Characterization of Kitchen Waste as a Feedstock for Biogas Generation by Thermophilic Anaerobic Digestion

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Abstract

Kitchen waste collected from the University Cafeteria was collected, mixed, analysed and used for production of Biogas under thermophilic anaerobic digestion. The samples were collected for two periods of about 13 weeks in different weather conditions. The analyses were arranged for both cases separately. The characterization of so-called non-source waste material revealed that the average MC, TS, and VS for daily week-long samples were 85.5%, 14.5%, and 88.2%, respectively, with standard deviations of 5.5%, 5.5%, and 4.6%, respectively. The average MC, TS, and VS for a twelve-week-long weekly sampling were 85.7%, 14.3%, and 87.5%, respectively, with standard deviations of 2.3%, 2.3%, and 1.9%, respectively. The C/N ratio for selected samples varied in the range 19.5-28.7 with an average C/N ratio of 23.3. Overall variability and consistency of collected kitchen waste was analyzed by ANOVA. Biogas was generated in a bench scale setup from the waste material for different TS concentrations. The analysis of the leftover material after anaerobic digestion indicated that 90% of organic material can be degraded within a period of 3 weeks at initial TS concentrations of 8% and lower. This observation supports the use of kitchen waste for thermophilic anaerobic digestion and biogas generation.

Introduction

In recent years, solid waste treatment has become a serious issue worldwide [1]. Solid waste generation is increasing gradually with the passage of time due to population explosion and urbanization. Each urban resident generates 0.35–1.0 kg solid waste every day [2]. It has been estimated that the urban areas of Pakistan generate over 55,000 tons of solid waste daily, with more than 7,000 tons of solid waste being generated daily in Karachi alone [3]. Conventional treatment methods for solid waste treatment are composting, land filling, and incineration, etc. [4, 5]. But these techniques have severe environmental issues associated with them such as air pollution, and leachate flow from dumped waste causing water contamination, etc. Recently organic wastes have been recognized as reusable resources, and biological treatment of organic solid wastes has considerably increased. Food/kitchen waste includes uneaten food and food preparation leftovers from residences, commercial establishments such as restaurants, institutional sources like school cafeterias, and industrial sources like factory lunchrooms, and is the single-largest component of the municipal solid-waste stream by weight [2, 5]. Kitchen waste is characterized by a high organic content, most of which is composed of easily biodegradable compounds such as carbohydrates, proteins, and smaller lipid molecules. As a result of these characteristics, interest in anaerobic digestion has increased for the efficient management of kitchen waste [1].

Non-source-separated kitchen waste contains both biodegradable organic and non-biodegradable organic and inorganic materials [6]. The components of kitchen waste include spoilt vegetables, peelings and trimmings, fruit skins and spoilt fruit, cooked and uncooked meat, bones, fats, egg-shells, used teabags, coffee grounds, bread and pastries, cooked food waste, tissue papers, packing materials, plastics, glass and water, etc. Due to relatively high moisture content of kitchen waste, bioconversion technologies, such as anaerobic digestion, are more suitable compared to thermo-chemical conversion technologies, such as combustion and gasification [5]. About 95% of biodegradable portion of kitchen waste is suitable for anaerobic digestion [7]. Kitchen waste generation is increasing gradually with the passage of time due to population explosion, urbanization, and because of eating habits of individuals becoming more luxurious. Its generation and variability depends on the behavior of people, their eating habits, level of income, and weather conditions in a particular area.

Anaerobic digestion is material degradation without oxygen in the presence of microorganisms to form biogas. Physical and chemical characteristics of organic waste such as moisture content (MC), total solids (TS), volatile solids (VS), nutrient contents (in terms of C/N ratio), particle size, and biodegradability (in terms of ratio of volatile solids to total solids, i.e., VS/TS ratio) are the important factors for designing and operating anaerobic digesters for biogas generation [5]. A number of researchers have evaluated the potential of several feed stocks such as night soil sludge and kitchen waste mixture [8], poultry slaughterhouse waste [9], food waste [10, 11], waste activated sludge [12], fruit and vegetable solid waste [13, 14], household waste [15], solid potato waste alone and in combination with sugar beet leaves [16, 17], dairy manure [18, 19], sewage sludge [20, 21], alfalfa silage [22], kitchen waste [5, 7], municipal solid waste with domestic sewage [23], waste paper [24], and swine manure [25], etc., for aerobic and anaerobic digestion.

The objective of this study was to characterize mixed kitchen waste for evaluating its potential as feedstock for biogas generation through thermo-

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philic anaerobic digestion. Overall daily and weekly variability and consistency of mixed kitchen waste samples were analyzed using single-factor ANOVA. Daily rate of biogas generation and cumulative biogas yield over a period of 21 days was also measured in a bench-scale setup at different TS concentrations.

Methods

A. Kitchen Waste Collection and Characterization

Mixed kitchen waste collected from university sports cafeteria was sorted, segregated, processed, sampled and analyzed in laboratory using the following procedure.

B. Collection of Kitchen Waste

Kitchen waste collection system includes specification of location, collection time and interval, type of collection bags, and the storage bins, etc. Bins were provided and collected from the specified location at predefined intervals. Samples were initially taken on six days (Monday through Saturday) for one week and then taken on every Thursday for twelve weeks. Average generation of mixed kitchen waste in the selected cafeteria is about 40-45 kg/day, and a representative sample of 4-5 kg was taken each time.

C. Pretreatment of Kitchen Waste

The major problem associated with the mixed kitchen waste collected directly from the source is its high content of non-biodegradable and toxic materials, and its physical and chemical heterogeneity. Mechanical pre-treatment is necessary before the anaerobic digestion to remove these impurities to protect the biogas plant from mechanical failure and ensuring the safety of the stabilized sludge [26]. As a preliminary step, the non-source-separated kitchen waste was manually segregated in organic biodegradable part, non-biodegradable inorganic part, components containing toxic substances, and components that can mechanically damage the anaerobic digester unit. Quartering technique was used to get a representative sub-sample from the organic biodegradable part, which was then shredded twice in a meat mincer to get a consistent feed sample and collected on a plastic sheet. This shredded sample was mixed manually and about 20-30g was used for further analysis.

D. Analysis of Kitchen Waste

Kitchen waste was characterized in terms of its proximate and ultimate analyses. Proximate analysis is physical characterization and involves assessment of pH (APHA, 1998, method 4500H; using Pronto HI 981402 pH meter), moisture content (APHA, 1998, method 2540B), total solids (APHA, 1998, method 2540B), and volatile solids (APHA, 1998, method 2540E). The ultimate analysis of waste was carried out to determine carbon (C), oxygen (O), nitrogen (N), hydrogen (H), and sulfur (S) contents, and carbon-to-nitrogen ratio (C/N) and carbon-to-hydrogen (C/H) ratio using Elementar Vario MICRO CHNS Analyzer (Method: 2mgChem80s).

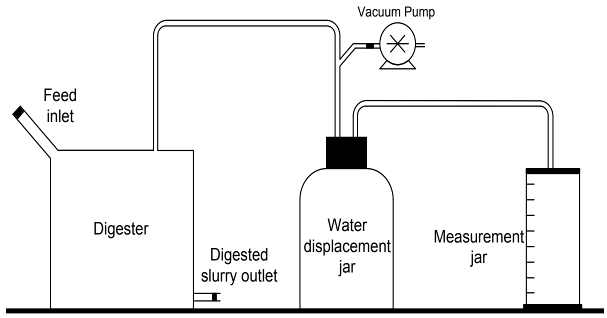

Figure 1: Experimental Setup for Anaerobic Digestion Test

Biodegradability of kitchen waste was determined using a bench-scale batch anaerobic digester. Archaebacteria belonging to methanococcus group are most suitable micro-organisms for thermophilic anaerobic digestion and exists naturally in the gastrointestinal tract of cattle [27]. Conditions for optimum growth of thermophilic methanococcus inoculum used for digestion are a temperature of 65˚C and a pH range of 7–9 [28]. Inoculum was prepared by blending a shredded cattle-intestine obtained from a slaughterhouse with stagnant water from a pond in a high-power blender, neutralizing the blended slurry with 0.1M NaOH, and then placing it for two weeks in a 1-liter flask in a water bath, covered with a thick black plastic sheet to ensure protection from sunlight, at a constant temperature of 65˚C. Sample of mixed kitchen waste was shredded in a meat mincer to ensure particle size reduction (less than 2 mm) and homogeneous slurry formation.

The total volume of the digester was 2 liters. After the sample and inoculum were added, the digester was filled with water up to 1.5 liters, and tightly closed by using rubber and screw arrangement. To maintain anaerobic conditions, vacuum pump was used to remove air from digester. Temperature was kept constant at 60±1˚C by using a water bath to provide thermophilic conditions.

The experiment was conducted with six different TS concentrations between 4 and 14% while keeping temperature (60 °C), initial pH of the slurry (neutral), total volume of slurry (1.5 liters), and quantity of inoculum used (100 mL) constant for a fixed retention time of 21 days for all TS concentrations. During the test run, digester contents were manually shaken at least once a day. Daily biogas production was measured using displacement of a colored solution in a graduated cylinder (Figure 1). After 21 days, the digested slurry was again characterized to check its biodegradability.

Statistical Analysis

Single factor ANOVA (analysis of variance) was performed to examine daily and weekly compositional differences of mixed kitchen waste samples. F-value or F-statistic and p-value were evaluated to determine the overall variability and consistency of kitchen waste samples using Microsoft Excel®.

Experimental Results & Discussion

A. Characterization of Kitchen Waste

Results obtained from characterization of kitchen waste samples are summarized in Table 1. Complete results for MC, TS, and VS for daily and weekly samples are provided in Figures 2 and 3, respectively. Results of pH measurement for daily and weekly samples are provided in Figures 4 and 5, respectively. In Figures 2-5, standard deviations are indicated by Y-error bars.

B. Proximate Analysis of Kitchen Waste Samples

Optimum pH range for thermophilic anaerobic digestion reported in literature is 6.6–7.6 [29]. However, pH values of mixed kitchen waste samples vary between 5.8 and 6.5. Average pH value was 6.17 for daily week-long sampling and 6.37 for weekly twelve-week-long sampling, with standard deviations of 0.21 and 0.13, respectively. Based on these results, initial pH of feedstock slurry was adjusted to neutral using 0.1M NaOH solution. This addition of alkali serves to increase the initial buffering capacity of the digester [16].

Optimum TS contents reported in literature is 7–9% for maximum biogas yield [6]. Average TS contents were 14.5% for daily week-long sampling and 14.3% for weekly twelve-week-long sampling, with standard deviations of 5.49% and 2.27%, respectively. The feedstock was observed as relatively dry and unsuitable for utilization because of high TS concentration. Therefore, for using this feedstock, it must be first diluted to get required TS concentration by addition of appropriate quantity of water.

VS contents represent biodegradable portion of feed. The average VS contents were 88.2% for daily week-long sampling and 90.1% for weekly twelve-week-long sampling, with standard deviations of 4.62% and 1.92%, respectively. Such high values of VS contents show that the feedstock is quite rich in volatile/biodegradable material, and has great potential for giving good biogas yield. Further, it can be expected that little sludge will be produced after digestion.

Ultimate Analysis of Kitchen Waste Samples

Unbalanced C/N ratio inhibits the anaerobic digestion efficiency due to formation of ammonia nitrogen and volatile fatty acids (VFAs). Accumulation of high concentrations of ammonia nitrogen has an inhibitory effect on the glycolytic pathway via which glucose hydrolyzed from carbohydrates is degraded [30]. Accumulation of high concentrations of VFAs also inhibits the methanogen efficiency by lowering the pH of digester contents and decreasing the buffer capacity of the system. The optimal C/N ratio for anaerobic digestion is in the range of 20–30 [31]. If a selected feedstock for anaerobic digestion does not have required C/N ratio, it should be mixed with some suitable waste to get a better C/N ratio and nutrient recipe [24, 32]. The average values of the experimental results of ultimate analysis of kitchen waste sample collected at different dates, analyzed by CHNS Elemental Analyzer, are shown in Table 2.

TABLE 1.
AVERAGE CHARACTERISTICS OF KITCHEN WASTE

Parameter	Average
pH	6.3
Weight of sample (g)	50.00
% Total solids (TS) (wet-sample basis)	14.4
% Moisture content (MC) (wet-sample basis)	85.6
% Volatile solids (VS) (dry-sample basis)	89.5
C/N ratio	23.3
C/H ratio	7.5

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TABLE 2.
AVERAGE ULTIMATE ANAYSIS OF KITCHEN WASTE

Parameter	Average
Weight (mg)	4.9500
N [%]	2.21
C [%]	45.90
H [%]	5.899
S [%]	0.109
C/N ratio	20.7577
C/H ratio	7.7810

The results show that the C/N ratio of the samples is within the range 19.5–28.7 with an average value of 23.3, which fits well in the optimum range of 20–30 reported in literature [31].Further, the sulfur content in the segregated feedstock is only about 0.1% which is not dangerous for the anaerobic bacteria.

The results of ultimate analysis of a representative kitchen waste sample (that was used as feed in bench-scale anaerobic digester) were used to develop an approximate molecular formula for the waste sample ($C_{3.789}H_{5.870}O_{2.933}N_{0.117}S_{0.004}$), and then to estimate the theoretical methane yield or biochemical methane potential using the Buswell's equation [33]:

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2$$

$$Theoretical\,Yield = \frac{\left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) 22.4}{12n + a + 16b} \left(STP \frac{Liters\ CH_4}{g - VS}\right)$$

Where 22.4 liters is the volume of one mole of gas at STP conditions.

The theoretical methane yield for the representative waste sample was estimated to be 0.43 liters of CH_4/g-VS (STP conditions). With 60% methane content in the biogas, it is equivalent to 0.72 liters of biogas/g-VS (STP conditions).

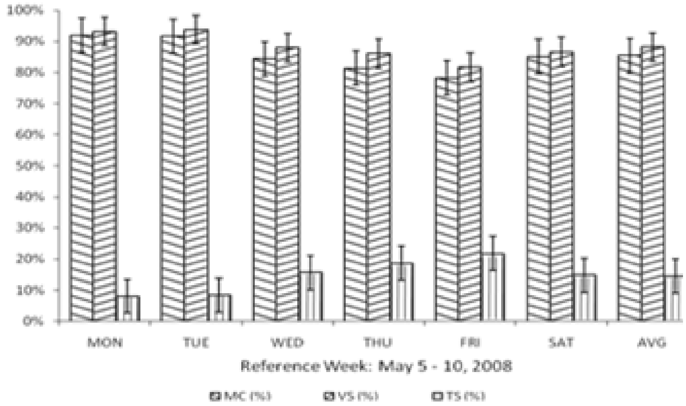

Figure2: Daily Variation of Kitchen Waste Characteristics

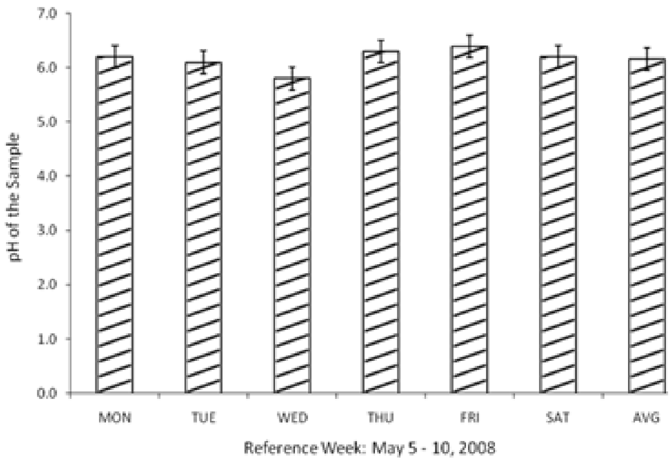

Figure 4: Daily Variation of pH of Kitchen Waste

From the results of proximate and ultimate analysis of kitchen waste samples, it can be expected that the rate of digestion of this feedstock will be sufficiently fast, and particularly, little volume of sludge will be produced on digestion. Also the biogas produced from this feedstock will contain low H_2S fraction and special treatment for odor control may not be required.

C. Anaerobic Digestion Test Results

The bench-scale batch digester setup was used to test the biodegradability of kitchen waste samples. Six different experimental setups were run in parallel with different initial TS concentrations between 4 and 14% (initial loading rates of 34–119 g-VS/L). Results for daily production rate of biogas and overall biogas yield for 21 days are presented in Figures 6 and 7, respectively.

The degradation of the substrate started almost immediately and daily production of biogas increased until day 6, and then gradually declined until the end of experiments (Figure 6). High rates of biogas generation in the first few days are because of increasing biological activity, and a major portion of the material is degraded in these days. Towards the end of the experiment, the organic biodegradable content left in the digester goes on decreasing and results in lower biogas production rates. At lower TS concentrations (4–8%), the overall biogas yield increased at higher TS concentrations.

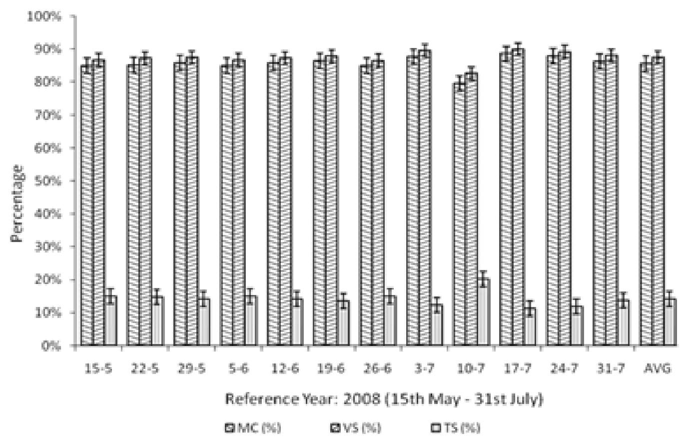

Figure 3 Weekly Variation of Kitchen Waste Characteristics

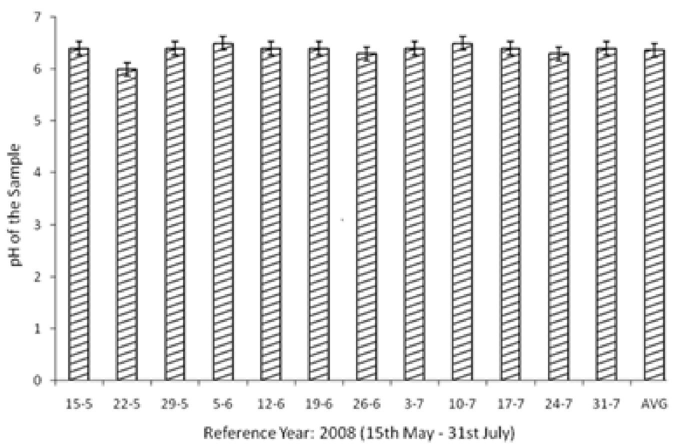

Figure 5: Weekly Variation of pH of Kitchen Waste

Highest overall biogas yield was obtained at 8% TS (initial organic loading of 68.0 g-VS/L). For 10% TS (initial organic loading of 85.0 g-VS/L), the overall biogas production was much lower than the overall biogas production at lower TS concentrations. The effect was even more pronounced at 12% and 14%
TS (initial organic loadings of 102.0 and 119.0 g-VS/L, respectively) where the biogas production completely stopped after day 4. It may be expected that higher values of TS would yield greater volumes of biogas by virtue of larger quantities of biodegradable material present in the system. However, at high TS concentrations, the amount of water in the system decreases, thus reducing the level of microbial activity, resulting in lower biogas yields at higher values of TS. Furthermore, high TS concentrations lead to high VFA formation, which lower down the pH of digester contents below 5.0 and stop the microbial activity altogether.

Statistical Analysis

ANOVA was done to locate the source of variability in kitchen waste characteristics. F-test statistic represents the probability information for variation due to sample source (domain) and P-value represents the probability that the variation between samples may have occurred by chance.

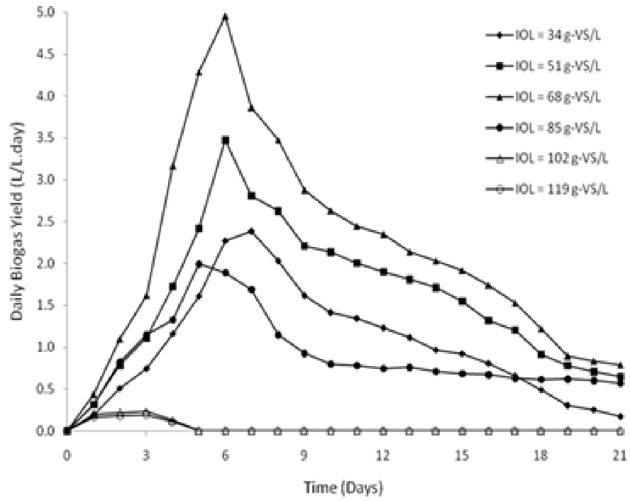

Figure 6: Daily biogas yield over a period of 3 weeks at different initial organic loadings (IOL) (Experimental conditions: Temperature = 60±1 °C; Initial pH of slurry= 7; Volume of slurry = 1.5 Liters; Inoculum volume used = 100 mL)

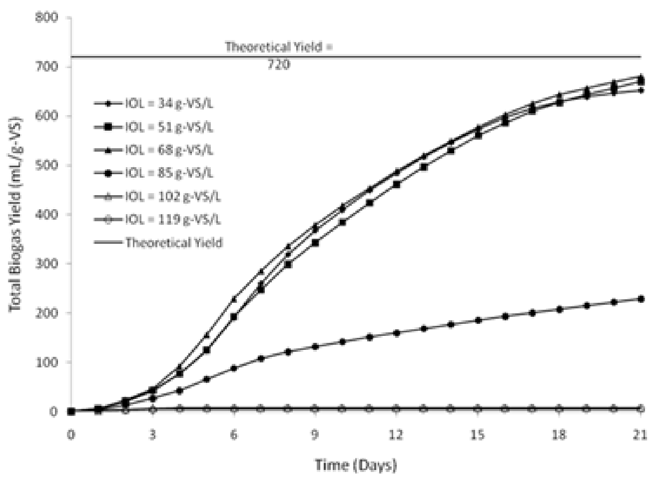

Figure 7: Total biogas yield over a period of 3 weeks at different initial organic loadings (IOL) (Experimental conditions: Temperature = 60±1 °C; Initial pH of slurry= 7; Volume of slurry = 1.5 Liters; Inoculum volume used = 100 mL)

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From ANOVA test results, it can be concluded that:

- F-test statistic values are extremely larger than the critical F-values, which means that there is statistically significant difference between groups (rather than within groups), and such large differences cannot be explained by chance.
- Extremely small p-values indicate that a nearly uniform composition had been achieved within the grinded sample (slurry).
- It can be concluded that the source location of kitchen waste has some fundamentally associated variation with it (as a result of which compositional changes occur over a time period). This can be explained mainly by changes in daily menu, and to some extent, by the quality of cooked food on a particular day.

Conclusions

The potential of mixed kitchen waste as feedstock for biogas generation through thermophilic anaerobic digestion was evaluated through its proximate and ultimate analysis. The overall variability and consistency of kitchen waste for its utilization for biogas production was also examined by using ANOVA. It was concluded that pH of the feedstock slurry needs to be slightly adjusted using an alkali. In addition, the feedstock has a very high TS content, and the slurry must be diluted by addition of an appropriate quantity of water. The feedstock is quite rich in volatile biodegradable material and has great potential for further consideration. The C/N ratio of the feedstock indicates a proper nutrient balance and no further step needs to be considered in this respect. It can be expected that the rate of digestion will be sufficiently fast, and particularly, little volume of sludge will be produced on digestion. ANOVA results indicate that the source location of kitchen waste has some fundamentally associated variation with it (as a result of which the compositional changes occur over a time period). This can be explained mainly by changes in daily menu, and to some extent, by the quality of the cooked food on a particular day.

A batch anaerobic digester setup was used to test the biodegradability of kitchen waste samples at different initial organic loading rates. The results show that at low organic loadings, more than 90% of VS present in the feed can be degraded within a period of 3 weeks. Higher organic loadings result in decreased gas production rates because of accumulation of high concentrations of volatile fatty acids. It was concluded that the initial TS concentration should be kept less than 8% in the feedstock.

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