

Study of Different Parameters of Mixing on Biogas Production from Food Waste

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Abstract. Food waste generation is an increasing issue, and the disposal of it is controversial. It raises food prices, and the municipal solid waste contains 8.4% food waste by weight. The current study generates a pilot plant for converting food waste to biogas production as an energy source for tremendous paths. The present work deals with the study of the effect of mixing on biogas production from food waste in the pilot-scale digesters. A propeller agitator was employed for mixing in an anaerobic digester. Multiple experimental trials were addressed to optimize the parameters participating in the process of biogas production in semi-continuous operation at mesophilic conditions. Different mixing duration and mixing frequency was studied at the mixing speed of 5 rpm and a comparison was carried out with reference to the digester without a mixing facility. The highest biogas production of 0.12 m³/(kg dry mass) was observed at the mixing time of 5 min compared with the duration of 10 min and 15 min and without mixing conditions. Mixing once in a day obtained biogas production in the range 0.048 to 0.071 m³/(kg dry mass) while mixing at two times in a day obtained biogas production in the range of 0.019 to 0.0357 m³/(kg dry mass). Hence, mixing frequency once a day provided almost double biogas production. Effect of temperature and pH was also studied with different mixing duration and found that mixing duration of 5 min was the best for biogas production from food waste. Minimum mixing of 5 min is required once a day in semi-continuous digestion for stable biogas production. The study concluded to a point that mixing is important for stable processes and maximum biogas production.

Keywords: Biogas production, mixing effect, mesophilic digestion, pilot scale, food waste

1. Introduction

Anaerobic digestion of waste has a greater potential to provide energy for various working operations apart from facilitating the waste treatment [1]. Increase in population density is proportionate to the municipal solid waste as well as food waste. Current methodologies find landfills as the major operation for food waste disposal. Acute amount of wastage of food disposal is carried out through incineration and composting. Landfilling emits various harmful gases contributing to global warming [2, 3]. Contrary to this, anaerobic digestion helps not only to digest food waste but produces energy while decomposition. Thus, anaerobic digestion serves as the best alternative to food waste

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digestion [4, 5]. Recycling of materials, energy, and nutrients causes an increase in efficiency of process there by a part of the circular economy [6]. The use of food waste for biogas generation causes recycling of material, nutrients and producing energy. pH, temperature, type of substrate, and carbon to nitrogen ratio majorly affect the production of biogas by decomposition of food waste.

The uniformity in the fluids is attained by a physical process called mixing. Mixing eliminates temperature and concentration gradients in the slurry. The primary goal of stirring an anaerobic digester's content is to create close contact between bacteria and substrates, which promotes methane output [7]. Hydrolytic, acidogens, acetogens, and methanogens are the four types of bacteria that make up an anaerobic digester. Heat and mass transfer becomes complex when these microorganisms interact as well as the interaction of these microorganisms with the substrate [8]. To ensure biological, chemical as well as physical consistency throughout an anaerobic digester, mixing is a must. Similarly, mixing is also necessary for grit removal. It is also important for substrate dispersion to avoid stratification, the creation of surface crust, and to increase transfer area [9, 10].

Biogas production is directly affected by the mode of mixing and intensity with which the slurry is mixed. In the anaerobic digester, however, there are different competing viewpoints on agitator design, decreased mixing intensity, or unequal mixing [11, 12]. According to Karim et al., spontaneous mixing was enough to provide sufficient mixing when the solid concentration was less than 5%, but when the solid concentration was larger than 10%, in many applications, an additional mixing facility was required for the digester to function properly [13, 14]. A study reveals a higher COD reduction for a digester with a mixing facility compared to a stratified digester [15]. Weak mixing can cause sediments to sink at the bottom of the digester, whereas aggressive mixing inhibits anaerobic bacteria development. In terms of average velocity and flow fields, Binix 2014 indicated that confined mixing outperforms unconfined mixing in terms of mixing power [16].

Several researchers reported studies for different types of agitators and the effect of mixing on biogas production. Submersible mixers, paddles, centrally mounted mixers, and combinations of these were used in the majority of investigations [7, 17]. The kind, design, and placement of baffles in an agitator have a significant consideration in determining flow patterns in the anaerobic digester. Satjaritanun et al. suggested that introduction of baffles resulted in higher biogas production [18, 19]. Researchers reported that mixing was improved in anaerobic digesters with different designs such as draft tubes [20-22]. Along a similar line, researchers also proposed designs of roller mixers or self-agitated reactors [23-25]. Biogas production and uniformity in the anaerobic digester are majorly affected by the speed of the agitator. Lindmark et al. reported in a study that higher agitator speed resulted in lower biogas production. This could be concluded as the report mentions a comparative stating lower biogas production at an agitator speed of 150 rpm than at a speed of 25 rpm [26, 27]. Contrary to it, stirring requires power and thus power consumption possesses an issue as compared to stratified digesters. The current study reveals that 54% of the power required by an anaerobic digester is consumed by a stirring mechanism [8, 28].

Collectively, we find no clear perspective on designing an anaerobic digester for biogas production under mesophilic conditions. The kind of biomass, agitator design, operating parameters, concentration, bacteria concentration, vessel scale, and mode of mixing all affect biogas generation. Mixing has a direct impact on the production of biogas, but the magnitude absence makes it cloudy to have a reliable design for optimized production.

The composition of food waste changes with each batch of collection from door-to-door and day-by-day. This poses a problem to have a uniform study on the effect of parameters

on biogas production. The current study undertakes soyabean flour as a synthetic food waste for biogas production. The process of producing biogas is carried out at mesophilic conditions to study the effect of mixing time and corresponding mixing frequencies on the amount of biogas produced. This is in the form of stable and maximum production. The mixing effects are compared to the digester without a mixing facility, considering it as a reference digester. Optimizing parameters of mixing helps in the improvement of biogas production and decomposition of food waste.

2. Material Requirement and Method Adaptation

2.1 Substrate description and seed sludge.

Food waste from homes, restaurants, and food synthesis plants includes a wide range of foods. Food waste from hotels, canteens, and residences was analyzed, and it was discovered that the majority of food waste consists of wheat, rice, and protein-based diet, contributing to the main source of carbon in Indian cuisine. Instead of using whole grains, flours of these grains were used to avoid non-uniformity. Soyabean flour was used as synthetic food waste for all of the pilot-scale experimental trials because it has a C/N ratio of roughly 31, which is close to the C/N ratio ideal for anaerobic digestion. As a seed sludge, digested sludge was used from a large-scale anaerobic digester operating on food waste (Thyssenkrupp Industries India Pvt. Ltd., Pune, India) with a substrate to inoculum ratio of 0.05 kg/kg of substrate.

2.2 Biogas production through anaerobic digestion of food waste.

Synthesis of biogas was accomplished from synthetic food waste manufactured from soyabean flour in a pilot plant scale digester with a capacity of 200 L. The digestion is carried out in a fixed-dome digester. The current study used three fixed dome digesters with similar designs. The first anaerobic digester was without a mixing facility and used as a reference digester for comparison. The other two digesters had a propeller-type agitator of diameter 16.2 cm with 6 blades in the present study to understand the effect of mixing on biogas production. The blade dimensions are 4x3 cm. The six-bladed propeller agitator was installed 45 cm from the top and 15 cm from the bottom of the anaerobic digester. Plastic impellers are used to reduce the shear effect. The speed controlling mechanism was used to control the agitator's speed.

Three semi-continuous anaerobic digesters with a capacity of 200 L, running under mesophilic conditions, make up the experimental setup. Two of the digesters have a propeller agitator fitted to help with mixing, but the third does not. These anaerobic digesters were constructed of mild steel and were coated to prevent corrosion. The agitator's speed was controlled using a one-of-a-kind speed control unit. The digesters were airtight and featured a motor on the top. To make a slurry solution, 43 gm of soyabean flour was combined with 430 mL water. It was used as a substrate for all the experimental trials. The substrate was fed to each digester every day at a fixed interval of time for 21 days. As a seed culture, 1 kg sludge from a food waste digester at Thyssenkrupp Industries India Pvt. Ltd., Pune, India was introduced to each digester. For all of the experimental trials, the solid concentration in an anaerobic digester was retained at 10% (w/w). At room temperature, all of the digesters are flipped on.

Two semi-continuous operations were conducted. The first semi-continuous operation deals with the mixing speed of 5 rpm with a mixing time of 10 min. Two anaerobic digesters with a mixing facility were subjected to different mixing frequencies of mixing

once a day and twice a day respectively and the third digester is the reference digester with no mixing facility. The second semi-continuous operation had the same mixing speed of 5 rpm but with varied mixing times. The mixing time for digesters with a mixing facility was 5 min and 15 min respectively with a mixing frequency of once a day for both the mixing time. The third digester was the reference digester with no mixing facility.

Temperature measurements were taken twice daily in mesophilic conditions, and the average value was used. Weekly pH readings were taken with a pH sensor. The average of three values was calculated. Daily biogas synthesis was measured as a pressure differential in a U-tube manometer and manually withdrawn from a top exit at a set interval. A rise in pressure was used to quantify the volume of biogas. The moles of the gas were estimated using the ideal gas law, $PV=nRT$, and their equivalent volume at normal temperature pressure (NTP) was reported.

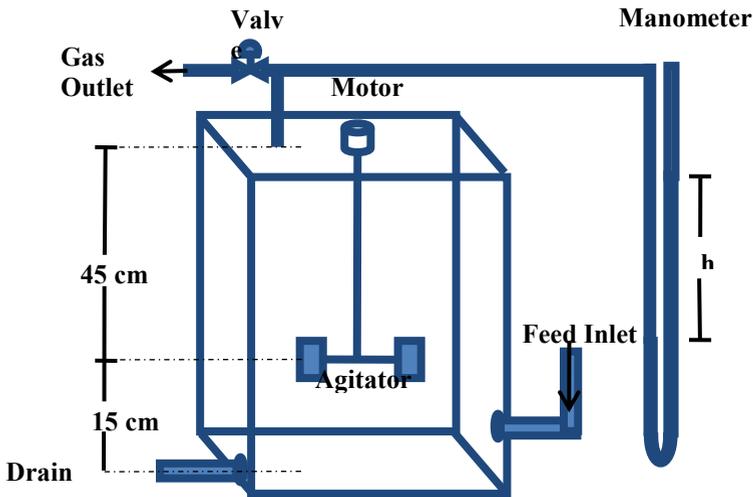


Fig. 1a. Schematic diagram of Anaerobic digester.



Fig. 1b. Anaerobic digesters each connected to a U-tube manometer.

2.3 Analysis of biogas production.

Biogas composition was analyzed using gas chromatography (GC-Horizon Services Ltd, Pune, India) equipped with a thermal conductivity detector (15 m x 0.53 mm x 15 mL) and CP-Porabond Q (25 m x 0.53 mm x 10 mL) column.

3. Results and Discussion

3.1 Mixing effect at 5 rpm for semi-continuous process with varied mixing frequency.

In this run, the mixing speed for the digesters with a mixing facility was maintained at 5 rpm and a mixing time of 10 min with different mixing frequencies of mixing once a day and twice a day respectively. Kariyama et al. stated that the efficiency of anaerobic digestion depends on the mode of mixing, mixing time, and mixing interval [29]. Therefore, in this study, mixing intervals of 24 h and 12 h were selected and carried out mixing once a day and twice a day. The previous study obtained intermittent mixing at 5 rpm as an optimum speed for a pilot plant scale digester and produced a higher amount of biogas [30]. So, in this work, 5 rpm was selected as the mixing speed. The biogas produced in the digesters with a mixing facility is compared with the reference digester, one without a mixing facility, which operated for 21 days. The initial 7 days of the biogas production showed variation and steady-state was achieved after 7 days as shown in Fig. 2.

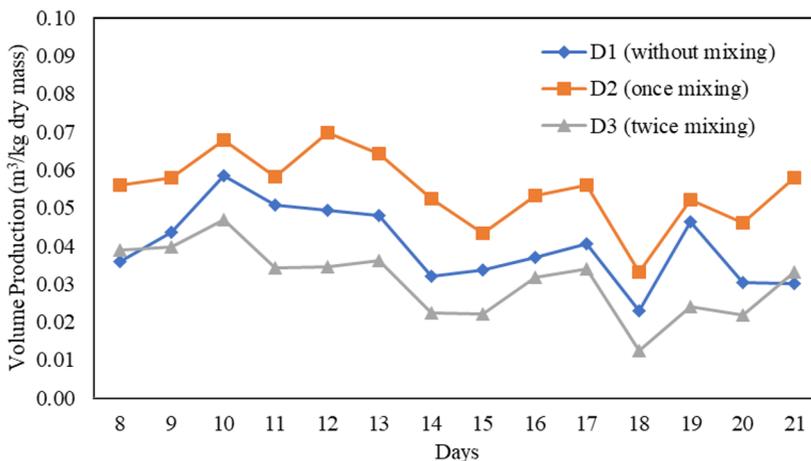


Fig. 2. Biogas production at mixing speed of 5 rpm with mixing time of 10 min and varied mixing frequencies

The volume of biogas produced in digester 1 (D1) with no mixing facility ranges from 0.03 m³/(kg dry mass) to 0.05 m³/(kg dry mass) in a steady state. On the other hand, 0.05 m³/(kg dry mass) to 0.07 m³/(kg dry mass) of biogas was produced by digester 2 (D2) with a mixing time of 10 min and mixing once a day. Digester 3 (D3) with the same mixing time of 10 min but with a mixing frequency of mixing twice a day produced biogas in the range of 0.02 to 0.04 m³/(kg dry mass) at a steady state. Digester 2 (D2) produced the highest amount of biogas with a mixing time of 10 min and mixing once a day which was double the biogas produced in digester 3 (D3) with the same a mixing time of 10 min but with mixing frequency of mixing twice a day. Biogas production in digester 2 (D2) was 60% higher than biogas production in digester 1, the stratified digester. Similar results were obtained in frequently adhered experimental trials. Kowalczyk et al. reported that a larger mixing interval produced a higher quantity of biogas than a smaller duration of mixing intervals and caused a reduction in power consumption [28]. In the current work, higher biogas production was obtained at a longer duration of mixing interval i.e., 24 h which is nothing but mixing once a day. The findings in this work are in line with the results reported in the literature. Therefore, it was observed that mixing favors biogas production with a minimum mixing frequency of once a day.

3.2 pH effect on biogas production at 5 rpm for semi-continuous process with varied mixing frequency.

In anaerobic digestion, the pH of the slurry is the major parameter that affects biogas production. Repeated runs were carried out and after statistical analysis, the results of biogas production at different pH were shown in Fig. 3. Variation in pH resulted in the difference in volume production of biogas. Fig. 3 elaborates the biogas produced over a range of pH from 4 to 6.3, the medium of production being acidic, for the digesters having an agitator speed of 5 rpm and mixing time of 10 min with varied mixing frequencies of once in a day and twice in a day. This volume production was compared to a reference stratified digester. The reference digester produced 0.019 m³/(kg dry mass) to 0.05 m³/(kg dry mass) of biogas within the reported pH range. Digester 2 (D2) with a mixing frequency of mixing every 24 h produced 0.023 m³/(kg dry mass) to 0.062 m³/(kg dry mass) of biogas within the same pH range. 0.011 m³/(kg dry mass) to 0.037 m³/(kg dry mass) of biogas was produced by digester 3 (D3) which was operated at a mixing frequency of mixing every 12 h. The range of biogas production clearly states that the production is higher in digester 2 which is operated at a mixing time of 10 min with a mixing frequency of mixing once a day. The graph interprets that increasing the pH of the slurry increases the amount of biogas produced. Maximum biogas production can be observed at pH 6.3 in digester 2. Nasir et al. stated that mixing affected pH value in anaerobic digestion which ended up in variation in biogas production. The current scenario obtained different biogas production at different mixing intervals. Thus, the results obtained in this investigation are in line with results reported in the literature [31].

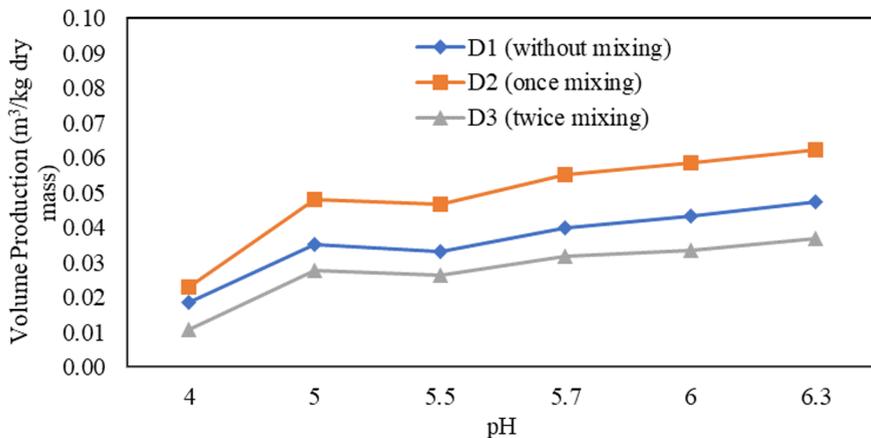


Fig. 3. pH effect on biogas production at mixing speed of 5 rpm with mixing time of 10 min and varied mixing frequencies.

3.3 Temperature effect on biogas production at 5 rpm for semi-continuous process with varied mixing frequency.

Alongside pH, the temperature has a huge impact on anaerobic processes, especially biogas production. The temperature range for biogas production under mesophilic conditions is 20°C to 40°C. Multiple experimental trials were performed and after statistical analysis, the results of biogas production at different temperatures were shown in Fig. 4. The average room temperature range is 20 to 30°C, so the temperature range of 20°C to 26°C was selected. Fig. 4 characterizes the amount of biogas produced at the temperature range of our interest under a similar mixing time of 10 min but varying

mixing frequencies. The amount of biogas produced was compared with the reference digester having no mixing facility. The reference digester (D1) produced $0.026 \text{ m}^3/(\text{kg dry mass})$ to $0.05 \text{ m}^3/(\text{kg dry mass})$ of biogas within the temperature range of interest. Digester 2 (D2) with a mixing time of 10 min and frequency of mixing once in a day produced biogas in the range of $0.03 \text{ m}^3/(\text{kg dry mass})$ to $0.063 \text{ m}^3/(\text{kg dry mass})$. Biogas produced in digester 3 (D3) with the same mixing time of 10 min and mixing frequency of mixing twice in a day lies in the range of $0.014 \text{ m}^3/(\text{kg dry mass})$ to $0.038 \text{ m}^3/(\text{kg dry mass})$. The biogas production ranges pointed to prefer the operation with the mixing time of 10 min with a mixing frequency of mixing once a day. The temperature range of 24°C to 26°C showed stable production of biogas for all the mixing frequencies and operation without mixing facility. Maximum biogas was produced in digester 2 at the temperature of 26°C .

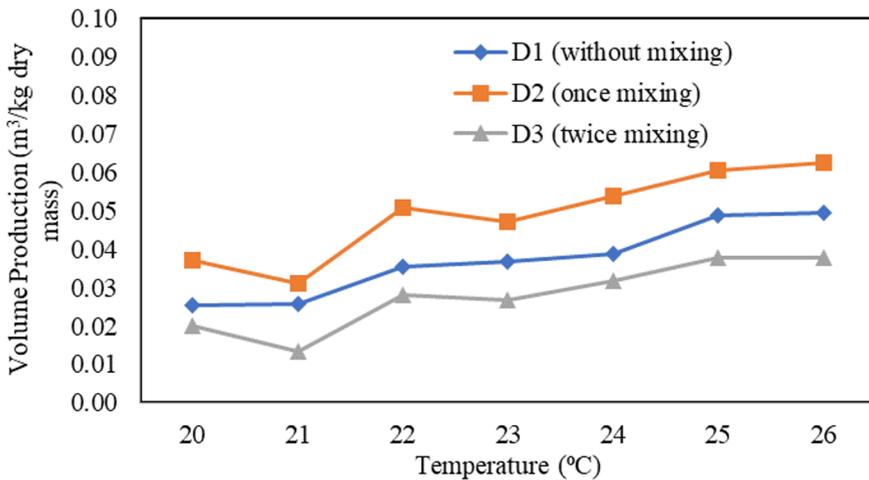


Fig. 4. Temperature effect on biogas production at mixing speed of 5 rpm with mixing time of 10 min and varied mixing frequencies.

3.4 Mixing effect at 5 rpm for semi-continuous process with varied mixing time.

In this run, the mixing speed for the digesters with mixing facility was maintained at 5 rpm and parameter mixing time was varied that of 5 min and 15 min respectively with the same mixing frequency of mixing once in a day (i.e. every 24 h). Fig. 5 defines the entire biogas production each day in a semi-continuous operation. The biogas produced in the digesters with mixing facility was compared with the reference digester, one without a mixing facility, which operated for 20 days. The initial 7 days of the biogas production in anaerobic digester required it to attain steady state later to which the analysis was reported. Biogas produced in the reference digester, digester 1 (D1) with no mixing facility, ranges from $0.03 \text{ m}^3/(\text{kg dry mass})$ to $0.05 \text{ m}^3/(\text{kg dry mass})$ in a steady-state. Contrary, digester 2 (D2) with a mixing facility operated for 5 min with a mixing frequency of mixing once in a day reported biogas production in the range of 0.08 to $0.12 \text{ m}^3/(\text{kg dry mass})$ of biogas. Digester 3 (D3) with the mixing time of 15 min and the same mixing frequency of mixing once in a day produced biogas in the range of 0.02 to $0.04 \text{ m}^3/(\text{kg dry mass})$. Since mixing improved the quantity of biogas production, a minimum mixing time of 5 min with a mixing frequency of mixing once a day obtained better results in terms of volume production.

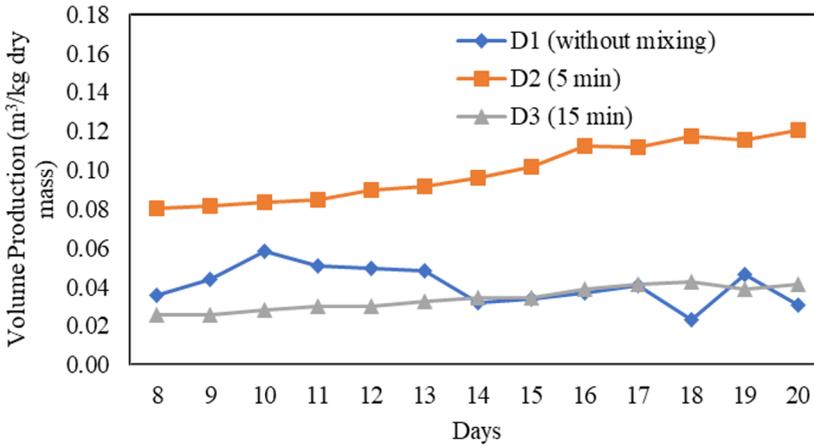


Fig. 5. Biogas production at mixing speed of 5 rpm with varied mixing times of 5 min and 15 min and same mixing frequency of mixing once in a day

3.5 pH effect on biogas production at 5 rpm for semi-continuous process with varied mixing time.

pH has an impact on biogas production not only at constant mixing time with varied frequencies but also imparts its participation at varied mixing times with constant mixing frequency. Repeated runs were carried out and after statistical analysis, the results of biogas production at different pH are presented as visual graphs. Fig. 6 depicts the volume of biogas produced for varying mixing times of 5 min and 15 min each with a mixing frequency of mixing once in a day over a pH range of 5.5 to 6.9. The biogas production in mixing facilities was compared to the biogas produced in a reference digester. Digester 1 (D1), being a reference digester with no mixing facility, produced biogas in the range of $0.03 \text{ m}^3/(\text{kg dry mass})$ to $0.086 \text{ m}^3/(\text{kg dry mass})$. Digester 2 (D2) operated at a mixing time of 5 min with mixing frequency of mixing once in a day produced $0.056 \text{ m}^3/(\text{kg dry mass})$ to $0.12 \text{ m}^3/(\text{kg dry mass})$ of biogas in the pH range of interest. Digester 3 (D3) with mixing time of 15 min and frequency of mixing once in a day reportedly produced biogas in the range of $0.016 \text{ m}^3/(\text{kg dry mass})$ to $0.04 \text{ m}^3/(\text{kg dry mass})$. pH affected the biogas production for each digester. The range of biogas production showed that maximum biogas was produced in digester 2 with a mixing time of 5 min with a mixing frequency of mixing once a day.

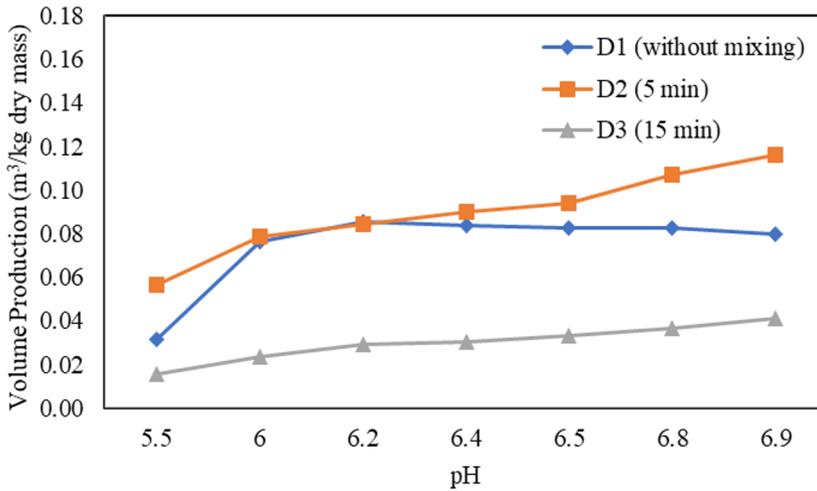


Fig. 6. pH effect on biogas production at mixing speed of 5 rpm with varied mixing times of 5 min and 15 min and same mixing frequency of mixing once in a day

3.6 Temperature effect on biogas production at 5 rpm for semi-continuous process with varied mixing time.

Temperature variation in biogas production affects the volume of biogas produced. The biogas volume produced has a sensitive relationship with temperature. Hence, the current interest range of temperature for this study is 27.5°C to 29°C. Frequent experimental runs were carried out and after statistical analysis, the results of biogas production at different temperatures were delivered. Fig. 7 shows the variation in volume production of biogas at different mixing times and varying temperatures. The biogas produced in mixing facilities was compared to the reference digester with no mixing facility. The digester 1 (D1) having no mixing facility produced 0.024 m³/(kg dry mass) to 0.083 m³/(kg dry mass) of biogas within the mentioned temperature range. Digester 2 (D2) with a mixing time of 5 min and mixing frequency of mixing once in a day produced biogas in the range of 0.054 m³/(kg dry mass) to 0.116 m³/(kg dry mass) in the similar temperature range. Biogas production in digester 3 (D3) with mixing time of 15 min and mixing frequency of mixing once in a day lies in the range of 0.015 m³/(kg dry mass) to 0.04 m³/(kg dry mass). The ranges of biogas production in each digester were compared and stated that digester 2 with a mixing time of 5 min and mixing frequency of mixing once in a day produced a higher volume of biogas. Stable biogas production can be observed in the temperature range of 28°C to 29°C. Digester 2 produced maximum biogas at 29°C.

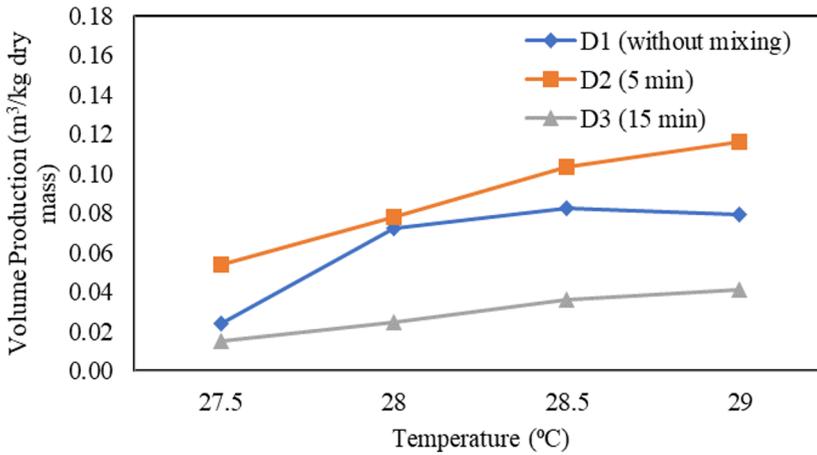


Fig. 7. Temperature effect on biogas production at mixing speed of 5 rpm with varied mixing times of 5 min and 15 min and same mixing frequency of mixing once in a day.

3.7 Mixing time effect on biogas production.

In this particular analysis, biogas production at various mixing times of 5 min, 10 min, and 15 min each with a mixing frequency of mixing once in a day (i.e. every 24 hr) was subjected. The mixing speed for all the digesters was maintained at 5 rpm. All these digesters were compared for the production of biogas for 20 days. The initial 7 days of the biogas production were required to attain a steady state later which the analysis was reported. Biogas produced in the digester with a mixing time of 5 min with mixing once a day was in the range of 0.08 m³/(kg dry mass) to 0.12 m³/(kg dry mass). The anaerobic digester with a mixing time of 10 min mixing once a day produced biogas in the range of 0.05 m³/(kg dry mass) to 0.07 m³/(kg dry mass). 0.02 m³/(kg dry mass) to 0.04 m³/(kg dry mass) of biogas production was acquired from a digester with a mixing time of 15 min and mixing once a day. Stable production of biogas was observed in the anaerobic digester with mixing times of 5 min and 15 min with a mixing frequency of mixing once a day for each digester. Apart from stabilized biogas production, the maximum volume of biogas was produced in the digester with a mixing time of 5 min and a mixing frequency of mixing once a day which was double than biogas production in a digester with a mixing time of 10 min and thrice mixing time of 15 min. Methane production obtained at 5 min mixing was 73% while methane content at 10- and 15-min mixing was 71%. Hence, a minimum mixing time of 5 min with a mixing frequency of once a day showed maximum and stabilized biogas production. Ratanatamskul and Saleart reported that 60 min per day was the optimum mixing time for the production of biogas from food waste [32]. In the present investigation, the highest biogas production was obtained at a mixing time of 5 min per day which was 15 times smaller than the reported value and resulted in a drastic reduction in power consumption.

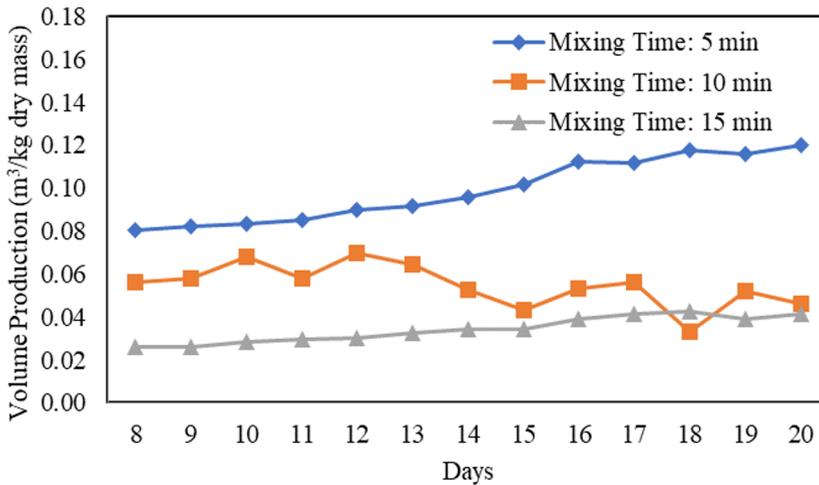


Fig. 8. Biogas production at mixing speed of 5 rpm with varied mixing times of 5 min, 10 min and 15 min and same mixing frequency of mixing once in a day

4. Conclusion

Anaerobic digestion of food waste at a mixing speed of 5 rpm was examined based on varied mixing times and corresponding frequency of mixing for biogas production. The major conclusions of the current investigation are listed below.

- Higher biogas production was observed in a digester with a mixing frequency of mixing once a day than in a digester with a mixing frequency of mixing twice a day. As compared to the digester with no mixing facility, 60% higher biogas was produced in the digester with mixing once a day.
- For the varied mixing time of 5 min and 15 min each with a mixing frequency of mixing once a day, the digester with a mixing time of 5 min produced the maximum amount of biogas. It quantifies three times the amount of biogas produced in a digester with a mixing frequency of 15 min and a digester with no mixing facility.
- Apart from stabilized biogas production, the maximum volume of biogas was produced in the digester with a mixing time of 5 min and a mixing frequency of mixing once a day which was double that biogas production in a digester with a mixing time of 10 min and thrice than mixing time of 15 min. Hence, a minimum mixing time of 5 min with a mixing frequency of once a day showed maximum and stabilized biogas production.

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