# Autonomous system for remote control of anaerobic CSTR reactors

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**Abstract**

Anaerobic digestion (AD) is an effective process for the valorisation of organic waste and the production of a renewable source of energy, biogas. AD reactors demand regular monitoring to avoid process instability and inefficient biogas production. However, the measurement of critical AD parameters is a costly and time-consuming procedure. A low-cost approach towards the remote control of AD reactors is the use of verified sensors combined with single-board computers and IoT platforms. Two identical Continuously Stirred Tank Reactors (CSTR) were operated under the same conditions and substrate composition; one was controlled automatically and the other manually. The results related to biogas, methane and temperature show no significant difference between the two reactors and corresponded to a relative difference of 4.57%, 4.42% and 0.02%, respectively.

## 1. Introduction

The continuous production of organic waste and its ineffective management is one of the most important reasons for the increase in greenhouse gas emissions. A promising and continuously developing method of utilization of organic waste is its anaerobic treatment. AD is a process performed by a large number of microorganisms in which organic carbon is converted to carbon dioxide and methane in the absence of oxygen (Scarlat et al., 2018). AD consists of four consecutive stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Meegoda et al., 2018).

The success of anaerobic digestion is a function of various parameters, which must be at specific levels in order to ensure the growth of microorganisms under optimal conditions and the maximum yield of biogas produced. Critical factors are oxygen, as conditions must be strictly anaerobic, temperature, pH, hydraulic retention time (HRT), substrate composition, organic loading rate (OLR), C/N ratio, concentration of volatile fatty acids (VFA), nutrients, trace elements, toxic compounds and ammonia (Rehman Laiq Ur et al., 2019). Consequently, to ensure process stability and efficient biogas production, monitoring as many of these critical factors as possible is necessary (Wu et al., 2019). However, the manual monitoring of many AD parameters in experiments with many reactors is a costly and time-consuming that usually cannot be totally achieved. Therefore, the number of the continuous reactors involved in an experimental setup is often defined by the personnel and time availability. Furthermore, even if all parameters could be recorded, the logging data often relates to only one period of the day when a person is monitoring the experimental setup (Yan et al., 2021).

One possible solution would be the constantly evolving Internet of Things (IoT) technology combined with the use of single-board computers (such as Raspberry Pi) and verified sensors, that could enable scientists to collect a wide range of real-time data (Jolles, 2021).

The aim of this study is to examine the accuracy of biogas, methane and temperature measurements of a reactor equipped with respective sensors connected to a Raspberry Pi which measurements are sent to an IoT platform, compared to an identical reactor fed with the same organic waste, in which these measurements are obtained manually by using conventional methods.

## 2. Materials and Methods

### *2.1 Inoculum, substrate and CSTR reactors*

The inoculum was obtained from a mesophilic biogas plant in Central Macedonia, Greece and consisted of 41.5 g $L^{-1}$ Total Solids (TS) and 29.7 g $L^{-1}$ Volatile Solids (VS), while cow manure (33.8 g $L^{-1}$ TS – 28.2 g $L^{-1}$ VS) was used as substrate. The experiment was carried out in two identical CSTR reactors (R1 and R2), where the total and working volume of each was 2.0 L and 1.8 L, respectively. Both were operated under mesophilic conditions (37˚C ± 1˚C) and were continuously stirred with a magnetic stirrer (Stuart, stir UC151). The maintenance of constant temperature was achieved by a heat exchanger located inside the reactors where hot water was recirculating. During the experiment, reactors operated at an HRT of 29 days, an OLR of 0.97 gVS $L^{-1}$ $d^{-1}$ and were semi-continuously fed twice per day with a peristaltic pump (Watson Marlow 360s, Falmouth, Cornwall, UK) for each reactor.

### *2.2 Experimental setup*

The main difference between the reactors was the control of temperature, biogas and methane production. Specifically, R1 was supplied with a single-board computer, Raspberry Pi 3 Model B (RasPi 3), which is equipped with a 1.2GHz Broadcom BCM2837 64bit CPU quad core. A temperature sensor (DS18B20 - Maxim Integrated) was connected to the RasPi 3 for the record of R1 temperature range. The recording of biogas and methane production was carried out by using two gas counters, which operated by the method of displacement of a certain volume of water. In particular, the gas produced from the reactor was fed into the 1st gas counter where the amount of biogas was measured. The outlet of the biogas counter was connected to the inlet of a gas scrubber (filled with 1N NaOH solution) designed to capture CO2 from the biogas. The outlet of the biogas scrubber led to the inlet of the methane gas counter, which works in a similar way to the biogas counter already mentioned. The connection of the above gas counters was made to the RasPi 3 computer through its analog inputs. Through RasPi 3, all data was sent to a cloud IoT platform where it was stored, examined and exported.

## 3. Results and discussion

The results refer to a study period of 58 days (2 HRT) after the achievement of steady state conditions which was reached after 47 and 49 days for R1 and R2, respectively. The performance of the reactors in terms of biogas and methane production is shown in Figure 1 and temperature of the reactors is presented in Figure 2. Average biogas production of R1 was 414.35 mL d$^{-1}$ while R2 was 396.25 mL d$^{-1}$, corresponding to a relative difference of 4.57%. The relative difference between the two reactors in terms of methane production was 4.42%, as R1 had an average methane production of 253.15 mL d$^{-1}$ and R2 of 242.42 mL d$^{-1}$. Finally, the temperature of the reactors varied by 0.02% as R1 had an average daily temperature of 36.76 °C and R2 of 36.75 °C (results shown in Figure 2).

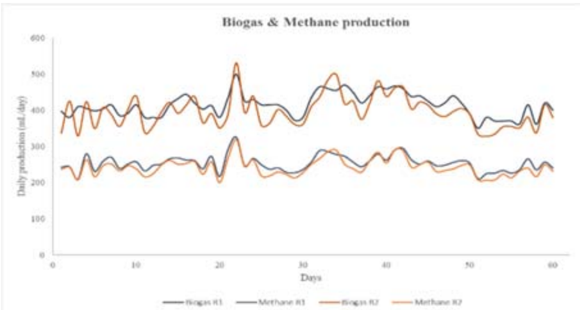


*Figure 1. Biogas and methane production for two HRTs from the anaerobic reactors R1 (with RaspPi) and R2 (manual monitoring).*

The results regarding biogas, methane and temperature show no significant differences between the autonomous and the manually operating reactors. However, the small deviation observed in those two lab-scale CSTR reactors can be attributed to the lack of uniformity of the substrate used or to the inhomogeneity of the inoculum, as they were obtained from real sources.

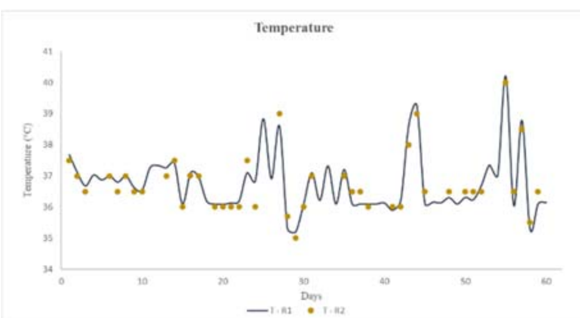


*Figure 2. Temperatures for two HRTs from the anaerobic reactors R1 (with RaspPi) and R2 (manual monitoring).*

The monitoring of AD process by IoT-enabled technologies introduces significant advantages in relation to conventional methods, including: 1. remote control of important process parameters, 2. early warning indicators at any time, 3. monitoring of multiple reactors working simultaneously, 4. data security through the storage ability to the cloud or local (memory card), 5. creation of a database that can be easily viewed and processed, 6. low cost of additional equipment.

## 4. Conclusions

In this work, an effective and low-cost system for monitoring important process parameters of anaerobic digestion has been proposed. Results of biogas and methane production were similar to both of the anaerobic reactors. Significant temperature fluctuations between the two reactors were not observed. As technology is constantly evolving, more and more advanced and precise sensors could be connected to the proposed monitoring system for the surveillance of multiple parameters (e.g. pH, $NH_3$ etc.) that indicate the stability of the process. Furthermore, an automatic feeding operation could be achieved by controlling the reactors peristaltic feeding pumps through programming the RaspPi.

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