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Research Article

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Manufacturing and Performance Evaluation of an Experimental Purpose Prototype Biogas Reactor

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Abstract In this study, an experimental laboratory type biogas reactor was designed and manufactured in order to produce biogas under controlled conditions. In this reactor, the ambient temperature and pH are controlled during the digestion process. In addition, controlled mixing is also carried out in order to ensure the homogeneous distribution of microorganisms. Cattle manure, seaweed, whey with different biomethane potential were digested at a 30:20:50 mixing ratio and 45 ºC temperature and the composition of the obtained biogas was determined. During the digestion, all data were recorded in the computer environment. The Gas Chromatography device in the Biosystem Engineering Laboratory was used to determine the gas composition. The rate of biomethane in the total biogas produced as a result of the digestion process was measured as 55.22%.

Keywords Biogas, Anaerobic digestion, Biomass, Biogas reactor

1. Introduction

Renewable energy sources have gained importance due to the increase in global energy demand and environmental concerns arising from fossil fuels [1].

Renewable energy production unit costs decrease over time in connection with technological developments. The use of renewable energy is very important in terms of ensuring sustainability, but incentives and social awareness activities related to energy efficiency and energy saving are also considered as an important factor [2].

To reduce carbon emissions and reduce our dependence on energy exports, the most appropriate scenario would be to focus on renewable energy technologies [3].

One of the main environmental problems of today's society is organic waste, which is constantly increasing because of production activities. In many countries, efforts to prevent waste with sustainable waste management, reduce pollution and greenhouse gas emissions, thus mitigating global climate changes gain importance.

Biomass is an important renewable energy source that can be obtained biologically and has energy potential. Biogas produced as a result of anaerobic digestion of biomass of animal and vegetable origin has an important share among these sources. Biogas is also important in terms of minimizing negative environmental effects by emitting less CO2 emissions than other energy sources, both in production and consumption stages. It also has advantages in terms of providing the recovery of organic matter and some minerals in the digested residual slurry after biogas production. Organic fertilizer obtained from waste is widely used in plant production [4].

Algae are aquatic plants with high energy potential as a source of liquid and gaseous biofuels. However, microalgae and seaweed are not currently grown for energy purposes due to high harvesting, condensation and drying costs.. Anaerobic digestion of algae biomass has demonstrated the need for new processing methods to theoretically reduce the costs associated with drying wet biomass before processing and increase the net energy

balance. Algal biomass is a potential source of green bioenergy for biomethane production when processed using anaerobic digestion methods [5].
To achieve a sustainable approach to microalgal biogas production, the development of cost-effective harvesting technologies and optimization of growing and harvesting conditions are required. A technically stable and economically viable digestive system needs to be established. The development of reactors or digesters for trouble-free and cost-effective anaerobic digestion from microalgae should be a priority in further research efforts. Designing stable and reliable reactors with appropriate technical and economic data for anaerobic digestion may hold the potential for microalgal biogas production [6].
The efficiency of the biogas reactor is primarily affected by the residence time of the organic materials in the reactor, the contact between the surviving methanogenic bacteria and the organic materials entering the bioreactor. Microorganisms are dispersed evenly by mixing organic materials in the anaerobic bioreactor. The mixing process also reduces the particle size of organic materials. Thus, it helps the pretreatment effect and the release of biogas from the mixture [7], [8].
Biogas has positive features in terms of using organic waste as an energy source, reducing greenhouse gas emissions, contributing to the economy, and providing more hygienic conditions in waste disposal [9].
Substituted the energy crops of biomass with marine macroalgae and evaluated the potential environmental impact categories such as global warming, acidification, eutrophication and land conversion. In the results, they found positive effects on emission reduction in the mixture of algae fertilizer with chicken manure. They showed that sustainable energy production is possible with the co-digestion of chicken manure (40%) and macroalgae (60%). The collection of algal biomass from costal lines for biogas production purposes will significantly reduce the total farmland impacts caused by terrestrial crop production [10].
Determined the biogas production by mixing whey and cattle manure, which are milk industry waste, in various proportions. With the addition of whey, an increase of 2.23 times was achieved in biogas production [11].
Wastes such as algae and whey, especially cow dung, have a high organic pollution load and pose an environmental hazard. For this reason, waste is often a matter of concern. In fact, when a good analysis is made, it will be seen that vegetable and animal waste and residues are an asset for clean energy production. Wastes such as seaweed, whey and cow dung are valuable biomass for biogas production, and the energy obtained from these biomass is used for cooking, lighting, etc. In addition, the waste slurry obtained as the final product can be used as soil nutrient.
However, due to the complex interrelationships between biological processes and chemical processing conditions, it is not sufficient to explain the efficiency of anaerobic decay theoretically. At the biological level, the process largely depends on a complex synergistic relationship of different anaerobic bacteria to process different reactive feedstocks. The organic matter feedstock used in anaerobic digestion consists largely of complex species such as proteins, fats, and soluble lipids, and therefore must be biologically broken down into amino acid monomers, fatty acids, and simple sugars. The resulting products of this chemical hydrolysis are fed into sub-processes called acidogenesis, acetogenesis, and methanogenesis. All of these complicating factors result in a gap between anaerobic digestion process conditions and theoretical predictions. The ability to predict the performance and output quality of an anaerobic digestion process largely depends on the development of tools to study the process at laboratory scale.
In this study, a laboratory scale biogas reactor was designed and fabricated. In order to determine the performance of this reactor, a mixture of cow manure, seaweed (algae) and whey was used as raw material.

2. Materials and Methods

2.1. Material

In this study, cattle manure, seaweed and whey were used to produce biogas. The result of the raw material analyzes of the materials used are given in Table 1.

Biogas reactor

The designed and manufactured PLC controlled biogas reactor is shown in Figure 1. The reactor diameter is 300 mm, and the height is 650 mm. The volume from the bottom of the reactor to a height of 500 mm is used for the raw material mixture. The remaining 150 mm height is left empty for the purpose of storing the biogas formed. The effective height of the reactor with its cover is 680 mm.

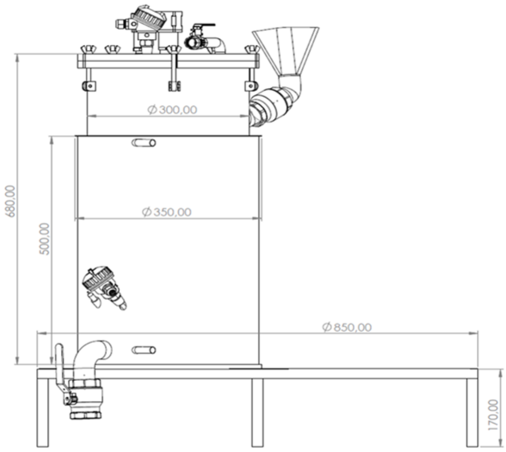

Figure 1: Biogas reactor schematic representation and main dimensions

The reactor cylinder is made of high temperature and corrosion resistant stainless steel (AISI310S) with a thickness of 5 mm. Other units are made of 3 mm thick manufacturing steel (St37). The units of the biogas production system, whose manufacturing has been completed, are given in Figure 2.

A hot water jacket is placed around the reactor cylinder to provide the required fermentation temperature. The diameter of the reactor with the water jacket is 350 mm. For the performance parameters to be followed during biogas production, there are 5 connection points on the reactor: 2 thermocouples, 1 pressure sensor, 1 pH probe and 1 pH regulator connection. There is also a gas outlet connection to take the produced gas from the system.

Homogeneous mixing of the materials in the reactor is ensured by an automatically driven mixer located in the middle of the reactor. WiseCircu brand water circulator device was used to circulate the water at the appropriate temperature in the water jackets of the designed reactor and to keep the temperature of the system at the desired value. The device can be used to the desired temperature between -20°C - 100°C.

System Components

PLC

The CPU module used for biogas plant automation is GMTCNT brand GLC-196T model. PLC GLC-196T module has 24VDC supply, 9 channels 24VDC PNP/NPN input, 6 channels 24VDC 300mA short-circuit protected transistor output and 3 channels 20kHz with 3-axis servo/step drive. Modular structure, support up to 271 points with the possibility of connecting a maximum of 16 expansion modules, network access with 100MB ethernet port, RS232 and RS485 communication ports, MODBUS RTU protocol support, decimal operation support, 12ns command processing speed, DIN RAY mounting and 3 pcs possibility of connecting a double-phase (A, B, Z) encoder or 3 fast counters (20kHz), it can be programmed via the mini-USB port.

PLC expansion modules

One-unit GXM-40U and one GXM-42A expansion module are used. These modules work together with the CPU module and are internally powered by the CPU module. The GXM-40U temperature sensor expansion module has 4 channels of universal inputs. 15-bit resolution, 0.1°C reading accuracy. Sensors with which the module is compatible; B, C, E, J, K, N, R, S, T type thermocouples, PT-100 or PT-1000 type RTDs (resistance thermal resistance) can be counted. Supports 2 and 3 wire connection types. Line resistance is 20 Ω maximum. The input repeat rate is 10 Hz. Power consumption is 2 W maximum. GXM-40A analog input module has 4 channels, optional input values can be selected as 0-10 VDC, 0-20 mA, 4-20 mA. Channels can be used as different input types independent of each other. Channels are galvanically isolated. Resolution is 16 bits (0...65535), accuracy is +/-0.5%. Reading speed is 50 Hz. Power consumption is 2 W maximum.

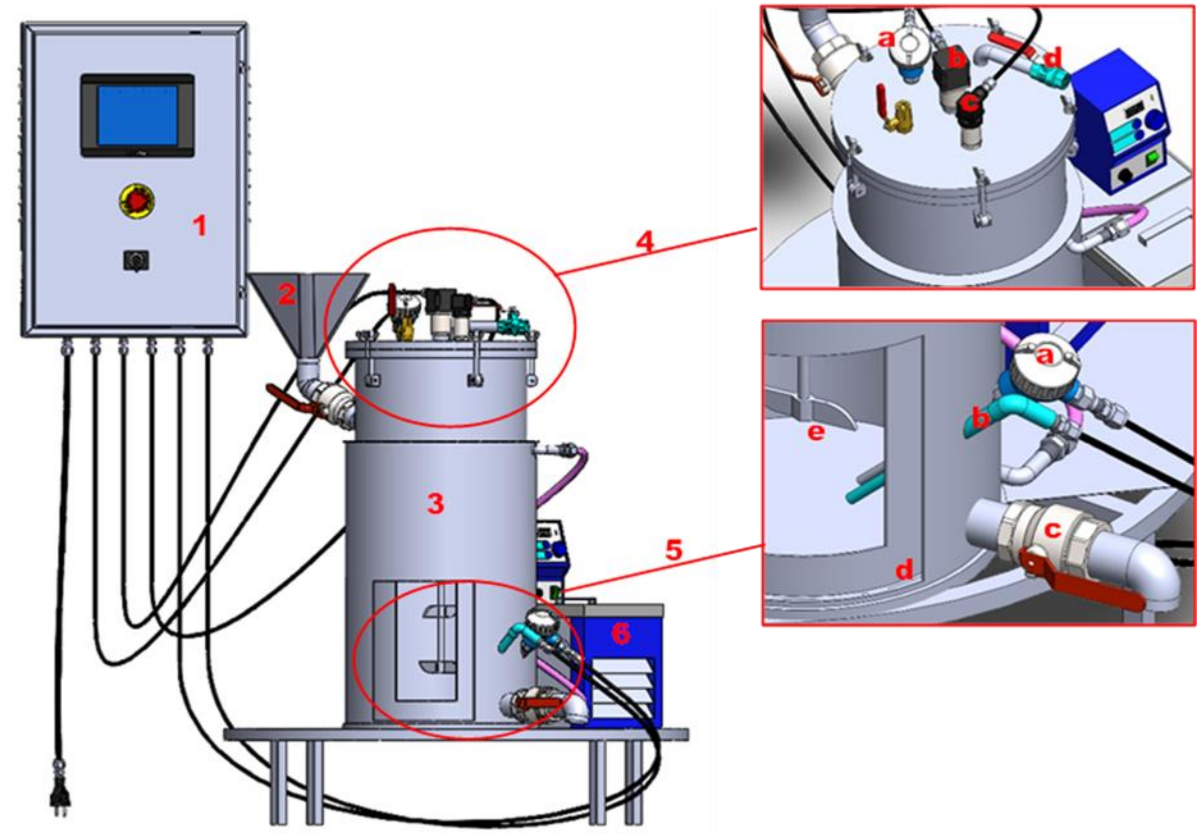

Figure 2: Manufactured biogas reactor

1. Automation board (PLC hardware, HDMI panel) 2. Mix inlet 3. Biogas reactor (digester) 4a. Temperature probe 4b. Mixer motor 4c. Pressure probe 4d. biogas intake pipe 5a. Temperature probe 5b. pH probe 5c. Digestate outlet 5d. water jacket 5e. Mixer 6. Hot water circulation device

Operator panel (HMI)

In PLC-based systems, operator panels (HMI-Human Machine Interface) are used to enable operators to communicate with the system. Thus, the operators can observe the process variables through these screens and make inspections by changing them when necessary. The operator panel used is in the Enda EOP 41-70ETE model. It has 7" operator panel, 65536 colors, TFT screen, 32-bit 800MHz CPU, 16MB flash, 32MB SDRAM memory, RTC (Real Time Clock), USB port, RS232/RS485/RS422 communication port.

Inverter

In the system, the frequency control of the mixing motor is done with the GMT CNT inverter. The inverter placed in the automation panel is controlled via the operator panel (HMI).

Mixer motor

FINEX brand E1610-40-17B-C geared alternating current 3-phase miniature motor is used as mixer motor. The motor has 40 W power, 0.358 A and a frequency of 50 Hz. It reaches a maximum of 1350 rpm.

Pressure Sensors

BCT-22-10b-v-g1, pressure sensor was used in the study. The input range of the sensor is 0…10 bar and the output range are 4…20 mA. The supply voltage is in the range of 12…30 VDC. Mechanical pressure connection is G ¼” male thread.

Thermocouples

The PT100 temperature sensor, also known as a resistance thermometer, can measure temperature data faster and more precisely than thermistors. The PT100 temperature sensor can measure from -200 °C to +600 °C, with an accuracy of 0.1 °C. Due to these features, it is preferred especially in industrial and laboratory applications. In this study, ISISO brand PT100 temperature sensor was used.

Ph probe

Seko SPH-3-WW pH probe, which is used for galvanic process, wastewater treatment, cooling tower water pH measurement applications is used due to its ability to measure pH in environments with a conductivity of 5 micro siemens in the temperature range of 0 – 80 0C.

pH control panel

Seko brand Control 40 Single Parameter pH controller was used to calibrate the pH probe and transfer the pH value read from the reactor to the PLC microprocessor. The device is wall mounted. There are 2 relay outputs on the controller. It gives 4-20 mA current output in connection with PLC. Probe connection is BNC connection type.

System Software

Endasoft editor program and editor programming software developed for Enda operator panels (HMI) were used to program PLC in the system.

PLC Programmer

EndaSoft PLC editor program was used as PLC programmer. This editor program supports the Ladder method, which is widely preferred in the industry. ENDA Soft program, with the simulation plug-in installed on it, has the feature of simulating the PLC program written without a PLC offline and performing the necessary controls. It is necessary to introduce the PLC CPU type and expansion modules used in the real system to the editor program. In addition to these, it should be defined which modules' input/output points will be placed at which addresses.

HMI Programmer

The ENDA_V2.0 HMI editor program was used as the HMI (Human Machine Interface- operator panel) programmer. Visual and functional design of the operator panel is carried out on this programmer.

2.2. Method

Data collection, storage and control processes were carried out by connecting the sensors, working elements and the relevant inputs and outputs of the PLC used in the laboratory type gasifier system equipped with the data collection system designed in the research. An operator panel was used to monitor the data collected during the working processes of the reactor on the screen and to send the necessary commands to the system. The general measurement points of the prototype data collection system are presented in Figure 2. The temperature, pH and pressure information are measured and saved in a flash memory attached to the operator panel. Thus, data collection, monitoring and recording processes can be performed without the need for a computer.

PLC Program

PLC and expansion modules communicate with the operator panel in RS232 standard using Modbus function. Before the PLC programs created with the ladder method using the Endasoft PLC editor program, they are uploaded to the PLC with the simulation plugin, offline simulations were made. After the necessary changes were made in the PLC program as a result of the simulations, it was uploaded to the PLC, trials were made, and the program was made desired. The data received via PLC was sent to the HMI panel and saved in the flash memory attached to the HMI panel.

Operator Panel Screen Design

An operator panel was used to monitor and record the process variables (temperature, pressure, pH, mixing time and cycle) of the gasifier system. The operator panel was written with the Enda_V2.0 program installed on the laptop and loaded on the panel with a USB cable. The connection of the panel with the PLC is made via RS232 serial communication over the COM port.
The main screen of the program, which was designed and finalized by making offline simulations, is shown in Figure 3.

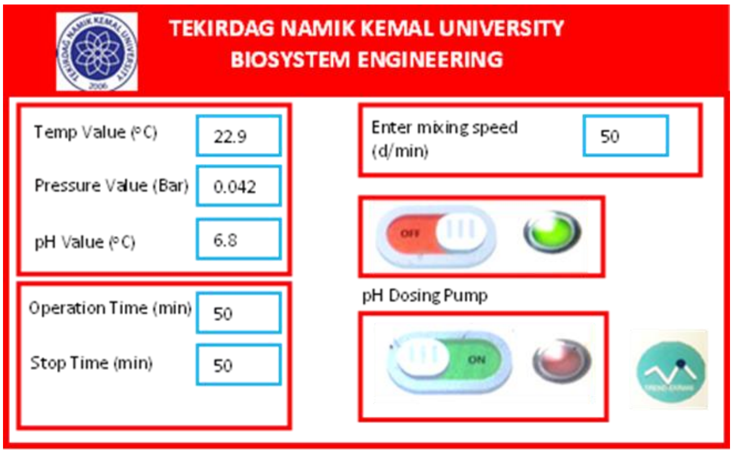

Figure 3: Main screen view of the control program

Determination of the performance of the biogas reactor

In the biogas reactor developed within the scope of the study and with a digestion volume of 30 liters, cattle manure, algae and whey, which have different biomethane potential, were digested with 12% dry matter, a mixture ratio of 30:20:50 and a temperature of 45 ºC, and the composition of the obtained biogas was determined. In this experiment, the hydraulic retention time (HRT) was set to 12 days. The pH, pressure and temperature changes recorded in the automation system were evaluated.
At the beginning of the experiment, the pH of the mixture was adjusted between 6.8-7.0 by adding NaOH. The digester was mixed for 1-2 minutes, 3 times a day, in order to prevent precipitation on the bottom of the digester and to ensure the homogeneity of the mixture and to prevent the formation of crusts on the upper level of the mixture. Fertilizer, seaweed and whey used in the experiments were used without any pre-treatment, as supplied, without waiting. In order to determine the properties of the materials used in the experiments, all analyzes were performed using standard methods before anaerobic digestion. Raw material was used for dry matter determination. In order to provide the desired dry matter ratio in the experiments, the dry matter (DM) of each material was determined by keeping it in an oven at 105 oC until it reached a constant weight. Ash (XA) and volatile solids (UK) were determined by burning the materials in a muffle furnace at 550 oC [12].

Determination of the composition of biogas

The gas content (carbon dioxide and methane) formed in the reactor was determined using the AGILANT 7890B GC gas chromatograph. As a result of the analysis, the sample taken to detect the methane and carbon dioxide gases in the gas formed in the reactor was injected into the gas chromatography device manually with an injector. The biomethane (CH_4) and CO_2 ratios of the obtained gas were recorded using the software of the GC device. Figure 4 shows an example of a gas analysis report made.

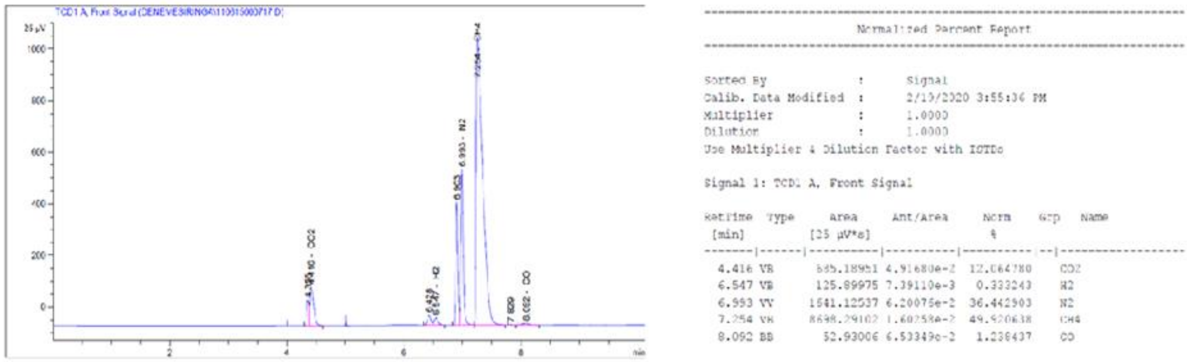

Figure 4: Example of a biogas analysis report with the Agilent 7890B GC gas chromatograph

3. Results and Discussion

3.1. Raw material analysis results

The results of the analyzes performed to determine the solid matter, volatile solids and ash determinations of dairy cattle manure, seaweed and whey used in anaerobic digestion experiments are given in Table 1.

The %TS value of the cattle manure used in the research was close to the previous studies. [13]; [14] and [15] stated in their research that the %TS value of cattle manure is 22.75%, 21.78% and 2.6%, respectively. In studies on seaweed, %TS values were found to be 17% [16] and 17.30% [17]. In studies conducted with whey, %TS values were found as 5.88% [18] and 5-6% [19]. It has been observed that the %TS values of seaweed and whey used in this research are close to the values obtained in previous studies.

Table 1: Some physical properties of feedstocks used in the co-digestion

Feedstocks	Total Solid (TS) (%)	Volatile solid (VS) (% TS)	Ash (%TS)
Cattle sludge	23,47	80,51	19,49
Algae	17,20	63,89	36,11
Cheese whey	5,43	79,26	20,74

3.2. Anaerobic digestion test results

Biogas production continued for 12 days in laboratory-scale anaerobic digestion trials.[20] reported that biogas production was completed in 8-14 days in their study where they used algae addition to investigate its effect on biogas production.

The pH values recorded during digestion in the reactor are given in Figure 5. While the pH value decreased rapidly in the first 2 days, it then increased and reached equilibrium after the 6th day. The rapid decrease in pH value in the first days is due to the increase in the concentration of free fatty acids in the medium during the transition from the hydrolysis stage to the acidogenesis stage [21]. As a result of the use of free fatty acids by microorganisms in the acetogenesis stage, the formation of some ammonia and the addition of NaOH to the digestion, the pH value increased and stabilized at 7 levels.

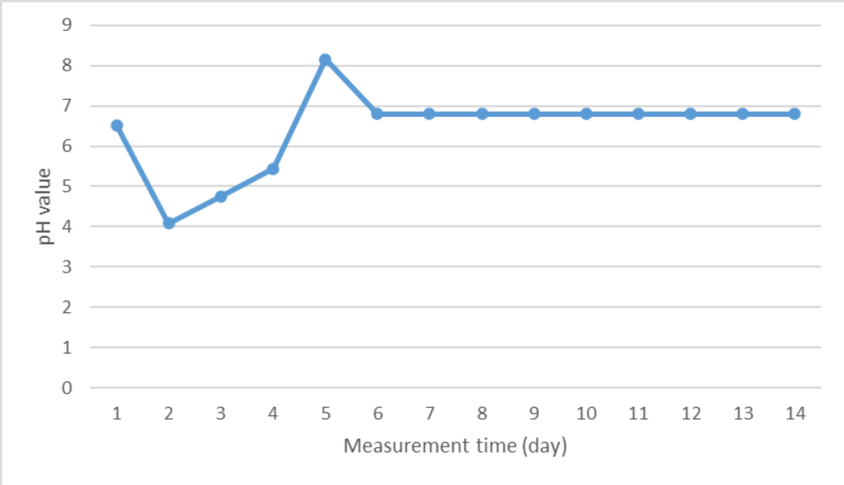

Figure 5: pH values recorded during digestion

The recorded gas pressure values are given in Figure 6. While the gas pressure is low in the first days due to the fluctuation in the pH value, it is seen that there is a regular increase in the gas pressure when the system reaches equilibrium.

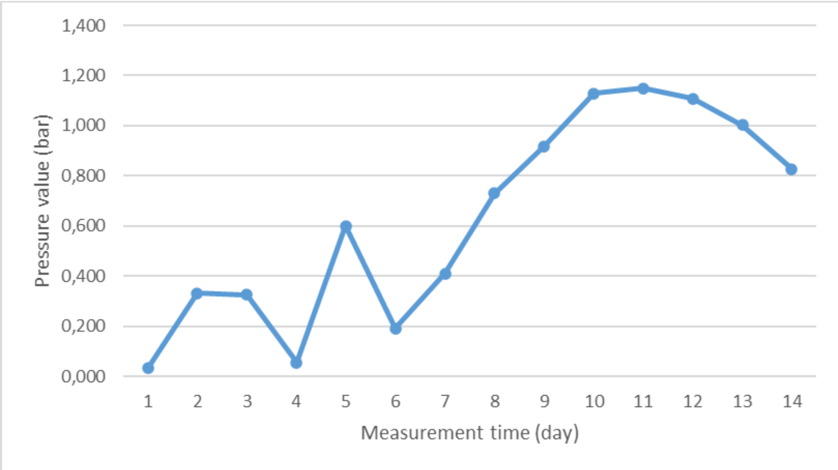

Figure 6: Biogas reactor pressure change values recorded

The average gas temperature recorded in the gas collection area of the reactor was around 41.14 0C (Figure 7). Gas temperatures varied between 39 ºC and 43 ºC during digestion.

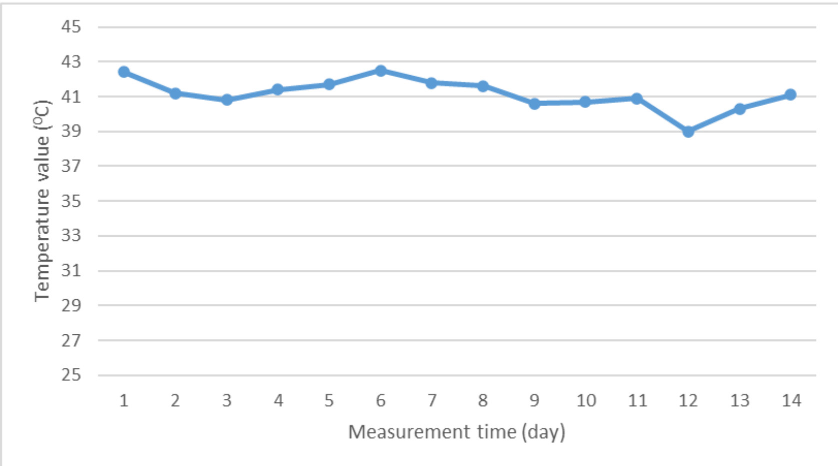

Figure 7: Gas collection zone temperature values recorded in the biogas reactor

The biomethane ratio of the biogas produced as a result of the digestion process was measured as 55.22%.

4. Conclusion

In order to be used in the biogas experiments within the scope of this study, an automated biogas rector with 300 mm reactor diameter and 680 mm effective height, which can record and control the parameters required for biogas production, was designed and manufactured. Used effectively and successfully in the trials.

In the anaerobic digestion experiment carried out in the automated reactor with a capacity of 30 liters, the rate of biomethane in the total biogas produced as a result of the digestion process was measured as 55.22%.

The use of biogas reduces greenhouse gas emissions, one of the most important responsible for global warming. In addition, the increase in biogas production as a renewable energy source is an important part of the development of energy agriculture. Promoting biogas production will make a significant contribution to the socio-economic development of producers. The use of digested residue, which is the product of anaerobic digestion, in soil fertilization will reduce energy consumption, as well as protect environmental benefits and financial resources.

Anaerobic digestion must be environmentally friendly, environmentally beneficial and economically efficient. The supply of high-quality raw materials is an indispensable prerequisite for obtaining optimum gas efficiency. Instead of conventional anaerobic digestion in biogas production, the application of the co-digestion technique (co-fermentation) of organic materials will ensure the use of different materials in anaerobic digestion, thereby diversifying the digestion raw materials and increasing the efficiency.

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