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Performance Augmentation of Household Batch Digester using a Circular Horizontal Extended Surface

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Keywords:
Anaerobic digestion; Biogas; Cow dung; Extended surface; Household digester.

Highlights:

- *Impact of different interior extended surface area of digesters on AD performance.*
- *CD was used as a substrate in digesters under mesophilic conditions.*
- *Digester D has a favored performance due to high extended surface area.*

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Abstract: The digester geometry significantly enhances household batch digesters' performance, especially the internal surface area. The present study investigates the impact of different extended surface areas augmented around inside digesters on anaerobic digestion performance. Four batch digesters were used, i.e., A, B, C, and D, with no extended surfaces, with four horizontal circular extended surfaces of width 2, 4, and 6 cm, respectively. Cow dung was used as a substrate in those digesters under mesophilic conditions. Experimental results show that the highest peak of methane contents were 70.78, 72.61, 73.82, and 74.22 %. High daily biogas production volumes were 18.4, 19.4, 19.5, and 20.8 L, and high accumulative biogas production volumes were 354.1, 425.3, 471.4, and 509 L for digesters A, B, C, and D, respectively. During the experiment start-up phase, pH values dropped to 6.5, 6.4, 6.2, and 6.1 for digesters A, B, C, and D, respectively. The four digesters' methane (CH_4) content values increased in the first days of the anaerobic digestion (AD) process. Favored performance and better biogas production outlined with digester D had a high interior extended surface area. The future work, organic loading rate (OLR), and temperature at different reactors to demonstrate its potential use in industrial applications. Co-digestion of STW with multiple organic wastes originating from a significant quantity of biogas at a single point can be investigated further.

تعزيز اداء الهاضم الدفعي المنزلي باستخدام سطح دائري افقي ممتد

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الخلاصة

يعمل شكل الهاضم على تحسين أداء هاضمات الدفعات المنزلية بشكل كبير، وخاصة مساحة السطح الداخلية.تبحث حداثة هذه الورقة في تأثير المساحات السطحية الممتدة المختلفة المعززة حول أجهزة الهضم الداخلية على أداء الهضم اللاهوائي.تم استخدام أربعة هاضمات دفعية A وB و C و D بدون أسطح ممتدة، مع أربعة أسطح دائرية أفقية ممتدة بعرض ٢ و ٤ و ٦ سم على التوالي. تم استخدام روث البقر كركيزة في تلك الهاضمات تحت ظروف متوسطة الحجم. أظهرت النتائج التجريبية أن أعلى قمة لمحتوى الميثان كانت ٧٠,٧٨، ٧٢,٦١، ٧٣,٨٢، ٧٤,٢٢٪؛كانت أحجام إنتاج الغاز الحيوي اليومية المرتفعة ١٨,٤ و١٩,٤ و١٩,٥ و٢٠,٨ لترًا، وكان حجم إنتاج الغاز الحيوي التراكمي المرتفع ٣٥٤,١ و٤٢٥,٣ و٤٧١,٤ و٥٠٩ لترًا للهضم A و B وC وDعلى التوالي. أثناء مرحلة بدء التجربة، انخفضت قيم الرقم الهيدروجيني إلى ٦,٥ و٦,٤ و٦,٢ و ٦,١ للهضم A وB وC وD، على التوالي. زادت قيم محتوى الميثان (CH4) في أجهزة الهضم الأربعة في الأيام الأولى من عملية AD يتميز الأداء المفضل وإنتاج الغاز الحيوي الأفضل الموضح بالهاضم D بمساحة سطح داخلية ممتدة عالية. العمل المستقبلي، ومعدل التحميل العضوي(OLR) ، ودرجة الحرارة، وما إلى ذلك وفي مفاعلات مختلفة لإثبات إمكانية استخدامه في التطبيقات الصناعية.يمكن إجراء مزيد من البحث في الهضم المشترك لمخلفات النفايات العضوية مع العديد من النفايات العضوية الناتجة عن كمية كبيرة من الغاز الحيوي في نقطة واحدة.

الكلمات الدالة: هضم لاهوائي، غاز حيوي، روث البقر، سطح ممتد، هاضم منزلي.

1.INTRODUCTION

One of today's environmental problems is the increase in organic waste products and how to remove them. Many countries are taking initiatives to minimize pollution and greenhouse gas emissions and ameliorate global climate changes. Anaerobic digestion (AD) of waste represented the best method to remove these wastes and convert them into biogas used as an industrial energy source, and degraded substrates high in nutrients offer a natural fertilizer for agriculture. AD is a microbiological process in organic wastes, such as sewage, industrial and agricultural, animal, solid, and water degrades organic waste without oxygen to create biogas in airtight reactor tanks known as digesters. This process includes numerous microorganisms that excrete enzymes and make monomers that function for themselves on or on a specific surface, as well as other organisms that transform substrate complicated substances into easily assimilated products. Bacteria or microorganisms degrade organic matter, which is found in complex groups and groupings that occupy large surface areas. Their broad dispersion, metabolic activity, growth, and reproductive depend on these surfaces. Therefore, huge surface areas result in speedy conversion, robust digestion, and quick microbe reproduction [1]. As a result, the percentage of bacteria growth increases with the enzymes bacteria release; therefore, the metabolic rate accelerates. Accelerating these metabolic rates yields a better-performing reactor and reduces the time required for production [2]. Two primary approaches are utilized to convert organic wastes into energy or fuels: (i) thermochemical conversion and (ii) biochemical conversion. Thermochemical conversion encompasses various processes, such as direct combustion, pyrolysis, and gasification, which are illustrative examples. Two examples of biochemical conversion include anaerobic digestion and fermentation. According to Chen et al. [3], biochemical conversion has been identified as the optimal strategy for achieving the highest possible energy recovery from organic wastes. This method applies when an organic waste stream exhibits minimal metal content. Anaerobic digestion is a well-acknowledged and established biochemical conversion technique to decompose biodegradable organic substances. This process occurs in the absence of oxygen and involves the participation of bacteria, producing biogas as a secondary output. Process stability is of utmost importance in the anaerobic digestion process. Inhibition can be a contributing factor to the occurrence of instability among microorganisms. Various inhibitory substances can have an adverse impact on the anaerobic digestion process. These substances include sulfide, ammonia, and heavy metals, such as iron, zinc, nickel, cobalt, chromium, mercury, lead, and manganese. Additionally, organic compounds, such as chlorinated hydrocarbons, compounds with benzene rings, cyanides, phenols, alkyl phenols, lignin-related compounds, organic acids (specifically long fatty acids and amino acids), and citrus oils, such as limonene, have been found to affect anaerobic digestion adversely [4,5]. Microorganisms or bacteria live on surfaces. In the presence of the substrate, they release enzymes that degrade the substrates and conduct chemical reactions that convert them into other materials [6]. In turn, the bacteria grow and reproduce on these surfaces. When the surfaces increase, the growth of bacteria increases, the enzymes increase, and thus, the decomposing materials increase. Therefore, the chemical reactions accompanying the generation of gases, including methane and carbon dioxide, increase. In this study, the surfaces were increased by providing the anaerobic digesters from the inside with circular surfaces extending horizontally to increase the growth of bacteria and thus increase biogas production. Most of the experiments on optimizing biogas production and anaerobic digestion have focused on factors to consider when designing digesters, such as the type of feedstock, co-digestion, pretreatment, mixing, the effect of temperature, the shape, and the way the digester is set up. Sambusiti et al. [7] evaluated the impact of alkaline pretreatment on AD of ensiled sorghum forage. Applying various mechanical pretreatment processes to ensiled meadow grass to study their influence on substrate biodegradability has been investigated by [8-20]. Rodríguez et al. [21] compared the AD of the municipal solid waste organic fraction in a batch reactor at mesophilic and thermophilic temperatures. A series of batch tests were conducted to investigate the performance of mesophilic and thermophilic processes in the degrading organic fraction of municipal solid waste with a total solids content of 20% under dry conditions. The tests included an appropriate inoculum source, with the inoculum rate being 30% based on the total volume of the trash. Whittle et al. [22] investigated the concentration impact of volatile fatty acids under mesophilic and thermophilic conditions in AD on methanogenic communities. Two digesters, one operating in a mesophilic environment and the other in a thermophilic environment, were tracked, and samples were taken when VFA levels were low or high. Physical and chemical characteristics were measured, and a phylogenetic microarray was used to screen the diversity of methanogenic organisms. Li et al. [23] evaluated the AD performance of pig manure, cow dung (CD), and various ratios of their mixtures in a batch digester at mesophilic temperature. Laboratory reactors with a single stage were used for the research. Each bioreactor has an effective volume of 2.5 L, a 13 cm internal diameter, and a 25 cm height. The water bath used to maintain the capped reactors was kept at 35 °C, the ideal temperature for the mesophilic range. Each reactor featured four ports. Priadi et al. [24] investigated the AD of paper sludge produced from wastewater treatment and compared the influence of CD on paper sludge. Following production, wastewater proceeds to primary physical treatment, including sedimentation, and secondary physical treatment, including aerobic suspended growth tanks. The volume of the sludge from the primary and secondary treatments is then decreased using the primary clarifier and belt press. The biogas production from the mesophilic AD of CD using materials as a catalyst has been studied by [25-35]. Janke [36] evaluated the impact of various concentrations of urea supplementation and sodium hydroxide pretreatment to enhance volatile fatty acid (VFA) and increase methane production on the AD of sugarcane filter cake in a batch digester. Batch tests were conducted to evaluate sodium hydroxide (NaOH) pretreatment at various concentrations, and the cumulative methane yields were fitted to a dual-pool two-step model to offer a preliminary evaluation of AD. In a semi-continuously operated reactor, the effects of nitrogen supplementation in the form of urea and NaOH pretreatment for enhanced VFA generation were also assessed. Meadow grass can be a suitable co-substrate. If ensiled, the meadow grass can be supplied to biogas plants continuously throughout the year studied by [37]. Nevertheless, this substrate is quite recalcitrant; therefore, efficient pretreatment is needed to permit microbes easy access to the degradable components. Different mechanical pretreatment methods were applied to ensiled meadow grass to investigate their effect on biomass biodegradability. Two laboratory-scale digesters were constructed to digest cow dung. One set-up was used for digestion without a catalyst, and the other was for digestion with a catalyst. The digesters were made of glass conical flasks of 1-liter capacity each [38]. Nasir et al. [39] investigated a single-stage digester created and built on a laboratory scale. Tomato processing wastes utilized as feed materials for digestion were acquired from the Zoshk Khorasan Company (Mashhad, Iran). Some of the digested materials' characteristics were determined. Saghouri et al. [40] investigated fresh animal dung, including pig, cow, and goat dungs, from Maejo University's farm in Chiang Mai, Thailand. Sun Sweet Co., Ltd, Chaimai Thailand (98°50'53.4" E) provided the sweet corn (Zea mays L.) wastes of corn crust, sweet corn cobs, and corn seeds. Corm seed, corn cob, and corn husks were ground to a size of around 2 cm long. The qualities of these plants were evaluated using proximate analysis (%wt, dry basis) and ultimate analysis (%wt, dry basis). The maize cobs and husks were processed by soaking in 2% (w/v) NaOH for 48 hours at room temperature. Whereas grinded maize seeds were used immediately without alkali preparation. This paper is essential in producing biogas, used in lighting, cooking, and as a fuel in industrial facilities and electric power plants. It is an important renewable energy source easy to obtain and cheap. Moreover, it reduces gas emissions compared to fossil fuels and coal. Furthermore, it was concluded that the efficiency increases of biogas production from the household digester without incurring any costs or spending any energy by changing the shape of the digester. Unfortunately, few researchers dealt with this aspect, like many who dealt with improving biogas production by studying the effects of factors affecting anaerobic digestion. The present study investigates the impact of different extended surface areas augmented around inside digesters on anaerobic digestion performance. The study used four batch digesters, A, B, C, and D, with no extended surfaces and four horizontal circular extended surfaces of width 2, 4, and 6 cm, respectively. The study evaluates the performance of these digesters in terms of methane content, daily biogas production volumes, and accumulative biogas production volume. The results showed that the highest peak of methane content and biogas production volumes were achieved in the digester with the highest extended surface area. This finding suggests that increasing the internal surface area of household batch digesters can significantly enhance their performance and improve the efficiency of organic waste conversion into biogas. Therefore, the novelty of this study lies in its focus on the impact of extended surface areas on anaerobic digestion performance and its potential for optimizing the design and operation of household batch digesters.

2.MATERIALS AND METHODS

2.1.Substrate Preparation

The new CD can be collected from the farms in Mosul City, Iraq, as seen in Fig. 1. After cleaning, it was mashed into a paste using a hopper, as shown in Fig. 2. The substrate was prepared by mixing 1 kg of CD with 1 liter of river water to contain large amounts of bacteria, as seen in Fig. 3.

Fig. 1 Cow Dung.

Fig. 2 The Hopper.

Fig. 3 Substrate Prepared.

2.2.Calculation of CD Properties

The properties of CD, i.e., moisture content, total solid (TS), volatile solid (VS), and ash content, were analyzed according to examination standard methods for water and wastewater [41-43], as described below: A 100-g (W1) sample of CD was placed in a drying oven at 105 °C for ten hours to dry and drive off the water from the sample. After that, the sample is removed, cooled, and weighted (W2) with a digital balance. Finally, the dried sample was burned in an incineration furnace at 550 °C for three hours and then weighed again (W3). The moisture content, total solids, volatile solids, and ash content have been calculated using Eqs. (1)- (4) and based on the data shown in Table 1.

$$\text{Moisture content (\%)} = \{(W1-W2) / W1\}\times 100 \quad (1)$$

$$\text{Total solids (TS)} = 100 - \text{Moisture content} \quad (2)$$

where:

W1 = Weigh of the sample before drying.

W2 = Weigh of the sample after drying.

$$\text{Ash content} = (W3/W2)\times 100 \quad (3)$$

$$\text{Volatile solids (VS)} = 100 - \text{Ash content} \quad (4)$$

Where:

W3 = Weigh of the sample after burning.

Table 1 The Properties of Cow Dung.

Substrate	Moisture content, %	TS, %	VS, %	Ash content, %
CD	80	20	86.96	13.04

3.EXPERIMENTAL SET-UP

Four household batch cylindrical anaerobic digesters (A, B, C, and D) fabricated from PVC plastic of 6 mm thickness with 13 L total volume, 29 cm height, and 24 cm diameter. The lid was sealed so as not to allow air. Each batch digester's CD substrate working volume was 10 L (5 kg) at 22 cm height. Digester (A) had no extended surfaces. At the same time, digesters B, C, and D contained four circular horizontal extended surfaces with a thickness of 2.5 mm and width of 2, 4, and 6 cm, respectively. The spacing between extended surfaces was 5 cm, as shown in Fig. 4.

Fig. 4 An Arrangement of Extended Surfaces in the Digesters.

Four holes were on the top of each digester. The first hole was 5 mm in diameter. A rubber tube was connected to this hole to pass the generated biogas from the digester into the storage tank. The second hole had a diameter of 5 mm and was fitted with a pressure gauge. The third hole was used for a temperature sensor. The fourth hole had a diameter of 2.54 cm and was provided with a plug. It was used to feed the substrate into the digester. Finally, on the side of each digester at 11 cm height, there was a 1.27 cm-diameter drain hole with a plug. Figs. 5 and 6 illustrate the photograph and schematic for the household anaerobic digester set-up. A gas data analyzer device, type RASI 700 model, was used to calculate the percentage of biogas components, methane, carbon dioxide, oxygen, and hydrogen sulfide concentrations generated by the AD system. This instrument's measuring operations include a conventional set-up with O_2, CO_2, H_2S, and CH_4 percent utilizing infrared technology. The Data logger multi-channel instrument model AT 4508 was used to measure the anaerobic digester's temperature. The specifications of this instrument are 0.1 °C resolution, ± 0.2 °C precision, and a -200 – 1300 °C measuring range, see Table 2.

Fig. 5 Photograph of Domestic Anaerobic Digesters Set-up.

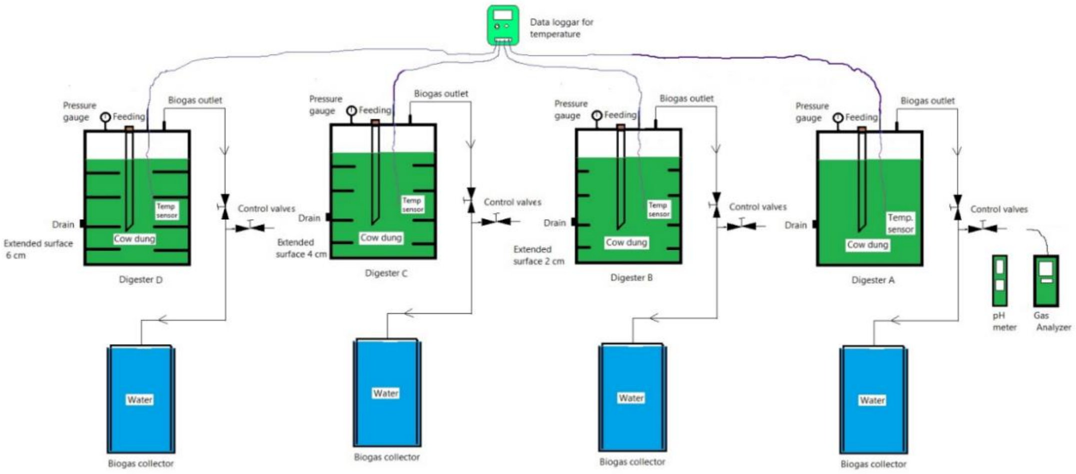


Fig. 6 Schematic Domestic Anaerobic Digester Set-up.

Table 2 Specifications of Data Logger Instrument.

Data Logger MultiChannel	
Meter Type	Tester
Model	AT 4508
Min Temperature	0°C
Max Temperature	50° C
Temperature Resolution	0.1°F (0.1°C)
Temperature Accuracy	±0.9°F (0.5°C) + 1 LSD
Temperature compensation	Automatic
Channel	8 ports
Senser	Type (K)

Eco Testr pH2 digital meter was used to monitor the CD's pH value in the digester daily. The pH meter was calibrated using three buffered pH=4, pH=7, and pH=10. This instrument is waterproof, has a 0 – 14 pH measuring range, and a ± 0.01 precision, see Table 3. All measuring devices were checked before use to avoid errors.

Table 3 Specification of pH Digital Meter.

Eco testr pH2 Digital Meter	
Meter Type	Tester
Display type	Digital
Min pH (pH)	0
Max pH (pH)	14
pH Resolution	0.1 pH
pH Accuracy	±0.01 pH
Buffer Recognition	NIST and USA

3.1.Experimental Procedures

Several necessary procedures were considered to obtain experimental data, which can be summarized by the following steps:

1) Prepare the digesters and biogas storage tanks.
2) CD collecting, then cleaning manually with gloves from impurities and inorganic wastes with gloves, and mechanical pretreatment was done using a hopper to mash the CD substrate into a paste for homogeneity.
3) Weigh 20 kg of CD and mix it with 20 L of water from the river by hand until homogenized.
4) Charge each digester with 10 L of the substrate.
5) Measure the pH and temperature of each digester and the ambient temperature as an initial condition.
6) Open the biogas storage tank valve and close the biogas outlet valve.
7) AD will be started.
8) After each 24 h, the ambient temperature, temperature value, pH value, the volume of generated biogas, and concentration of CH_4, CO_2, and H_2S for each digester were measured and recorded, besides the pressure of each digester should be observed.

3.2.Mechanism of the Experimental Work

The mechanism of this work involves increasing the internal surface area of household batch digesters by providing circular surfaces that horizontally extend; increasing surface area promotes the growth and reproduction of bacteria, which in turn increases the decomposition of organic materials and the generation of gases, such as methane and carbon dioxide. The study explores the impact of different extended surface areas on anaerobic digestion performance, and the results showed that larger surface areas lead to better performance in terms of biogas production. The study also evaluated the impact of various factors, such as feedstock type, co-digestion, pretreatment, mixing, and temperature, on anaerobic digestion performance. Overall, the mechanism of this work involved optimizing the design and operation of household batch digesters to increase biogas production and improve the efficiency of organic waste conversion into energy or fuels.

4.RESULTS AND DISCUSSION

The experimental results of the effect of different areas of circular horizontal extended surfaces attached to the inside of batch digesters on anaerobic digestion performance, represented by quantity and quality, time increase, and starting-up time of biogas production. Data were taken from experiments conducted in laboratories of the Northern Technical University, Iraq-Mosul, for digestion between 28/5/2022 and 13/8/2022 (77 days). Figure 7 illustrates the ambient and interior digester temperatures during the anaerobic digestion of CD with digestion time. The ambient temperatures varied between 37.5 °C and 44.5 °C during the data recording period. The ambient temperature increased during the first eight days of the experiment and then decreased during the 9th and 10th days. After that, the ambient temperature increased for four days, then reduced and continued with this fluctuating rise until the experiment ended, as seen in Fig. 7. The ambient temperature increase allows cow dung to be properly digested and helps biogas production by increasing microorganisms' activities in digesters. Conversely, when the ambient temperature decreases, the microorganism's metabolic activity is inhibited in digesters, reducing biogas production. The ambient temperature observation results correspond with earlier works [12]. Although the digester's temperatures are uncontrolled, monitoring investigated steady temperatures between 35.4 °C and 39.8 °C, indicating mesophilic conditions, as shown in Fig. 7, which agrees with Priadi et al. [24]. The CD substrate pH values were recorded daily for each digester for 77 days. The range of pH variation was 6.1 to 8.6 with digestion time. The initial pH value of CD was 7.5 for all digesters. However, during the experiment start-up phase, pH values dropped to 6.5, 6.4, 6.2, and 6.1 for digesters A, B, C, and D, respectively, as illustrated in Fig. 8, representing the pH variation of CD for digesters with digestion time during anaerobic digestion. The reason is producing volatile fatty acids (VFA) by acidogenic bacteria that consume the CD substrate. Digester D had a lower pH value than other digesters because it had a large extended surface area, increasing the degradation area available for bacteria. After that, the pH value gradually rose for all digesters, however, slowly in digester D due to a higher quantity of VFAs degraded than in other digesters. Finally, after the 30th day of the experiment, a stable pH value of 8.5 for all digesters was observed due to consuming all VFAs produced, ammonium bicarbonate production, and methane production. This pH variation behavior is compatible with previous works [41-43].

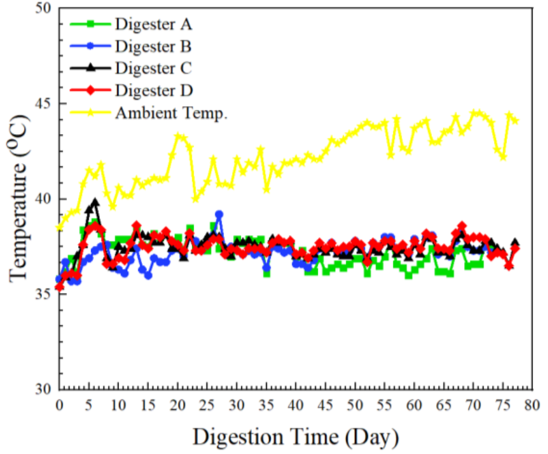


Fig. 7 Ambient and Inside Digesters Temperatures During Cow with Digestion Time.

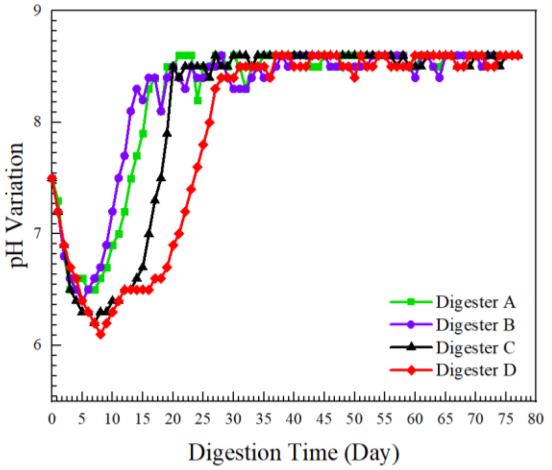


Fig. 8 pH Variation of the Digesters with Digestion Time During Anaerobic Digestion.

Figure 9 illustrates the hydrogen sulfide (H_2S) concentration in biogas products during AD with digestion time for digesters. It was observed that H_2S concentrations for all digesters rose from the first day to the 8th day of the experiment and then declined until the 30th day. The justification is the formation of H_2S from sulfur in the CD substrate and reaction with hydrogen products generated from other chemical reactions due to substrate degradation by bacterial activity. H_2S in AD is undesirable because it causes methane bacteria poisoning and inhibits methane production [44]. Therefore, the H_2S concentration behavior of the present investigation conformed to previous work reported by [45]. Also, it was observed that the H_2S concentration had a higher value for digester D of 1962 ppm and a lower value for digester A of 671 ppm than other digesters because digester D had a large extended surface area. As a result, the growth and activity of bacteria on surfaces that digest more substrate quantity increased, increasing reactant quantity, and chemical reactions resulted in sulfur and hydrogen forming H_2S gas with a high concentration. In addition, it is noted that the difference in the concentration of H_2S between digester D and other digesters was vast due to its sulfur concentration at a higher percentage than other digesters and its large extended surface area, which is out of control due to difficulty measuring substrate component concentrations.

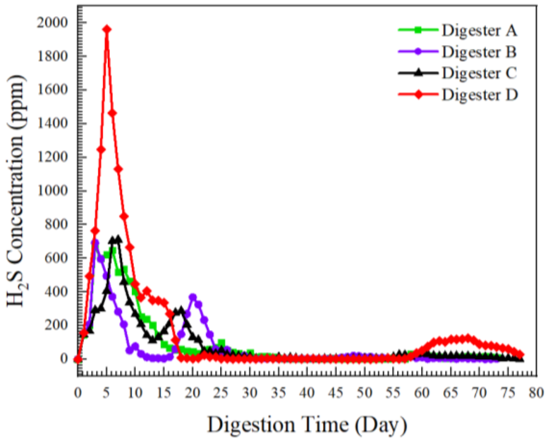
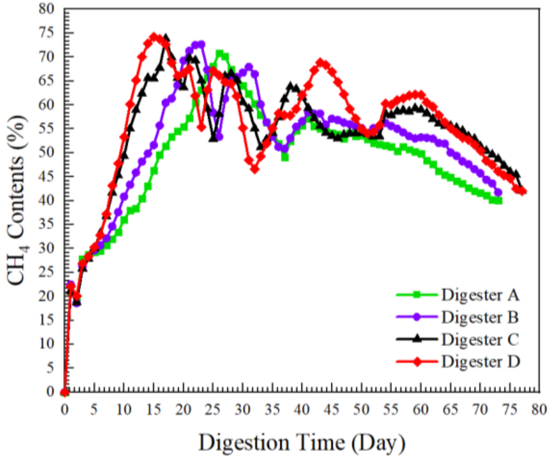
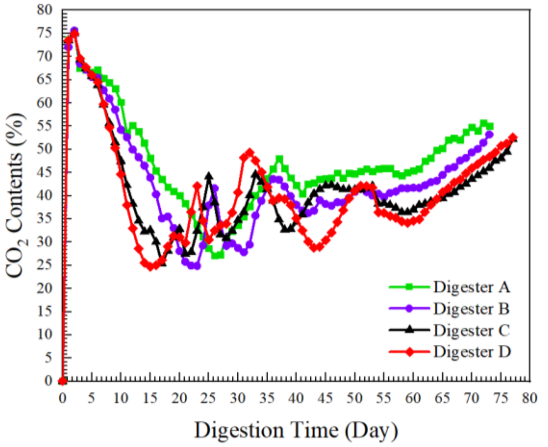


Fig. 9 Hydrogen Sulfide H_2S Concentration in Biogas Production During AD with Digestion Time for Four Digesters.

In the present work, four digesters' methane (CH_4) content values increased in the first days of the AD process. It reached its highest peak of 70.78, 72.61, 73.82, and 74.22 % on the 27th, 24th, 18th, and 16th days for digesters A, B, C, and D, respectively. Then, it decreased till the experiment's 38th, 27th, 21st, and 24th days, respectively; after that, it increased for five days for all digesters, as depicted in Fig. 10 (A). Figure 10 shows the CH_4 and CO_2 contents in biogas production with digestion time for four digesters because the methanogenic bacterial growth consumes the VFA and acetate and converts them to CO_2 and CH_4. The CH_4 content values of digesters A and B started declining during the residual four weeks of AD until the experiment ceased due to methanogenic bacterial death as a result of age or depletion of acetate. In digesters C and D, the CH_4 content values were raised and dropped twice until the experiment stopped, as shown in Figs. 10 (A). This fluctuation of CH_4 content values is due to the ambient temperature fluctuation, as illustrated in Fig. 7. Where the methanogenic bacteria are affected by temperature, the latter increased bacteria activity. Also, it was noticed from Fig. 10 (A) that digester D had significant CH_4 content, high CH_4 quality of 74.22 %, and faster CH_4 production on the 16th day than other digesters because digester D has a large interior extended surface area where more methanogenic bacteria grow on these surfaces and high methane concentration. Carbon dioxide (CO_2) content, which is a significant impurity produced in the biogas, rose in the first two days for all digesters, followed by a drop until the 27th,24th,18th, and 16th for digesters A, B, C, and D, respectively, then it increased with fluctuation, as depicted in Fig. 10 (B) because a significant amount of CO_2 was generated during the acetogenesis stage of the AD process when butyrate and propionate acids were converted to H_2, CO_2, and acetate. In addition, Acidogenesis bacteria evolve more rapidly than methanogenesis bacteria. As seen in Fig. 7, the ambient temperature fluctuation fluctuated the CO_2 content fluctuation. The results were obtained in conformity with other studies [14, 23].



A- Methane CH_4 Content (%).



B- Carbon Dioxide CO_2 Content (%).

Fig. 10 Daily Methane CH_4 and Carbon Dioxide CO_2 Contents (%) in Biogas Production of All Digesters A- CH_4 Contents. B- CO_2 Contents.

Figure 11 implies the biogas production volume with retention time for all digesters. Biogas production was high for the first two days of the experiment. Initially, the biogas had almost CO2 content formed from substrate degradation by acidogenic bacteria and VFA consumption by acetogenic bacteria during AD's acidogenesis and acetogenesis process. Then, it suddenly decreased till the 7th day for all digesters due to the VFA depletion and acetate and conversion to CH_4 and CO_2. After that, the biogas production started gradually increasing until reaching the peak of 18.4, 19.4, 19.5, and 20.8 L on the 28th, 27th, 27th, and 22nd days for digesters A, B, C, and D, respectively, because methane forming from acetate degradation by methanogen bacteria during methanogenesis process of AD. Then, biogas production declined until days 32nd, 28th, 30th, and 24th. Then, it rose to 10.1, 12.3, 17.5, and 18.5 L for digesters A, B, C, and D, respectively, due to no complete acetate consumption by methanogenic bacteria and increasing ambient temperature. Finally, it dropped gradually until the experiment finished, except digester D's biogas generation increased to 16 L on day 35th. After that, it decreased until the experiment ended due to methanogenic bacterial death, as shown in Fig. 11. The results were similar to [7, 22, 32]. Figures 10 and 11 show that digesters C and D have a more extended period for biogas production in the AD process of 77 days than other digesters, 73 days. Digester D had a faster start-up of the AD process and maximum biogas production than other digesters because the slurry exposed the greater surface area for rapid multiplications of the methaprogen to utilize the CD entirely [12].

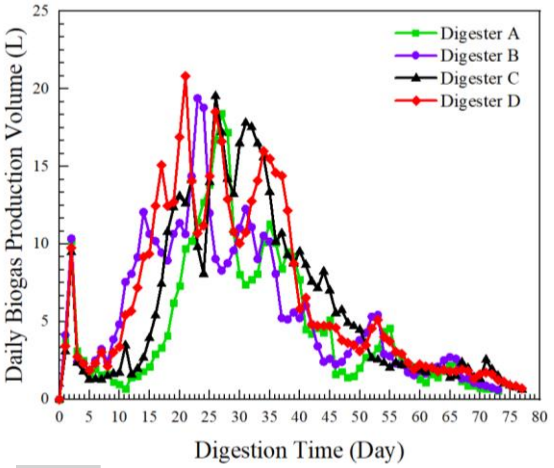


Fig. 11 Daily Biogas Production Volume (L) for Four Digesters.

The performance of this work shows a cumulative yield variation of biogas production volume with digestion time for all digesters, as shown in Fig. 12. The production values for CD cumulative yield were 354.1, 425.3, 471.4, and 509 L for digesters A, B, C, and D, respectively, indicating that digester A had a lower cumulative yield of biogas production. In contrast, digester D had a better accumulative gain. So, digester D performed better than other digesters because it had a larger interior extended surface area, exposing more CD to bacteria growth and metabolism resulting in more excellent digestion, higher biogas production, and performance improvement.

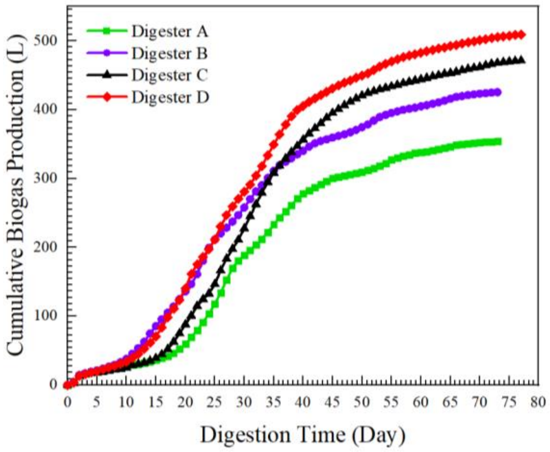


Fig. 12 Cumulative Biogas Production with Retention Time for Four Digesters.

4.1.Results Analysis

Based on practical results from experiments, the particle swarm technique optimization modeled by MATLAB 2018a program to select the optimum interior circular horizontal extended surface area of the household batch anaerobic digesters on biogas production as the performance enhancement. The experimental results showed that the digester's internal circular horizontal extended surface area, the anaerobic digestion performance, and biogas production increased. Digester D, which had a 6 cm wide extended surface, performed better than other digesters. Still, when the interior extended surface area of the digester D increased continuously, the performance might be stopped or reduced. Therefore, raising the internal extended surface area may lead to the suppression of the anaerobic digestion processes. Hence, the optimum width of the interior circular horizontal extended surface was 5.3 cm obtained from particle swarm optimization, depending on experimental results.

5.CONCLUSIONS

An experimental study has been conducted on the impact of various interior circular horizontal extended surface areas of household batch digesters on AD performance effectiveness and biogas production. The experiment produced biogas from digesters augmented with a different area of circular horizontally extended surfaces using 5 kg of cow dung for each digester at mesophilic temperatures. The present study showed that digester D had a higher peak value of methane content and accumulative biogas production volume of 74.22 % and 509 L, respectively, than other digesters, indicating that high quality and quantity of biogas production lead to enhancing performance. On the other hand, digester A had a peak value of 70.78 % and 354.1 L for methane content and accumulative biogas production volume, respectively, representing low performance. Furthermore, the AD processes started early and took more time for digesters C and D than other digesters, implying better performance. It was concluded that digester D had a preferable performance. Therefore, when the digester's interior circular horizontal extended surface area increased, the AD performance and biogas production increased.

The future work may be conducted under various operating conditions (organic loading rate (OLR) and temperature) and at different reactors (continuous and fed-batch systems), which were unconsidered in this study to demonstrate its potential use in industrial applications. Co-digestion of STW with multiple organic wastes originating from agriculture, municipal, and industrial wastes for producing a significant quantity of biogas at a single point can be investigated further. To ensure the purity and yield, evaluating the pretreatment of STW is possible.

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NOMENCLATURE

AD	Anaerobic Digestion.
CD	Cow Dung.
STW	Spent Tea Waste
TS	Total Solids.
VS	Volatile Solids.
VFA	Volatile Fatty Acids.

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