (2016) reported a wider range of 9–50. The TAN and TN of KW were 2.4 g/L and 2.9 g/L, respectively.

pH, VFA and TAN

The pH, VFA and TAN are important factors to determine the stability of AD. Continuous monitoring of these parameters helps to better understand the process as described in past studies (Huang *et al.* 2021; Xu *et al.* 2021). The present study was literally based on batch experiments and the reactors were sealed for the whole experimental period, so only the initial and final values of pH, VFA and TAN were determined following previous studies (Anwar *et al.* 2016; Rahman *et al.* 2019). It is difficult to explain the changes in these parameters over the digestion period as the pH, VFA and TAN were determined at the beginning and at the end of the experiment. The pH, VFA and TAN of KW during experiments are shown in Table 2. Initial pH of the substrates with different solid content showed an increasing trend with the increase in TS content for all test groups. The highest initial pH (6.95) was observed at 15% TS content and the lowest was observed at 5% TS content (6.56).

According to previously published literature, the favorable pH range for methanogens is 6.3–7.8 (Sarker *et al.* 2019). The pH value was favorable for methanogens to produce biogas. Final pH of KW varied from 6.34 to 7.42 depending on the TS content. In AD, organic matter is converted into VFA during hydrolysis and acetogenesis, then the VFA converts into biogas by the action of methanogenic bacteria. Any imbalance between acid-producing bacteria and methane formers leads to an increase in VFA disturbing the stability of AD, consequently reducing the biogas production. In our study, the initial VFA was between 0.16 and 0.21 g/L for all test groups. Some VFA was accumulated after the fermentation process. Final VFA value of KW of different TS contents was between 0.27 and 0.90 g/L. VFA concentrations over 3 g/L may lead to process failure and should be less than 2 g/L for proper AD (Nandi *et al.* 2020). Low VFA level indicates favorable condition for biogas production. The lowest VFA after digestion was 0.27 g/L for the 15% test group and indicates that most of the VFA that was produced during hydrolysis and acetogenesis stages was converted into biogas. The methanogenesis process of AD is performed by archaea. The archaea community is inhibited by ammonia and other heavy metals (Wang *et al.* 2016). Concentrations of TAN up to 1.5 g/L are considered normal for AD (Rahman *et al.* 2019). Too high a value of

Table 2 | Substrate and digestate characteristics

	Kitchen waste before digestion		Kitchen waste after digestion		
Solid concentration	pH	VFA (g/L)	pH	VFA (g/L)	NH_4-N (g/L)
5%	6.56	0.16	7.42	0.44	0.75
7%	6.61	0.17	6.92	0.50	0.7
10%	6.65	0.18	6.53	0.90	0.65
12%	6.72	0.20	6.43	0.51	0.7
15%	6.95	0.21	6.34	0.27	0.7

ammonia-nitrogen indicates process inhibition. In this study, the concentrations of TAN was between 0.65 and 0.75 g/L for all test groups, which indicates the smooth running of the digestion process without inhibition.

Temperature variation during the experiment

Day-to-day temperature variation throughout the experimental period is shown in Figure 1. The highest temperature was 31.85 °C on the 5th day. The temperature varied from 31.85 to 29.08 °C. The temperature between 29 and 35 °C is suitable for biogas production (Agrahari & Tiwari 2013). Therefore, the temperature of the experiment was favorable for biogas production.

Specific biogas and methane production for different TS

The KW was converted into biogas through AD. In this experiment, methanogens were in a stable condition after 60 days. Therefore, the experiment was conducted for 146 days until the gas production stopped. Specific biogas production, methane content and specific methane production in 146 days are presented in Figure 2. Both the specific biogas and methane production increased with the increase in TS content. The gas production increased because the pH was in the suitable range for AD and no accumulation of VFA occurred (Table 2).

Initially the biogas production was not significant. For the first five days, gas production at 5, 7, 10, 12 and 15% TS content was 5.77, 14.71, 24.01, 15.77 and 25.78 L/kg VS, respectively. After day 5, gas production for all test groups was reduced and a very small amount of biogas was produced until day 30. The digester with 15% TS content produced the highest biogas up to day 30 due to the high initial pH, whereas the digester with 5% TS content produced the lowest amount biogas within the same duration as a result of low initial pH. However, after day 30 the gas production started increasing in groups with 5, 7 and 10% TS content, while groups with 12 and 15% TS content took a longer time, 45 and 60 days, respectively (Figure 2(a)).

High load of feed caused by high TS content caused acidification at the preliminary stage of AD and may reduce the pH, disturbing the stability resulted in low gas production during this period. Up to day 60, groups with 10% TS content produced the most biogas (62.81 L/kg VS). Finally, the biogas yield from 5, 7, 10, 12 and 15% TS content was 57.16, 77.05, 123.1, 122.02 and 139.34 L/kg VS, respectively. The highest volume of biogas was produced at 15% TS content and KW with 5% TS content showed the lowest biogas production. Low solid concentration of the feed caused malnutrition to methanogens, leading to low gas production (Wu *et al.* 2010).

From Figure 2(b), it is evident that initially the methane content at low TS was slightly higher than high TS. After 5 days of digestion, the methane content for 5 and 7% TS content was around 39% and methane content for 10, 12 and 15% TS content was about 35, 33 and 33% respectively. On the 15th day of the experiment, methane content fell below 30% for all test groups. This was because the temperature fluctuated during this period, disturbing the activity of methanogens (Figure 1). A stable temperature is needed for optimum performance of AD (Nandi *et al.* 2020). From 30 days, higher methane content was found, as the temperature was consistent. The methane content after 60 days was between 49 and 81% until the end of the test. The average methane content at 5, 7, 10, 12 and 15% TS content was 56, 56, 55, 52 and 50%, respectively. Although the methane content was slightly higher at low TS content, it was offset by the higher biogas volume produced at higher TS content.

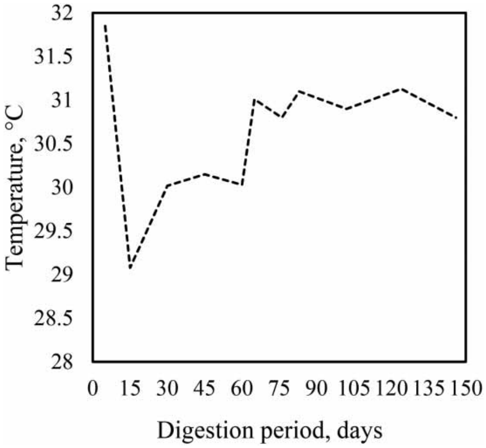

Figure 1 | Temperature variation throughout the data collection period.

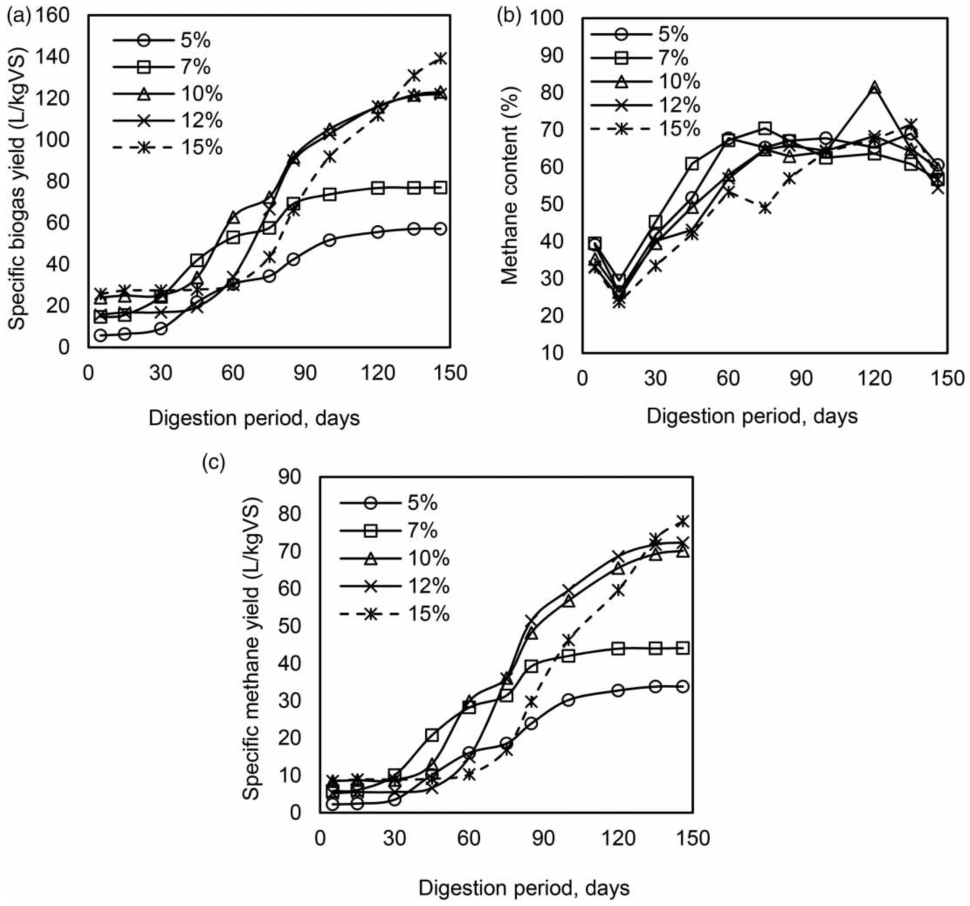

Figure 2 | (a) Specific biogas production at different solid concentrations. (b) Methane content. (c) Specific methane production at different solid concentration.

The methane production profile at different solid concentrations is presented in Figure 2(c). Maximum specific methane production was found at 15% TS content (78.12 L/kg VS). The second best was found at 12% TS content (72.41 L/kg VS) followed by 10% (70.19 L/kg VS), 7% (44.11 L/kg VS) and 5% (33.82 L/kg VS) TS content.

Total solid degradation (TSD) and volatile solid degradation (VSD) are two important parameters to determine the efficiency of AD. Variation of TSD and VSD at different TS content is shown in Figure 3. In this experiment, TSD for 5, 7, 10, 12 and 15% of TS content was 47%, 56.43%, 65.90%, 81.25% and 78.20%, respectively. The TSD at 12 and 15% TS content was high. A similar pattern was observed for VSD also. The VSD for 5, 7, 10, 12 and 15% of TS content was 55.11%, 64.39%, 72.58%, 86.02% and 82.07%, respectively. The VSD was higher at high TS content. It is evident from the results that the TSD and VSD increased with the increase in TS content from 5 to 12%, further increase in TS content resulted in a drop in degradation efficiency. Biogas production increased with degradation efficiency up to 12% TS content. Although the degradation efficiency at 12% TS content was higher than at 15% TS, the biogas production was higher at 15% TS. Similar results were obtained by Wang *et al.* (2020b), who reported higher degradation efficiency but lower biogas yield at 5% TS than at 15% TS.

Yi *et al.* (2014) also found that high TS content lower than 20% had a positive impact on methane yield. Rahman *et al.* (2019) showed that optimum TS content ranged between 11 and 13% for poultry droppings, press mud, sugarcane bagasse. Deepanraj *et al.* (2019) observed highest biogas production at 20% TS content, while examining the effect of different TS content on AD of rapeseed oil cake. The small difference in findings may be due to the substrate characteristics and the conditions under which the experiments were performed. The methane production in this study (33.82–78.12 L/kg VS) was much less than in the previous study (247 L/kg VS) (Wang *et al.* 2020a). This difference may be due to different substrate composition or different experimental conditions.

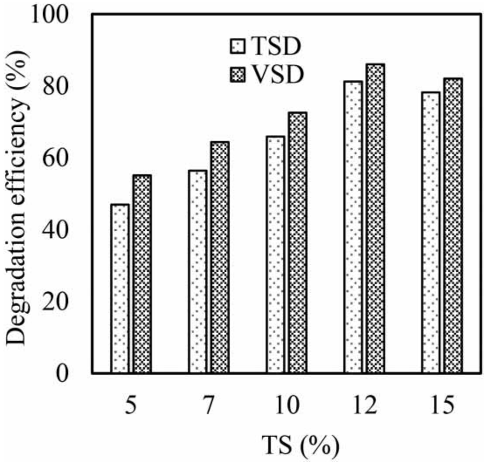

Figure 3 | Degradation efficiency at different TS content.

Kinetic study

Different kinetic parameters determined by fitting the experimental data with the logistic model are shown in Table 3. The coefficients of determination (R^2) for TS content were between 0.9733 and 0.992. For all cases the R^2 values were greater than 97%, indicating a good fit. The root mean square error (RMSE) was in the range 1.285–4.764 for all test groups. The predicted methane yields from this model were very near to experimental results.

Methane potential at 5, 7, 10, 12 and 15% TS content was 35.21, 45.05, 74.26, 74.51 and 81.25 L/kg VS, respectively. Maximum methane production rate was high at higher TS contents. The digesters with 5, 7, 10, 12 and 15% TS content went through an acclimation period with a lag phase of 25.21, 10.04, 25.78, 46.33 and 54.85 days, respectively. The high value of the lag phase was possibly due to the atmospheric temperature variation at the startup period of the experiment for which microorganisms took some time to be stable. To evaluate the soundness of the model results, the difference between predicted and measured values of methane yield was calculated. Experimental and predicted results showed only 1.2–4.3% difference in methane yield for different TS content. It indicated that the model could be used to predict methane yield from KW.

Model fitting and optimization

In this study, the relationships between predictor and response variables were developed using regression analysis. All independent variables were fitted to three different models (linear, quadratic and cubic models). The summary of model statistics is presented in Table 4. In this study, the TS content was considered as a predictor/independent variable and the methane yield and VSD were considered as a response/dependent variable. The best model was selected on the basis of highest

Table 3 | Results of kinetic study

	TS content				
	5%	**7%**	**10%**	**12%**	**15%**
Experimental methane yield (L/kg VS)	33.82	44.11	70.19	72.41	78.12
Predicted methane yield (L/kg VS)	34.30	44.62	71.11	73.75	74.75
Difference between experimental and predicted methane yield (%)	1.4	1.2	1.3	1.9	4.3
Methane potential (L/kg VS)	35.21	45.05	74.26	74.51	81.25
R_m (L/kg VS-day)	0.41	0.55	0.79	1.23	0.99
Lag phase (λ)	25.21	10.04	25.78	46.33	54.85
R^2	0.992	0.9915	0.9895	0.9898	0.9733
RMSE	1.285	1.612	2.931	3.121	4.764

Table 4 | Model statistics

	Methane yield		**VSD**	
Model	**Standard error of regression (S)**	**Regression coefficient (R^2)**	**Standard error of regression (S)**	**Regression coefficient (R^2)**
Linear	7.07	90.16%	5.55	85.61%
Quadratic	4.40	97.46%	4.60	93.39%
Cubic	5.65	97.91%	5.02	96.06%

coefficient of regression (R^2) and lowest value of standard error of regression (S). After applying these two conditions, the cubic model (Figure 4) was found to be the best model. For methane yield and VSD, the R^2 values were 97.91% and 96.06%, respectively. The S values for specific methane yield and VSD were 5.65 and 5.02, respectively. The regression equations obtained using the cubic model are shown in Table 5. These two equations were used to optimize the TS content. The TS content was optimized for maximum methane yield and VSD using Minitab. The optimum TS was found to be 14.90%, while maximum methane yield was 78.23 L/kg VS and maximum VSD was 83.48% (Figure 5). In optimization, composite, desirably, is an important factor that determines how well the input settings optimize a group of responses. In this study, the composite, desirably, was found to be 1. A composite desirably close to 1 indicates that the input settings have positive effect on maximizing response variables. The results of this study coincided with a previous study (Rahman *et al.* 2019). Rahman *et al.* (2019) showed that the optimum TS content lies around 13% while experimenting with different agro-industrial wastes.

Model validation

The measured values were compared with predicted values obtained from the cubic model to validate the model (Table 6). A small variation in the measured and predicted values of specific methane yield and VSD was further confirmed by the consistency between the obtained and predicted data.

CONCLUSIONS

Kitchen waste was experimentally digested in batch assay. High degradation efficiency proved KW as a potential feedstock for biogas production. No VFA accumulation was observed at the end of the experiment. Methanogens in high TS contents

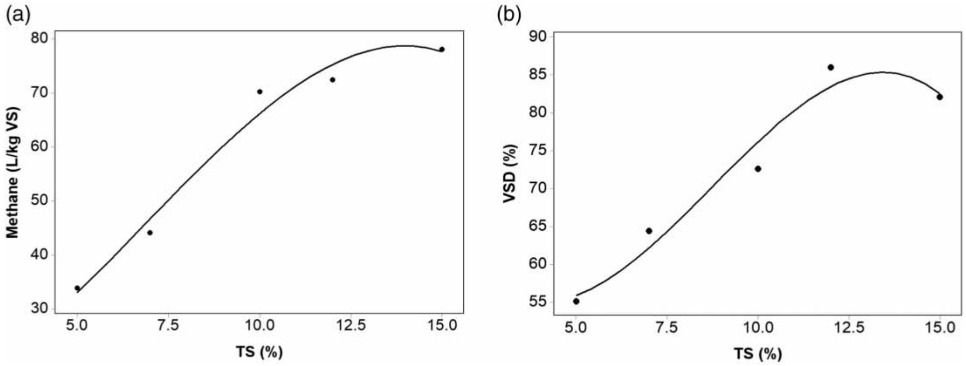

Figure 4 | Regression polynomial curve for (a) methane yield and (b) VSD.

Table 5 | Best fit regression equations using the cubic model

Predictor	**Response variable**	**Regression equation**
TS content (C)	Methane yield (M) VSD	$M = 12.64 + 0.47\ C + 0.95\ C^2 - 0.04617\ C^3$ $VSD\ (\%) = 76.62 - 11.92\ C + 1.920\ C^2 - 0.07329\ C^3$

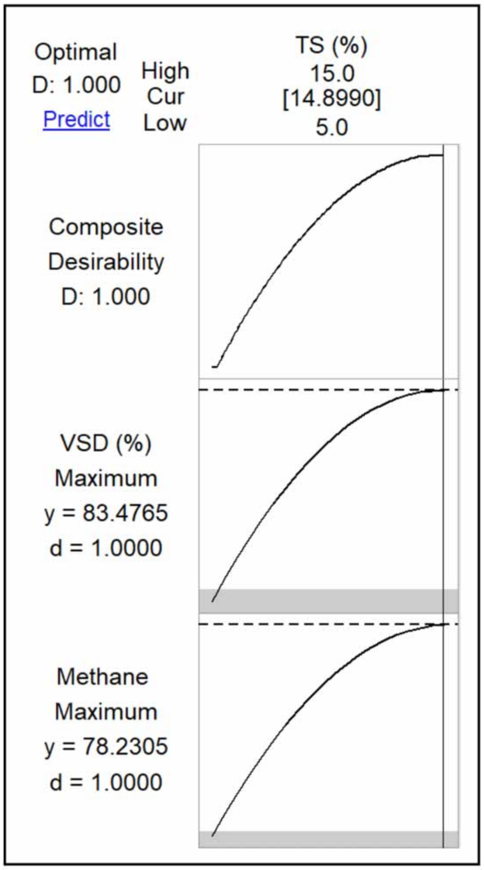

Figure 5 | Optimization plot for methane yield and VSD.

Table 6 | Comparison between measured and predicted values of specific methane yield and VSD

	Methane yield (L/kg VS)			**VSD (%)**		
TS content	**Experimental**	**Predicted**	**Error**	**Experimental**	**Predicted**	**Error**
5%	33.82	32.97	−0.02	55.11	55.86	0.01
7%	44.11	46.64	0.05	64.39	62.12	−0.03
10%	70.19	66.17	0.05	72.58	76.13	0.05
12%	72.41	75.30	0.04	86.02	83.41	−0.03
15%	78.12	77.62	−0.01	82.07	82.47	0.00

took longer time to become stable and continued to produce biogas at a higher rate for a longer period of time than the low TS content. The experiment was continued until the gas production stopped. After 146 days, 15% TS content produced the highest volume of biogas (139.34 L/kg VS) and methane (78.12 L/kg VS). The reactor with 12% TS content showed the second best performance with a methane yield of 72.41 L/kg VS followed by 10, 7 and 5% TS content. Methane production was increased with the increase in TS content. Optimum TS content was found to be 14.90% for maximum methane yield and maximum VSD. The logistic model was found adequate to describe the AD of KW.

This result would be useful in selecting correct solid concentration of feed material to maximize the biogas yield. This experiment was conducted under atmospheric condition. There is provision to conduct the same study for methane production at controlled temperature.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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