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DESIGN AND INSTALLATION OF A BIOGAS PRODUCTION UNIT OPERATING WITH AUTOMATIC CONTROL SYSTEM

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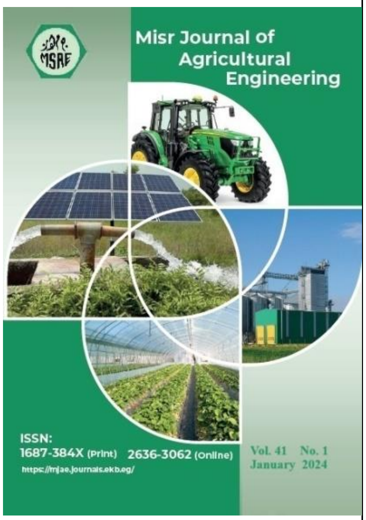

Keywords:
Renewable energy; Biogas; Digester design; Wastes; Automatic control.

ABSTRACT

The aim of this research is to design and construct a home biogas digester operating with automatic control system to improve gas production. A 72-liter home biogas digester with an automatic control unit was designed and built to control anaerobic fermentation factors. A mixing unit was used to mix and grind the waste before entering the digester. A stirring unit to control the stirring time and a heating unit to control the temperature as well as monitoring it inside the digester were added. an automatic control system including fire detector for safety, temperature, and gas sensors, through mobile application for monitoring and some other components were used to make the unit more controllable, easier, and safe. To evaluate digester performance, the digester was run for three phases (each with 30 days retention time). The first phase (I) was done without using control system at ambient temperature which ranged between 24 ºC and 26 ºC, while the second and the third phases were done at two different temperature levels, mesophilic at 35ºC (phase II) and thermophilic at 50ºC (phase III). The digester was continuously fed with 4 liters/day (2 liters waste + 2 liters water). Temperature, pH, and produced gas quantity were monitored daily (5 days a week). Cumulative gas quantities for phase I, phase II and phase III were 165.92, 498.92 and 616.56 L, respectively. This means that, raising temperature from ambient to 35 and 50ºC increased gas quantities by 2 and about 2.71, folds respectively.

INTRODUCTION

Biogas can be defined as a mixture of methane, CO_2, water, and small quantities of other gases generated from organic digestion under anaerobic conditions. This is considered as an alternative energy source. This energy can be utilized in both rural and industrial fields. Biogas technology offers a very attractive route to utilize certain categories of biomass. Unlike other forms of renewable energy, biogas has no any geographical limitations or required technology for producing energy and it is not complex or monopolistic (Balat and Balat, 2009; Petersson, 2013).

Anaerobic digestion (AD) is defined as bacteria degradation of biological and organic matter in the absence of oxygen generates biogas (Pain and Hepherd, 1985). Many various types of organic waste can be used as a feedstock such as livestock manure, sewage sludge and food waste. Depending on the feedstock, biogas is principally mixture of about 55-60% methane (CH_4), 35-40% Carbon dioxide (CO_2) and minute traces of 0-2% hydrogen sulphide (H_2S), 0-1% hydrogen(H), 0-2% nitrogen(N), 0-0.05% ammonia (NH_3) and 0-0.5% sulfur dioxide (SO_2) (Elashry, 2001; Vij, 2011).

Kitchen waste is an organic material which can efficiently be used to produce biogas due to its high calorific and nutritive value and biodegradability by microbes, which will decrease dependency on fossil fuels (Balat and Balat, 2009; Satyanarayana, S. & Srinvasa, 2017). Food wastage is different from country to another depending on their levels of development and consequently on the standards of living (Gustavsson *et al.*, 2011).

- **Factors affecting anaerobic digestion (AD) process.**

There are certain conditions that must be ideal to keep the microorganisms involved in balance to achieve satisfying microbial growth and activity. The critical parameters affecting microbial growth and activity are temperature, pH, hydraulic retention time (HRT), organic loading rate (OLR), stirring, total & volatile solid concentration (TS, VS) the carbon to nitrogen ratio (C/N ratio), The specific surface area of the material ,absence of oxygen, presence of toxic compounds and inhibitor concentration during the digestion process (Ahmed et al., 1999; Diaz and Savage, 2007; Induchoodan, Haq and Kalamdhad, 2022).

Temperature

Operating temperature is an important factor affecting the performance of the anaerobic digestion (AD) reactors because it is an essential condition for the survival and optimum adapting of the microbial activity and directly affect retention time and gas production. It can be distinguished between three ranges of temperature: psychrophilic (<20ºC), mesophilic (30-42ºC) and thermophilic (43-55ºC) (Elashry, 2002; Al Seadi *et al.*, 2013). Decrease in temperature has a detrimental effect on various AD operating parameters and imposes a strong negative impact on microbial growth and enzymatic activity(Akindolire, Rama and Roopnarain, 2022). Mesophilic and thermophilic are considered the most preferred temperature ranges for biogas production (Chen and Neibling, 2014) .

Acidity and alkalinity (pH value) of substrate

The pH is preferably to be within the range from 6.0 to 8.5 during the anaerobic digestion process (AD). The methanogens grow optimally at around neutral pH and a pH value outside this range can inhibit their growth, thus resulting in unstable digester performance and sometimes even process failure (Chandra, Takeuchi and Hasegawa, 2012). To maintain pH value to 7, the continuously fed digesters requires addition of sodium hydroxide (NaOH) (Vikrant, Ajit and Yogesh, 2014).

Hydraulic retention time (HRT)

Hydraulic retention time (HRT) is the average time that the slurry remains in a biogas digester. The minimum HRT should be longer than the doubling time of the microorganisms to avoid washout. Under mesophilic conditions, a typical HRT is 15-30 days and slightly shorter under thermophilic conditions (Braun *et al.*, 2010; Mao *et al.*, 2015).

Organic loading rate (OLR)

The organic loading rate (OLR) can be defined as the amount of organic material (volatile solids, VS) fed daily per liter of digester volume (g VS /L/day)(Mata-Alvarez et al., 2014 ,). This rate is range between 1.4 and 22 kg VS/m^3 for successful digestion of food waste (Liu *et al.*, 2017; Paritosh *et al.*, 2017; Xu *et al.*, 2018). OLR of 1.5 kg VS /m^3 is an optimum for steady methane production under mesophilic digestion of food waste (Liu *et al.*, 2017). On the other hand, Babaee and Shayegan(2011) reported that OLR of 1.4 kg VS/m^3 vegetable waste was an ideal material for obtaining highest and stable methane production .There is a positive relationship between OLR and total methane yield, however, the process can be unstable and process failure may even occur, if a certain OLR value is exceeded (Mata-Alvarez *et al.*, 2014).

Stirring

Stirring is one of the important parameters to be considered in the design of an anaerobic digester. It can increase the rate kinetics of anaerobic digestion, accelerating the biological conversion process, and allows uniform heating of the reactor. It can be done mechanically through motorized impellers or turbines within the reactor or pneumatically by injecting gas. Kaparaju et al., (2008) found that the methane production was improved by 1.3% and 12.5%, respectively for intermittent and minimal stirring.

Total & Volatile solid concentration (TS, VS)

Total solid (TS) is defined as the weight of the dry matter of an anaerobic digestion substrate. This weight is expressed as a percentage of the total weight of the substrate sample (Schmidt, 2005). TS content of the substrate is usually used to classify two different types of anaerobic digestion; wet digestion (TS content is less than 15%) and dry digestion (TS content is between 15-20%) (Karthikeyan and Visvanathan, 2013).

Volatile solid (VS) is the percentage of the solid material of the digestion raw materials inside the digester that can be broken down by the bacteria to produce biogas. This part varies from an organic waste material type to another. VS content can be calculated by dividing the weight of volatile solids in the raw material by the total weight of solids in raw material and normally expressed as a percentage of the total solids content (IRENA, 2016).

C/N ratio

Deublein & Steinhauser, (2011) reported that the carbon to nitrogen ration (C/N) should be about 16:1 to 25:1. The unbalance C/N ratio of feedstock can increase the rate of formation of volatile fatty acids and too low ratio the ammonia production and they gradually accumulate in digester lead to decrease process efficiency (Shahbaz *et al.*, 2020).

The specific surface area of the material

There is a positive relationship between biogas yield and surface area of the material (Deublein and Steinhauser, 2011). In general, mechanical or physical pretreatment of organic waste raises the accessible surface area, modifies the lignin structure, reduces the cellulose crystallinity and polymerization, and decreases the degree of hemicellulose (Monlau *et al.*, 2013; Zheng *et al.*, 2014).

- Monitoring and control anaerobic digestion (AD) parameters

AD process is considered a sensitive to any disturbance accrue in the process, which affects biogas production efficiency. Online process monitoring or controlling and automated instruments that can be used to ensure stable and efficient biogas production are still associated with high costs (Cruz *et al.*, 2019). The most important variables that can controlled in many biogas plants are limited to the daily evaluation of easily measurable parameters such as pH, temperature or biogas production rate, volume, and quality (Holm-Nielsen and Oleskowicz-Popiel, 2013). New technology has been evolved into stand-alone systems that can be used in all necessary processes by itself without any additional hardware (Güven *et al.*, 2017).

The objectives of current work were to:

- Design and construct a home biogas digester with an automatic control unit to improve biogas yield and to be controllable and simple to operate.
- Evaluate the system performance.

MATERIALS AND METHODS

This work is planned to design and construct a biogas digester for kitchen waste with some automatic control system to be easy to use and to control anaerobic digestion parameters to enhance biogas yield.

- Design principles

Assumptions:

Two liters waste/day (for a family of 4 persons produce 1-4 kg of wastes)

The ratio of dilution waste to water is 1:1

Retention time (12-30) days = 15 days (Sendaaza, 2018)

Assume 1 kg waste = 1 liter, at volatile solids (VS) content of 90%

Feeding rate (Q)= waste + water = 4 liter/day = 0.004 m^3/day

Vreactor= feeding rate ($\frac{m^3}{day}$) × retention time (days)

Where:

Vreactor: volume of the digester in liters

Vreactor = 0.004×15 = 0.06 m^3 = 60 liters

Amount of volatile solids (VS) = 2 kg wastes/day ×0.9 = 1.8 kg VS/day

Amount of volatile solids VS per m^3 (Cvs) = 1.8/0.06 = 30 kg VS/m^3

Organic Loading Rate (OLR):

Organic loading rate can be measured by using the following equation:

$$\boldsymbol{OLR = \frac{(Q)(C_{VS})}{V_{reactor}}}$$

$$\boldsymbol{OLR = \frac{(0.004)(30)}{0.06}} = 2 \text{ kg VS/m}^3$$

This rate agrees with (Sendaaza, 2018) who showed OLR as (1.4- 2.2 kg VS/m^3) .

Expected gas production:

Expected gas production(G) was calculated from the following equation:
G= OLR × $V_{material}$ × gas pro. Rate (m^3/kg VS)
= 2 * 0.03 * 0.44 = 0.0264 m^3/day

- Dimensions

Digester

$V_{reactor}$ =0.06 m^3

The safety factor from 10 to 30% (assume 20%) (Dupin, Kitanidis and McCarty, 2001)
Digester volume (Vd) = volume of the digester in liters (Vreactor) ×1.2
Vd = 0.06*1.2 = 0.072 m^3 = 72 liters

$$V = \frac{\pi D^2}{4} \times H$$

Assume height of the digester (H) equals double of the diameter (D)

$$V = \frac{\pi D^2}{4} \times 2D$$

So, D= 0.357 m take it 0.36 m, and H= 0.72 m
A 3 mm thickness-steel digester was constructed and equipped with 2 inches (5cm) PVC inlet and outlet pipes.

Gas holder

A plastic gas holder was attached to the digester with 4 plastic legs guide frame to be more controlled. The clearance between digester and gas holder is about 2 cm from each side. The diameter of the gas holder (Dg) was 0.40 m while the gas holder height (hg) was 0.44 m.

Inlet tank

Inlet tank was designed to be 5 liters volume because 2 liters of waste was added with 2 liters of water (4 liters total). Assuming the height (L) is twice the diameter (b), to give b= 0.15 m, L= 0.30m. A 6-inch (15.24cm) PVC pipe with an airtight cover was used to be an inlet room.

- The controlling units

To improve the performance and the gas yield, some extra equipment was attached to the biogas digester. The controlling units can be described as follows:

Pretreatment with mixing unit

A 62-Watt AC mixing motor was installed into inlet tank to grind food waste and premix waste with water before digestion to increase the specific surface area and to expose the cellular components of the organic waste for microbial breakdown.

The heating unit

Using a heat exchanger, the temperature inside digester was raised to be maintained in thermophilic range (43-55ºC)

The stirring unit

A DC motor of a low rotating speed of 80 rpm was used for stirring the materials inside the digester. The motor was fixed in the bottom of the digester attached with a shaft with two central blades at two different heights to ensure a complete mixing. The final shape of digester unit is shown in figure (1).

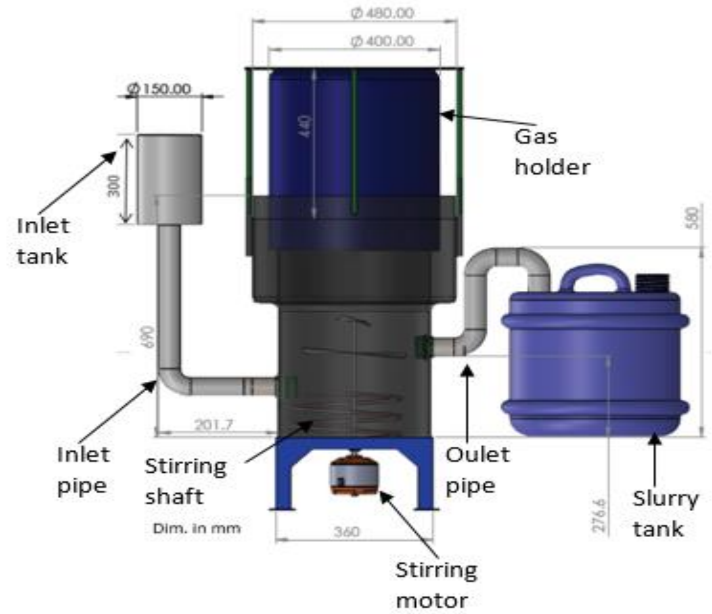

Figure (1): The final digester unit

- **Automatic control system**

The automatic control system was designed to achieve two purposes:

1- Control some AD parameter to optimize biogas production.

2- To be easy and safe to use at home.

As shown in figure (2) some sensors and other components were used in the control system for the purpose of monitoring gas and material temperature, adjusting stirring time, measuring gas quantity, and determining any gas leakage, controlling process temperature and some other additional functions.

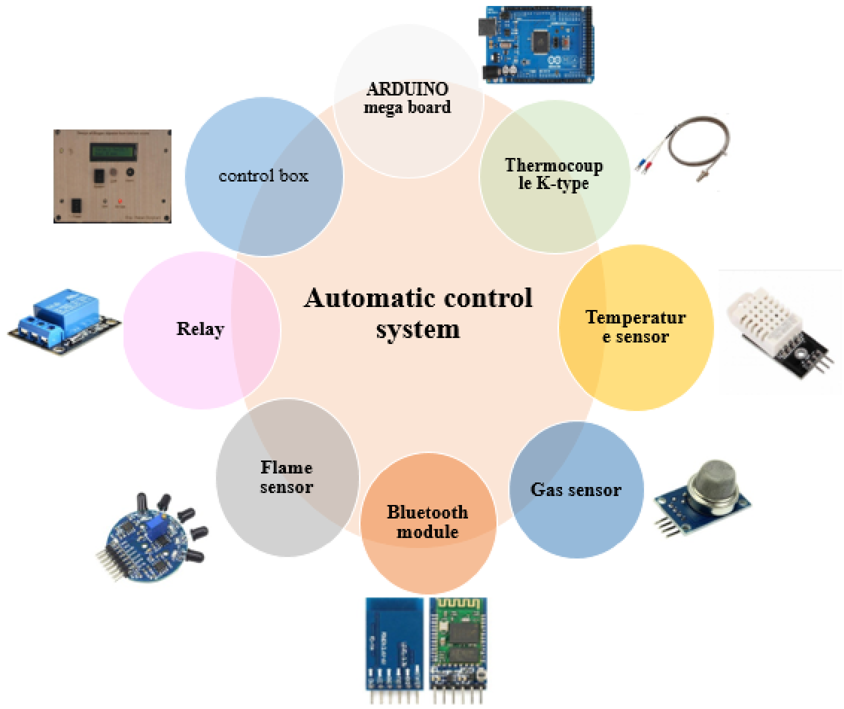

Figure (2): A sketch of automatic control system components

Microcontroller

Arduino Mega board was used to be the main electric component that performs the calculations and controls the working of the current set up by programming it in C++ language. This board needs a special IC max6675 that communicates with Arduino Mega through SPI communication protocol.

Arduino properties were; 1- 54 digital input/output pins, 2- sixteen analog inputs, 3- USB connection, and a power jack. these components are simply connected to a computer with a USB cable or powered with an AC-to-DC adapter or battery to get started.

Thermocouple K-type

To monitor temperature inside digester a K-type thermocouple was used. This type is nickel based and has good corrosion resistance. It can read in a temperature range between 0 and 800 °C.

The static characteristics of this thermocouple were; 1- internal insulations (fiberglass), 2- external shielding (metal shield), 3- total wire length (2 m), and 4- fork terminal spacing (4mm).

DHT22 Temperature sensor

To measure the temperature of biogas a DHT22 sensor was used. It is connected to Arduino Mega board using single wire communication protocol.

The static characteristics of these sensors were; 1- temperature range (40 -125 ºC / ±0.5 ºC), 2- humidity range (0-100% / ±2-5%), 3- sampling rate (0.5 Hz one reading every two seconds), 4- body size (15.1mm×25mm×7.7mm), 5- operating voltage (3-5 V), and 6- max current during measuring (2.5 mA).

MQ2 Gas sensor

The MQ2 gas sensor was used to measure the amount of gas produced in ppm. This sensor consists of a heater coil and resistance that will change its value when concentration of gas changes. Arduino Mega measures the resistance by method of voltage divider.

IR Flame sensor

A 5-way flame detector module was used to detect the presence of fire near the digester and triggers an alarm. It detects flame band in the range of 700-1100 nm, short-wave near-infrared (SW-NIR) and triggers an output via an electric signal when sensed.

The specifications of this sensor were; supply voltage (3.3V - 9V DC), outputs (5 Analog and 5 Digital), adjustments (on-board potentiometer for adjusting the sensitivity), indicator LEDs (five with one power indicator), frequency (760 nm to 1100nm), detection area (>120 degrees at approximately 80cm), and HC-06 Bluetooth module.

The HC-06 Bluetooth module enables Arduino Mega to use Bluetooth wireless technology to send data to a smart phone that enables users to recognize digester data more easily. Bluetooth module was programmed to inform the user with gas temperature (DHT), temperature inside digester (thermocouple), the quantity of gas found in ppm, fire state that if there is any gas leakage or fire, the state of mixing unit and the state of the heater.

Liquid Crystal Display (LCD)

A 16×2 LCD screen is used to display gas and material temperature and gas concentration inside the tank. Arduino Mega uses IIC communication protocol to display letters on this display.

Relay

Relays controls the opening and closing of the circuit contacts of an electronic circuit. Relays were used to control the 220V AC motor and the 12V DC blender.

All automatic control system components and Arduino board were installed in a plastic unique box containing system button for operating control units and power button for all system operating including data appears on LCD and data sent via Bluetooth.

Software

Eagle software is built by Autodesk Company that specializes in CAD software. This software is used to build the schematic of the electric circuit and organize the PCB layout. The PCB layout is shown in figures (3).

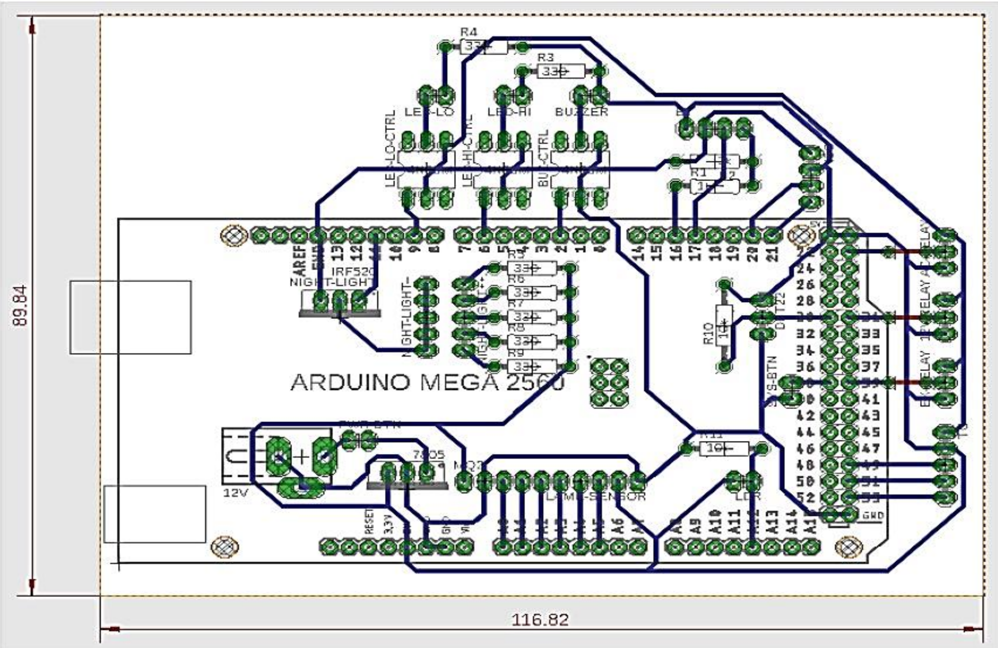

Figure (3): The PCB layout.

- **Filtration system**

As shown in figure (4) a filtration system of six stages for raw biogas purification was used to increase the methane concentration specially in case of using the gas in another purpose except cooking.

- First stage of the filtration system was carbon dioxide filter by using water scrubber. A 5-liter container was used with two gas pipes. The inlet pipe was submerged in water to allow the gas to bubble leaving the CO_2 in the water and the outlet pipe was fitted at the top of the container. The amount of water used was 3.75 liter covering three-fourth of the total volume of the container.

- Second stage was silica gel filter. This filter was used for water vapor adsorption, executed the chemical drying method. It was used twice in the system and placed after the water scrubber and sodium hydroxide solution filters. Each container of silica gel filter has dimensions of 30 cm height and 9 cm diameter filled with about 2 kilograms of silica gel which also reaches to about three-fourth of its total volume.

- Third stage was silica gel filter. This filter was used to remove the hydrogen sulfide, the dry oxidation process was used in which the use of iron oxide was implemented. In the form of iron sponge or steel wool, the iron oxide was placed after the silica gel filtration column to counteract the rusting of the iron sponge. The inlet pipe was placed at the bottom of the container while the outlet pipe was fitted at the top. The hydrogen sulfide filter was a container of 30 cm height and 9 cm diameter cylindrical plastic container whole filled with iron sponges.

-Fourth stage was Sodium Hydroxide Solution Filter. This stage was designed to remove the formed elemental sulfur and carbon dioxide from biogas using water and sodium hydroxide (NaOH). A four liters plastic cylindrical container was used.

The last stage was activated carbon filter which is known for its CO_2 and H_2S removal ability. This must not be exposed in wet state and too much hydrogen sulfide concentration, so it was placed after the silica gel filter.

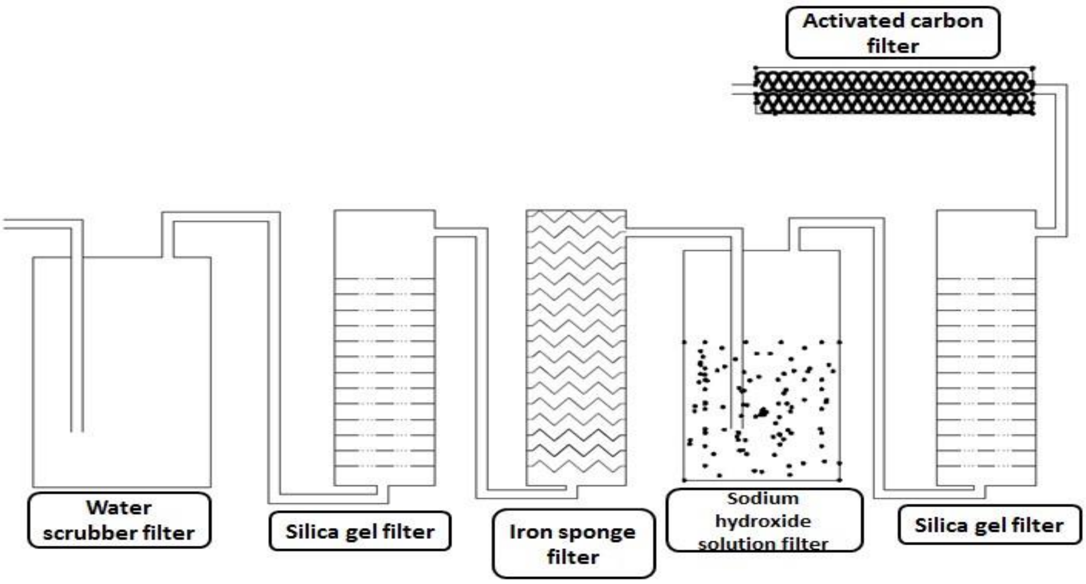

Figure (4): Schematic of filtration system stages

- Evaluating digester performance

Three phases of studies were carried out to evaluate digester performance utilizing kitchen wastes which were digested for 30 days retention time. Daily temperature, pH and produced gas quantity were measured. First phase was done without controlling anaerobic digestion (AD) parameters (without using automatic control system). Second and third phase were done with controlling AD parameters and temperature set at 35ºC and 50ºC respectively. Sodium hydroxide solution was added to adjust pH at about 7. the pH was measured at the start and end of each experiment daily.

RESULTS AND DISCUSSION

Figures (5), (6) and (7) show pH, daily produced gas quantity and cumulative gas quantity respectively in the three phases. Cumulative gas quantity for phase I, phase II and phase III were 165.92, 498.92 and 616.56 L, respectively. It means that raising temperature from ambient to 35 and 50ºC, gas quantity increased by 2 and 2.71, folds respectively.

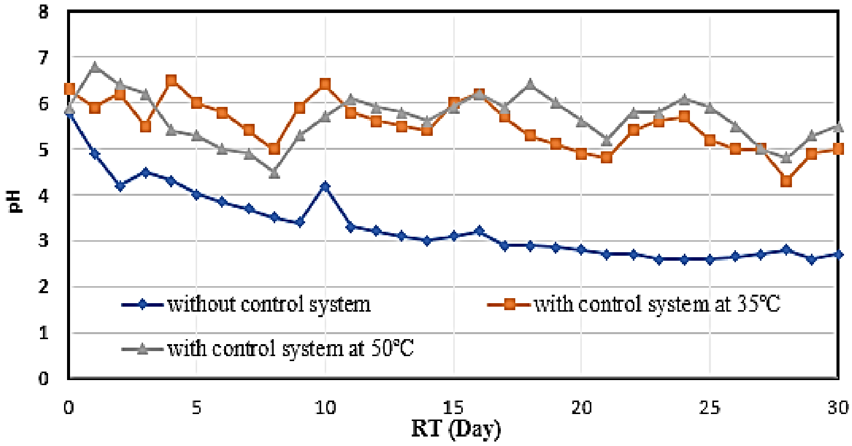

Figure (5): Daily pH monitoring during the three phases

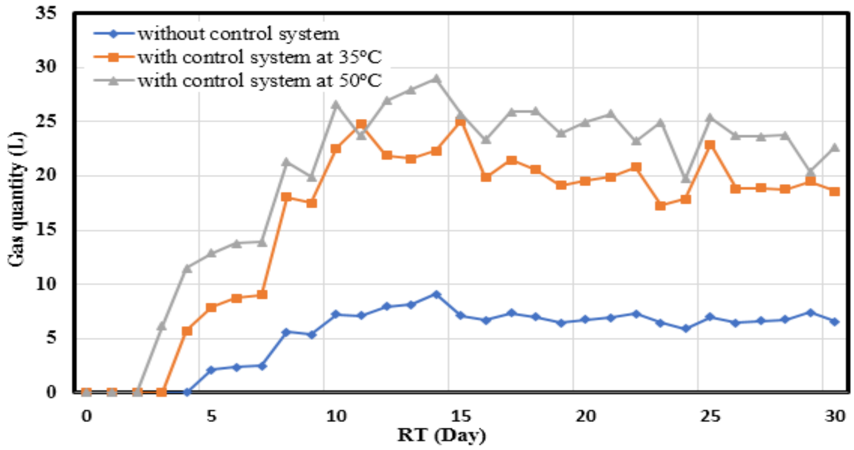

Figure (6): Daily produced gas quantity during the three phases

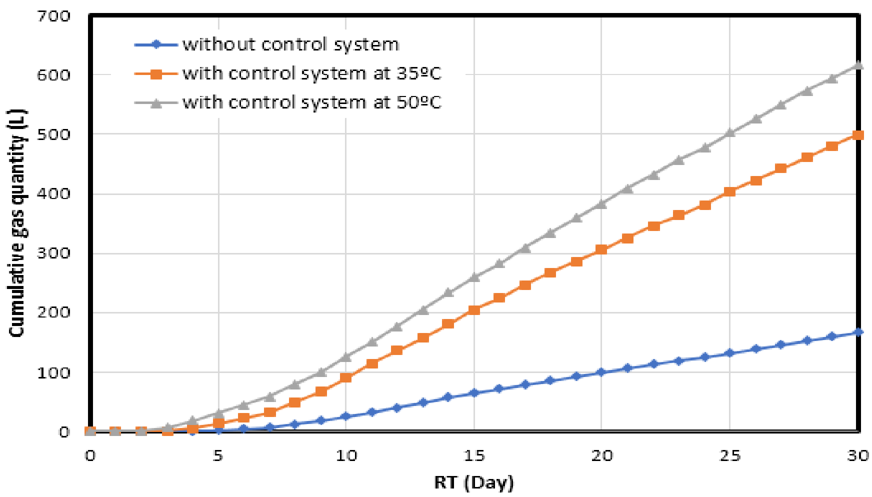

Figure (7): Cumulative gas quantity in the three phases

As shown in figure (8), using control system with temperature adjusting at 35ºC in phase II increased biogas yield from 20.9 at ambient temperature, which ranged between 24 ºC and 26 ºC phase I to 63 L/kg VS added (increased by 200%) and using control system and adjusting temperature at 50ºC in phase III increased biogas yield to 77.85 L/kg VS (increased by 23.57% more than controlling at 35ºC).

The statistical analysis was performed using SAS computer program. Table (1) showed a significant difference between the three phases at level 0.01.

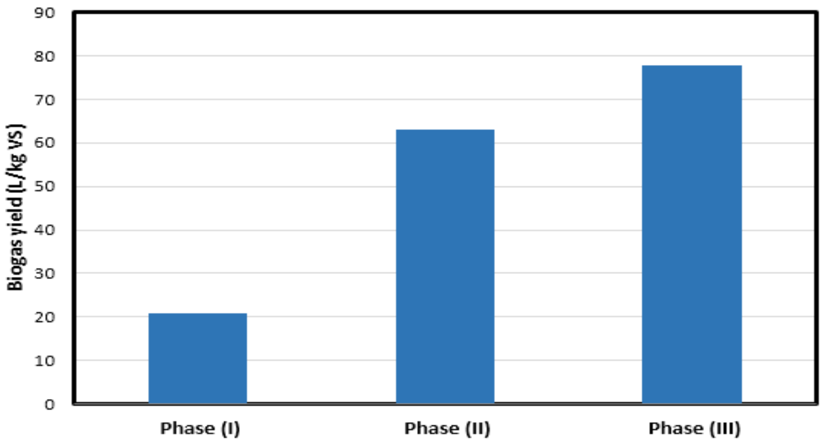

Figure (8): Biogas yield (L/kg Vs added) in the three phases.

Table (1) ANOVA statistical analysis for gas production

Source of Variation	DF	S.S	M.S	F value	F Pr
Model	2	5236.235	2618.118	345.8163	< 0.0001**
Error	6	45.425	7.570833		
Total	8	5281.66			

** Significant at level 0.01

CONCLUSION

Biogas from kitchen waste can play a vital role to solve both energy and waste problem in Egypt. Kitchen waste can be processed by every household into biogas with biogas digester technology. This process is so sensitive to any disturbances in operating conditions, which can affect the biogas production efficiency. This work was carried out to design and installation of a home biogas production unit for kitchen waste with automatic control system with more controlled anaerobic digestion (AD) parameters to enhance biogas production and be safe and easy to use. using control system and raising temperature from ambient, which ranged between 24 ºC and 26 ºC to 35 and 50ºC increased gas quantities by 2 and about 2.71, folds respectively.

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تصميم وانشاء وحدة انتاج غاز حيوي تعمل بنظام التحكم الآلي

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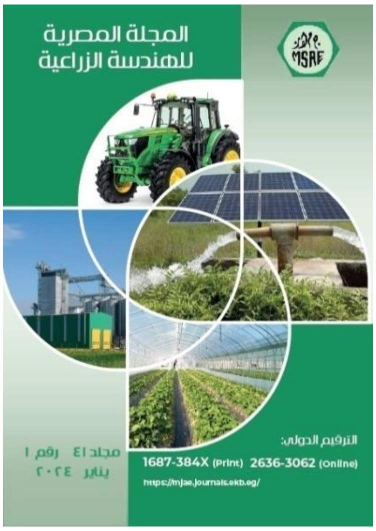

الكلمات المفتاحية:
طاقة متجددة؛ الغاز الحيوي؛ تصميم الهاضم؛ المخلفات؛ التحكم الآلي.

الملخص العربي

الهدف من البحث هو تصميم وانشاء وحدة منزلية لإنتاج البيوجاز من مخلفات المطابخ مزودة بوحدة تحكم آلى لتحسين انتاجية الغاز ولسهولة الاستخدام. ولتحقيق الهدف من البحث تم تصميم وبناء مخمر غاز حيوي منزلي سعة ٧٢ لترًا مزودًا بوحدة تحكم إلكتروني للتحكم في عوامل التخمير اللاهوائية. تم استخدام وحدة خلط كمعالجة أولية لطحن وخلط النفايات قبل دخولها إلى المخمر. تم إضافة وحدة تقليب للتحكم في زمن التقليب ووحدة تسخين للتحكم في درجة الحرارة ومراقبتها داخل المخمر. تم استخدام نظام التحكم الإلكتروني بما في ذلك كاشف الحريق لتأمين السلامة، وأجهزة استشعار درجة الحرارة والغاز، من خلال تطبيق الهاتف المحمول للمراقبة وبعض المكونات الأخرى لجعل الوحدة أكثر قابلية للتحكم وأسهل وأكثر أمانًا في الاستخدام. لتقييم أداء المخمر، تم تشغيل الهاضم على ثلاث مراحل (كل منها مع وقت استبقاء لمدة ٣٠ يومًا). تم تنفيذ المرحلة الأولى دون استخدام نظام التحكم في درجة الحرارة المحيطة والتي تراوحت بين ٢٤ م° و٢٦ م°، في حين تم تنفيذ المرحلتين الثانية والثالثة عند مستويين مختلفين من درجات الحرارة، المرحلة الثانية عند ٣٥ م° المرحلة الثالثة عند ٥٠ م°. تم تغذية المخمر بشكل مستمر بواقع ٤ لتر/يوم (٢ لتر فضلات + ٢ لتر ماء). تمت مراقبة درجة الحرارة ودرجة الحموضة وكمية الغاز المنتج يوميا (٥ أيام في الأسبوع). بلغت كميات الغاز التراكمية للمرحلة الاولى والمرحلة الثانية والمرحلة الثالثة ١٦٥,٩٢ و٤٩٨,٩٢ و٦١٦,٥٦ لتر على التوالي. وهذا يعني أن رفع درجة الحرارة المحيطة إلى ٣٥ م° و٥٠ م° يؤدي إلى زيادة كميات الغاز بمقدار الضعف وحوالي ٢,٧١ ضعف على التوالي.