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Research Article

# The Design, Development and Assessment of a Novel De-centralised IoT-Based Remote Monitoring of a Small-Scale Anaerobic Digester Network

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**Abstract**

The implementation of community-level de-centralised anaerobic digestion (AD) systems offers a sustainable solution for organic waste management and energy provision, but there is currently a need for low-cost methods of system control and management at this scale. The problem becomes accentuated with increasing deployment, as greater complexities are created by the need to both monitor and control a wider network of smaller, community-scale plants. This paper describes research to design, deploy and test such a system by creating a network of two independent biogas generation AD reactor sites situated in the United

Kingdom and Thailand. Internet of things (IoT) aspects such as inexpensive and widely available open-source control electronics was used in combination with small commercial gas analysers to log, transfer and share data with a central station, achieving real-time monitoring of performance for both networked digesters. The design proved beneficial for collaboration and knowledge exchange purposes along with providing off-site observations on reactor status. This information was used for early intervention to maintain biogas yields and enable the dynamic assessment of process economics. The concept showed potential for upscaling to larger multi-site networks of AD reactors that could maintain process optimisation without the need for skilled staff on site.

**Keywords**

Anaerobic digestion; energy from waste; remote monitoring; decentralisation; IoT; biogas

## 1. Introduction

Anaerobic digestion (AD) is a well-established treatment technology to convert organic waste into energy in the form of biogas, in the absence of oxygen. In the Global North countries, this has tended to take place in large industrial-scale reactors capable of processing significant quantities of material. Here, AD is used as a process for both waste management technology for treating waste like sewage sludge, as well as for generating biogas [1]. At this scale, biogas is mostly used in combined heat and power (CHP) engines for electricity generation or purified to biomethane for gas-to-grid injection. However, the technology is often adapted to small-scale reactors typically used in the Global South countries to produce gas for cooking and heating from locally available wastes, mostly cattle manure and agricultural residues. This de-centralised energy generation through AD using locally available renewable bio-resources offers multiple social, environmental and financial benefits to rural communities [2]. It also helps remote, often off-grid communities achieve independent, decentralised energy generation. Consequently, many countries have implemented a variety of measures to encourage system uptake at smaller scales including for individual families. At present, there are an estimated 43.8 million biogas plants of this type in China, and over 4 million in India [3], along with governmental programmes to encourage biogas generation in other developing Asian, African, and Latin American countries. Interest is now also being shown for small-scale on-farm and community AD systems in developed countries in Europe, America, and Australasia.

However, despite widespread use, AD systems remain extremely sensitive to changes in environmental variables, particularly with food and agricultural waste feedstocks. Satisfactory design and control of system parameters are seen as essential to maximizing process efficiency, increasing stability, and preventing system failure [4]. AD system failure is multifactorial and can include design, build, and operational problems. The lack of trained personnel and the high price of monitoring systems for stability performance parameters often lead to reactor failure and abandonment. Biogas production quantity and quality are key performance indicators for user satisfaction at all scales and there are challenges in process optimisation, especially on a small scale.

### *1.1 Anaerobic Digestion and Its Challenges*

Biogas production is an anaerobic process in which organic waste is converted into methane ($CH_4$) at ca. 60 Vol% and carbon dioxide ($CO_2$) at ca. 40 Vol% with trace amounts of hydrogen sulphide ($H_2S$), water, and other impurities. AD functions by maintaining a consortium of various micro-organisms in symbiosis: acidogenic, acetogenic, and methanogenic bacteria, with methanogenic bacteria being crucial for the final stage in the process. The $CH_4$, because of its high calorific value and clean burning characteristics, is then used as an energy vector for conversion into heat and/or electricity [5].

AD technology is sensitive to multiple operational parameters: pH, temperature, volatile fatty acids (VFA), and bi-product molecules such as $H_2S$, all of which are a function of composition and environmental conditions. Product gas quality is also dependent on the type and availability of organic feedstocks and the optimisation of operating conditions in response to external environmental fluctuations [6]. This, along with maintenance issues such as leakage from pipelines, blockage of gas tubing, overloading reactors, and general operators' inexperience, means that AD systems frequently suffer from operation instability [7]. For example, to achieve a consistent and high-quality biogas yield, timely addition and controlled loading of fresh material (ideally, of constant composition) is necessary. However, adding too much material to the reactor leads to a build-up of VFAs and low pH values because hydrolytic bacteria produce an excess of acids, which in turn cause methane formation to slow down [8]. Additionally, the $H_2S$ concentration should be kept as low as possible because of its corrosive nature [9] and to maximise hydrogen selectivity for $CH_4$.

The Internet of things (IoT) is an emerging concept that enables data exchange and communication with devices and systems using sensors, software, and other technologies. IoT has made its advent in different industries including waste and wastewater treatment. There is a need to demonstrate IoT-based anaerobic digesters at a pilot scale for their successful commercial implementation widely. To operate biogas reactors with maximum efficiency, robust sensors are needed to both monitor the processes and product species (typically $CH_4$, $CO_2$, $O_2$, and $H_2S$). Although most of the commonly used sensors are inexpensive, they are limited in terms of cross-sensitivity (thermal conductivity), unable to assess multi-species gases (e.g. $O_2/CO_2$, $CO_2/CH_4$), or cannot function at certain concentration ranges. Furthermore, there are calibration issues: electrochemical sensors show a typical drift of 4% in sensitivity, which means that the sensors must be re-calibrated every few months. The component $N_2$ can occur in biogas in concentrations of up to 5 vol%, but currently no sensor is available for monitoring $N_2$ directly and a total gas quantification is not possible [10].

There has been a steady increase in interest in process monitoring, reflected by a growing number of research publications in the field, as reported by Wu et al. [11]. However, very few studies have focused on fast, reliable, and online monitoring of AD processes as well as the development of efficient feedback alert and control strategies. Key indices should be adopted in this regard, including process monitoring, temperature, pressure, biogas production rate, and $CH_4$ yield, all of which are significantly affected by the type and amount of waste available. Automation systems are advantageous as they can help to improve efficiency and maintain steady-state biogas production. Information can include flow rates, pressures, and temperature profiles as well as performance data or $CH_4$ content, some of which must be monitored cyclically. It is important to ensure that the fermentation process runs smoothly; if for example the bacteria in the fermenter are not "fed" for six hours, methane production drops significantly [12]. Although sophisticated performance monitoring options are available and are employed only in large-scale industrial plants in Global North countries, their application is often beyond the scope of the community-scale AD user due to the very high cost of such instrumentation. These complex and expensive automated control systems have yet to be commercially replicated for small-scale digesters.

### *1.2 Review of Existing AD Monitoring Systems*

Monitoring of biogas production and digester performance has been well established on an industrial scale, through sophisticated automated equipment for achieving full control of the process and optimal biogas yield [13, 14]. Continuous on-line monitoring of digester stability allows for fast responses to cases where a process is unbalanced and prevents greater problems and ultimately failure of the digester which can be expensive and time-consuming to recover. Different on-line methods such as spectroscopy, chromatography, and titration can be utilized [11]. In large, industrial-scale plants, the cost of on-line monitoring systems is still very low in relation to the total investment cost of a plant. These sophisticated monitoring systems require complex processes, pre-treatments, specialized equipment, time and skilled staff. Surprisingly, monitoring on this scale is still far from optimal despite the great outputs and financial gains from such plants. For example, it has been reported that for 9000 digesters in Germany, only two thirds of the plants monitored the total biogas volume generation, and even less monitored gas composition [15]. It also has been noted that the exact composition and loading of such reactors are rarely known. Furthermore, for those plants which implement monitoring, it is usually limited to simple process information (e.g reactor temperature, mass input, tank level, gas output/quality), while more powerful approaches such as near-infrared spectroscopy (NIRS) which can provide info about the total VFA, pH, alkalinity, TS, VS, and COD are rarely used.

For small-scale plants, low financial returns limit the monitoring options, both in terms of monitoring frequency and the range of parameters. For these plants, off-line analysis often requires instrumentation and lab-facilities whose cost significantly exceeds the financial benefit of the generated gas. Further implementation of in-line monitoring becomes increasingly challenging at this scale, especially in lesser developed areas where every expense should be spared, when limited funds are available [16] and there is a shortage of trained personnel to tend each small-scale digester.

The lack of commercial lower-cost biogas monitoring systems presents a challenge. Some lower-cost devices have been developed; however, they focus on one variable such as gas flow rate and pressure [14]. This helps understand the quantity of biogas but does not help with the quality of the product which is necessary for optimisation. In theory, it is possible to develop a sensor system from electronic components to be configured appropriately, but this was not possible within the timescales and budget of the project. However, an off-the-shelf sensing platform was identified that had been developed for environmental monitoring of landfill gas. Landfill gas, due to the anaerobic nature of decay of organic material in deeper layers of landfills, has a similar composition to that of AD-generated biogas. The Ambisense GlasfluX sensor (Ambisense, Ireland) platform is an autonomous wireless gas sensing platform designed for landfill gas monitoring and long-term performance and reduction in component costs [17]. The unit consists of a control board, cellular mobile network radio, battery, extraction pump, sampling chamber and sensors, and a protective casing. Autonomy is achieved by a photovoltaic module charging the onboard battery and custom-programmed microcontroller circuitry, which also manages data logging and remote transmission (cellular mobile network). Data is sent to an online portal for monitoring and management. The sensors monitor $CH_4$, $CO_2$, $O_2$, humidity, pressure (atmospheric and within the reactor), temperature, and $H_2S$. The sampling regime and frequency are user-controlled.

### *1.3 Aims of This Study*

The aim of the study was to design, develop and assess a novel de-centralised remote monitoring AD network. This paper describes research to implement and assess such a biogas remote monitoring system for community scale, de-centralised anaerobic digestion for energy and resource recovery. The study involved a collaboration between researchers in the United Kingdom and Thailand using two independently operated waste-to-energy AD pilot plants. A central monitoring system was linked to each site and the study was designed to be representative of a small network of two digesters to demonstrate the concept. The aim was to assess the efficacy of such a network by considering how biogas yield could be optimised with minimal requirements for on-site supervision and specialist intervention, but also assess the utility of off-site gas monitoring and its potential applications. The data was accessible in real-time at the joint web portal, providing information about the stability of both reactors. The specific objectives were to design and develop two AD systems, to test and commission the AD systems, to set up a networked lower-cost remote monitoring network, and to validate the performance of the remote monitoring against standard laboratory analytical techniques. By addressing this current need for affordable and effective AD control and management, it was envisaged that the results of this trial could lead to greater system uptake and the development of smart community scale de-centralised AD system networks with centralized monitoring and control facilities.

## 2. Materials and Methods

The development of the UK-based pilot plant at Loughborough University and the Thailand AD system deployed at the Asian Institute of Technology close to Bangkok has been presented. The two systems were not identical due to the availability of equipment and the different climatic conditions between the temperate UK and tropical Thailand. Furthermore, the organic loading rates differ due to different feedstocks. However, the purpose of the study was to demonstrate remote monitoring and the ability to network two functioning AD reactors, rather than to study and optimise the AD process itself. Subsequently, the de-centralised remote monitoring systems were deployed at the two independently designed and operated anaerobic digestion pilot plants. A Web-based platform was developed through which the status (operational parameters and outputs) of both AD plants could be remotely monitored via an online network in real-time.

### *2.1 UK System*

#### 2.1.1 Anaerobic Reactor

The UK system (situated outdoors at Loughborough University Campus, Loughborough, East Midlands) consisted of an experimental 1.3 $m^3$ anaerobic reactor built in-house from a hard plastic chemical storage double-walled tank (Figure 1). It was designed to take a low solid feedstock (at ca. 8%), based approximately on that of UK water waste treatment plants, thus making it unconventional with respect to most anaerobic digesters which have a high solids content and a long hydraulic retention time (several days to weeks in some cases). The rationale was to design a reactor from readily available low-cost off-the-shelf components for higher efficiencies and easier management than could be achieved with the high solids reactors traditionally used in India and China for example.

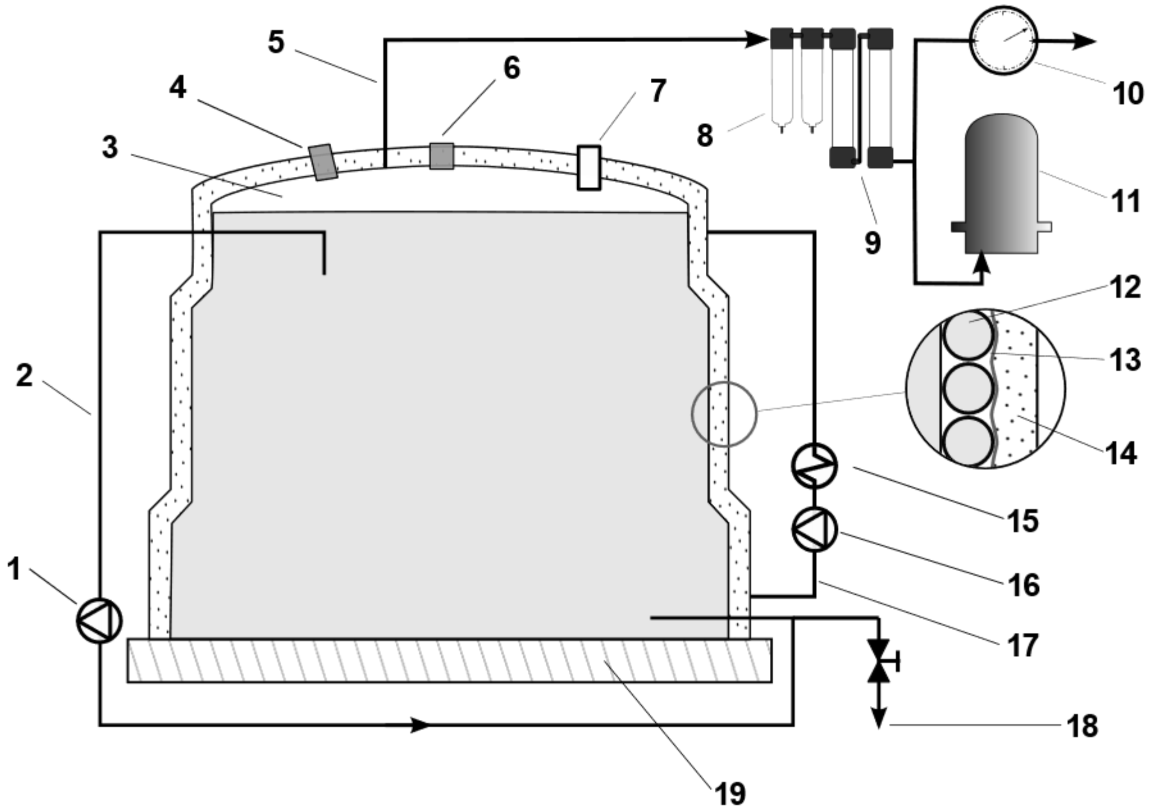


**Figure 1** Schematic of the pilot-scale mesophilic anaerobic digester (UK). 1. Digestate re-circulation pump, 2. Digestate re-circulation circuit, 3. Reactor head space, 4. Headspace pressure transducer, 5. Gas Outlet to conditioning and flow measurement unit, 6. Headspace pressure relief valve, 7. Feeding inlet, 8. Composite filter, 9. Silica Gel trap, 10. Drum gas meter, 11. Ambisense GasfluX sensor, 12. Heat exchanger coils, 13. Radiant barrier behind heating circuit, 14. Reactor wall insulation, 15. Heating circuit, 16. Heat circuit heating element, 17. Heating circuit pump, 18. Reactor extraction, 19. Ground insulation raft under the reactor.

The reactor was unstirred but mixed by way of a recirculation pump with slurry exit and entry points at the base and top respectively (80 l/min). The internal temperature was maintained around a set point of 38°C, with heat supplied by a non-contact heat exchanger from a closed circuit of a hot water pipe (15 mm Polybutylene) coiled tightly around the outside of the bioreactor tank but within the outer tank walls. An aluminum radiative insulation shield (0.752 W/m-K) was wrapped around the coils, while the tank's outer walls contained 80 mm of expanded polystyrene beads (0.752 W/m-K). The base of the reactor was unheated, but a layer of 150 mm polyurethane foam underneath the reactor (0.025 W/m-K) was used to supplement heat retention. Water was heated by an electric element (3.5 kW).

The reactor was inoculated using material from a local brewery waste processing AD digester (Unilever, Burton-upon-Trent) and top-fed with 3 l of brewery waste from the same plant (average COD of 20 000 mg/l) each weekday (Monday-Friday) through a 10 cm diameter screw cap aperture. A 3 cm-I/D manually operable gate valve at the base of the reactor was used to extract 3 l of digestate immediately before feeding.

### 2.1.2 Reactor Monitoring and Control

Reactor temperature, head-space pressure, slurry recirculation, ambient temperature, ambient pressure, fluid flow temperature, humidity, and energy usage were managed using the widely available low-power 8-bit microcontroller (ATmega328) the control software was developed in-house utilising a conventional proportional–integral–derivative (PID) control algorithm. Control and monitoring were achieved using readily available low-cost sensors manufactured predominantly for the automotive sector. The sensors used were four digital temperature sensors (DS18B20) accurate to ±0.5°C over the range -10 ≤ °C ≤ +85. These were situated: 50 cm below the digestate surface layer within the recirculation flow line, on the hot water circuit pipework and within the digester double-skin, on the immersion heater outlet, and on the hot water circuit pipework (return) leading to the pump; a headspace pressure transducer (TE Connectivity U7139-150PA-5W000); a barometric pressure sensor (BMP180 Bosch), a humidity sensor (DHT AM2302), situated within the filter/coalesce unit on the gas extraction lines, and a 3 W pulse energy meter to measure immersion heater electrical power consumption. Data was then logged on a personal computer, in-house software was developed to do the data logging using the widely available data science libraries implemented in the Python programming language.

Before reaching GasfluX unit sensors, raw biogas from the reactor was dehumidified using two in-series 310 ml composite filters (N771N, by Headline Filters, UK), supplemented by a two in-series silica gel trap arrangement, prior to gas volumetric flow rate and gas species composition measurements. Gas species composition measurement is performed using a GasfluX unit, this unit was designed specifically for environmental monitoring of landfill sites and was used for this application with permission from the manufacturer.

To measure the product gas' volumetric flow rate, initially a mass flow sensor (OMRON DFS) was used, but this was later replaced by a drum-type gas meter (Ritter type TG 0.5). The acquired reactor information was accessible online using Team Viewer software.

Gaseous product species ($CH_4$, $NH_3$, CO, $CO_2$, $H_2S$, and $O_2$) were analysed separately, along with product gas humidity and pressure, using the GasfluX unit. The platform was powered by solar PV (with battery backup) and was equipped with custom-programmed microcontrollers to manage data logging and remote transmission (3G cellular radio communications). Data sampling was user adjustable, but in this case was set up to obtain readings every four hours.

The units were operated for 9 months (March to November) at 4-hour sample frequencies. To assess the remote monitoring systems' accuracy, samples of biogas were tested on a daily basis using a hand-held gas analyser (Gas Data UK GFM-416), verifying concentrations of $CH_4$, $CO_2$, $O_2$, and $H_2S$ (the latter in ppm, the rest as a percentage).

In addition, the overall stability of the reactor was also monitored by weekly checks of pH, Ripley ratio (standard procedures), organic acids were checked using the Hach Organic Acids LCK365 test kit, and ammonia using the Hach LCK303 test kit.

### ***2.2 Thailand System***

#### 2.2.1 Anaerobic Reactor

The AD system in Thailand was located at an AIT research station. It consisted of a pilot level Continuously Stirred Tank Reactor (CSTR) made of stainless steel with a total volume of 0.942 $m^3$ and an active (working) volume of 0.675 $m^3$ (Figure 2). It was a conventional and established system, developed following laboratory-scale demonstration [18]. The digester was sited outdoors at an ambient temperature of 20-37°C (mesophilic condition) representing its application in tropical countries. The CSTR was cylindrical in shape with diameter of 1 m and a total height of 1.2 m including 0.86 m of working height. It had a conical feeding inlet of 0.05 m base diameter, circular glass window of 0.1 m diameter, stirrer motor, recirculation pump of 0.03 ml/D, and biogas outlet of 0.012 ml/D. An outlet for digestate and optional recirculation was provided in the lower section of the reactor. Two sampling points and a substrate level measuring scale were provided on the sides of the reactor. Metal mesh of 1 mm pore size was provided at the substrate inlet to prevent the ingress of large particles or impurities.

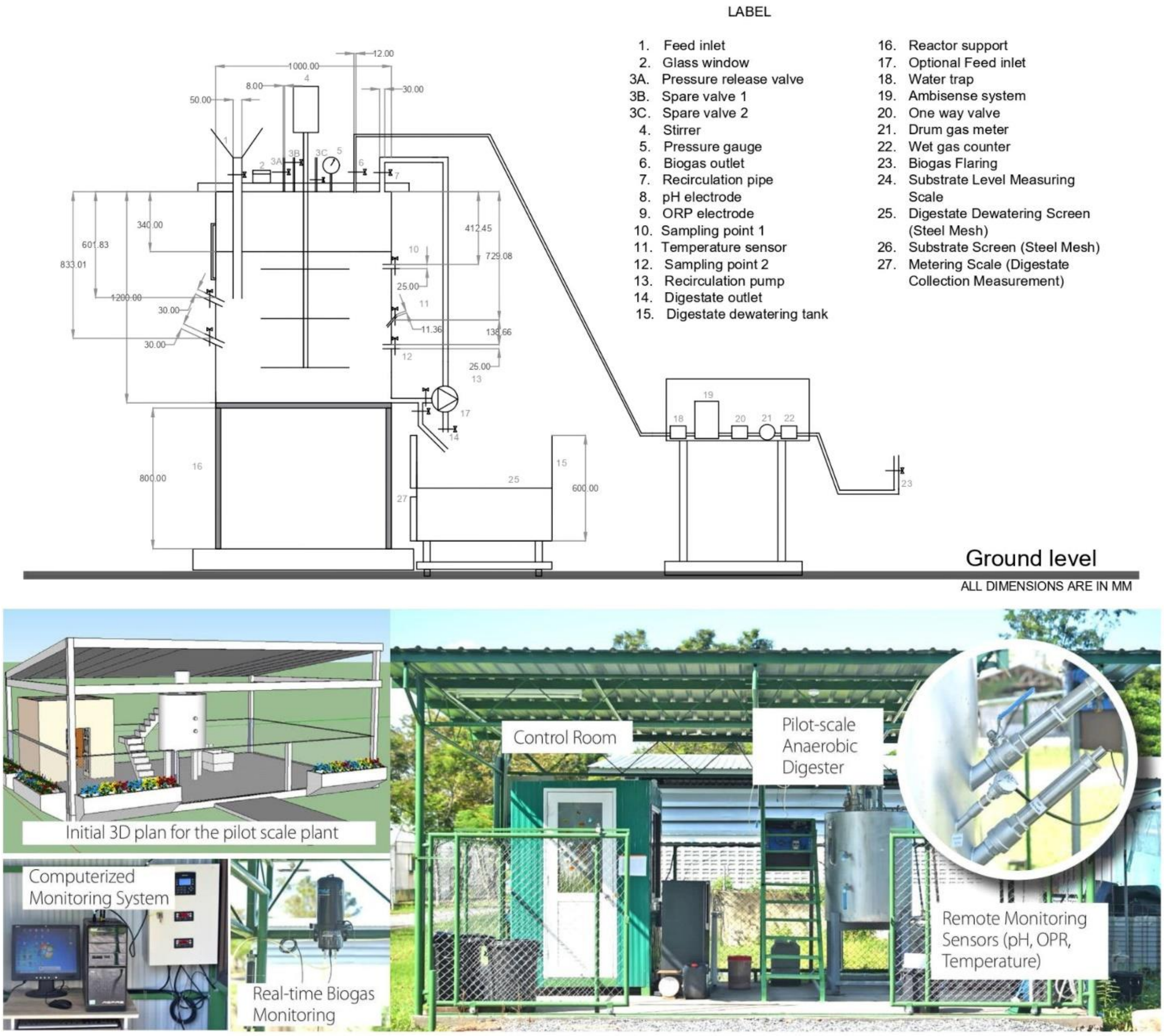


**Figure 2** Top: Schematic of pilot-scale mesophilic anaerobic digester (Thailand); Bottom: Pilot-scale mesophilic anaerobic digester (Thailand).

Probes to measure pH, temperature, and Oxidation-Reduction Potential (OPR) were embedded in the reactor. Moisture and other particulate impurities were also filtered from the biogas line before entering the Ambisense GasfluX sensor. A gas flowmeter (Landis-GYR, model 750) was used to measure the volume of biogas produced, with a one-way valve installed to prevent back-flow of water from the gas counter box. The digestate dewatering system consisted of a stainless-steel tank and a sieve with a pore size <1 mm.

Food waste collected from AIT Cafeteria was prepared by the separation of bones, plastics, and other unsuitable materials. Particle size was reduced to <0.6 cm. This was used as the feedstock and manually fed to the reactor which was operated with 10 % total solids content and a mixing rate of 16 rpm. The feeding was improved from the start-up phase using inoculum and molasses, onto a mixture of food waste and molasses, then finally to food waste only, starting with an Organic Loading Rate (OLR) of 1 kg VS/m$^3$-d.

2.2.2 Reactor Monitoring and Control

A Programmable Logic Controller (PLC) (EUTECH Thermo Scientific Alpha 190 Series) was employed to monitor the pH, temperature, and Oxidation-Reduction Potential (ORP) probes (Electrode Code: EC100GTSO05B, ECHTPTTSO05B) embedded into the digester. The frequency of recalibration of the electrodes was 6 months. Upon acquisition, the data was stored in a central server that could be accessed by other authorised devices. Data from the PLC could be monitored every second on a real-time basis. The user could track the performance of the system and make decisions by using Team Viewer application. The data was also recorded and transferred through Program Data Logger V130 with 512 GB micro SD card.

The composition of biogas ($CH_4$, $CO_2$, $O_2$) was continuously monitored by employing an in-situ online biogas analyser unit (AmbiSense Autonomous Gas Monitoring v4.05) which was equipped with custom-programmed microcontrollers to manage data logging and remote transmission (GSM communications). The AmbiSense online biogas analyser unit could also be powered by solar PV (with battery back-up). Sensors were typically calibrated every 6 months during servicing. The user-adjustable data sampling was set up to obtain four readings per day. Before entering the online analyser, the moisture and other impurities (like particulates) present in the biogas were removed. The volume of biogas produced from the digester was measured using a gas flowmeter (Landis-GYR, model 750). A one-way valve provision prevented water back-flow from the gas counter box into the biogas analyser. The pilot anaerobic digester was monitored by CCTV and was equipped with photosensors for energy conservation.

## 3. Results and Discussion

With the focus of the study being to test the utility value of the remotely monitored "network", the criteria used were mostly qualitative, namely: ease of operation and maintenance, cost implications, and efficacy. From this, the potential and limitations for future applications could be gauged.

It was found that the de-centralised monitoring system exhibited several merits. The reasonably simple and simultaneous online monitoring of AD processes at both sites was realised, and a rapid and accurate evaluation of AD reactor status was provided to both research groups. In addition, the automatic online storage of real-time operational parameters provided a dynamic and time-saving method of data acquisition. An example of the real-time remotely monitored AD "network" four hourly data is shown with the computer screenshot illustrated in Figure 3. In addition to species composition within the biogas, humidity, pressure, and hardware battery status were also displayed. What is notable in Figure 3 is the rapid changes in $H_2S$ concentrations for the Loughborough test unit. $H_2S$ levels show a rapid response to load variation [19]. A build-up of $H_2S$ produced by sulphur-reducing bacteria can inhibit methanogens, although the levels here only exceed 100 ppm (0.01%) on one occasion. The remote monitoring system was able to demonstrate sensitivity for $H_2S$ as an indicator of reactor health, with a rapid response for IoT online monitoring of the small AD reactor [19].

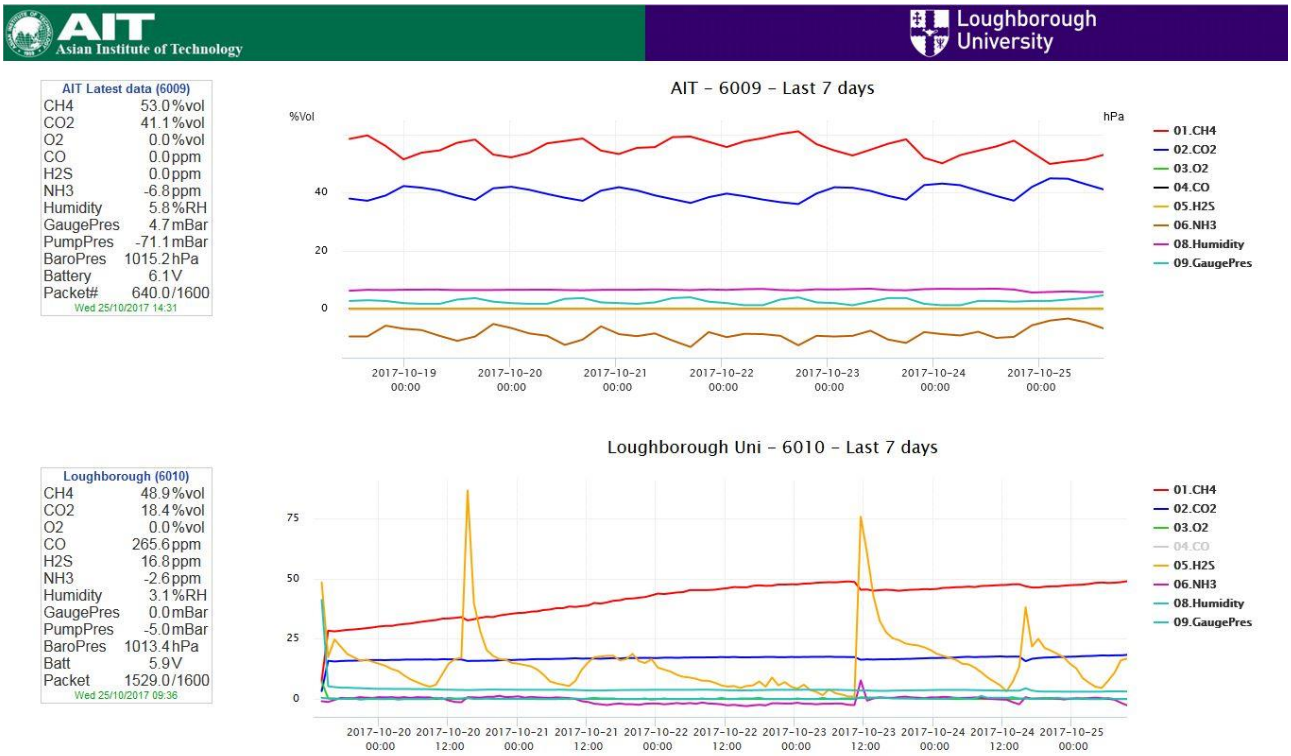


**Figure 3** Screenshot of remotely monitored anaerobic digestion "network" data outputs.

In addition, the biogas monitoring system also allows for the location of the systems to be georeferenced at the joint monitoring portal, which on a scaled-up operation would enable managers to locate AD plants to send technical staff to a specific site, should the need arise.

In a research context, these features facilitate wider collaboration and knowledge sharing; however, for both commercial and research, applications can be envisaged. A much larger network of AD units could be controlled from a central station where expertise is located so that messages could be passed to on-site personnel for the execution of remedial measures such as dosing with chemical corrective treatments (e.g., ferric citrate to balance $NH_3$ and cobalt salt for increases in $H_2S$). This would however still require on-site intervention, but one which did not demand any specific skill sets. Although the network was not designed with alarms set for activation around key parameter set points, this would likely be a cheap and easy to implement option. With this, it would then be possible to incorporate automated dosing and feeding mechanisms, although the cost of this might at present take it outside the design remit of an affordable community AD control system, as was the aim of this study.

Detailed biogas volumetric flow rates and gas species composition, along with other important variables, were remotely available at pre-set and specified time intervals. This was not only beneficial for system status monitoring and early identification of problems but has relevance for countries where financial subsidies are offered based on biogas quality and outputs, for example, the UK's Renewable Heat Incentive [20]. An example of gas output data is shown in Figure 4 (Thailand system), which enables the assessment of AD plant performance based on the mixed product of biogas production and methane as a function of different feedstocks over 75 days. The average methane yield was 0.39 $m^3$ $CH_4$/kgVS which is in line with other studies [21, 22]. For more detailed information on the process performance, the readers may refer to [23].

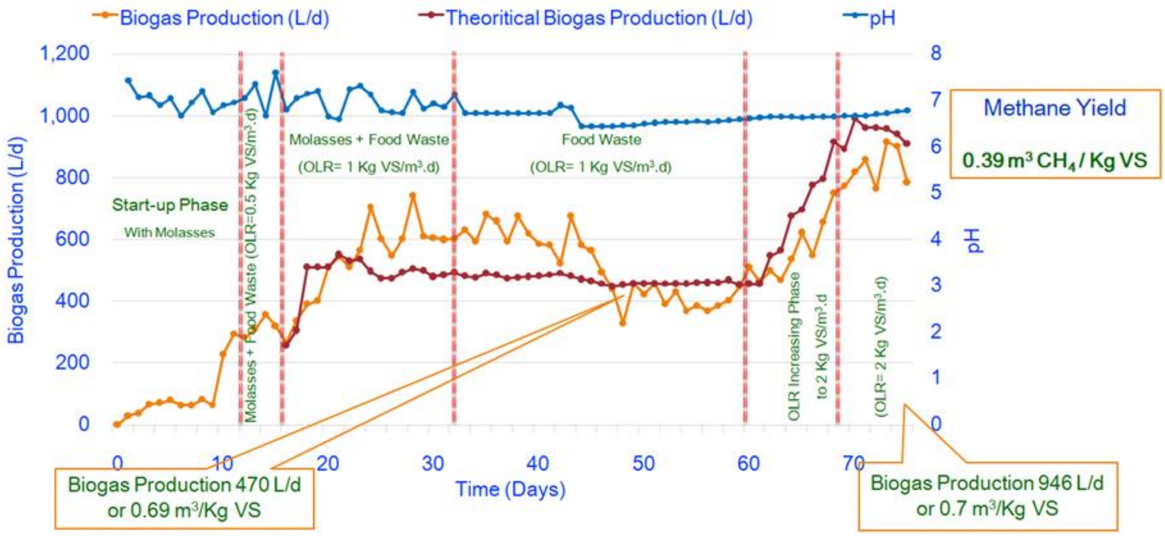


**Figure 4** Daily biogas production and $CH_4$ Vol.% and pH recorded by the Thailand AD system.

However, when the OLR was increased to 3 kg VS/m$^3$-d. (data not shown), the performance of the bioreactor suffered instability due to overloading and VFA accumulation. IoT elements in the system provided early warning for a system failure to enable precautionary measures [23]. Employing IoT in anaerobic digestion systems could prevent irreversible process failures. The decrease in methane content suggests inhibition in process performance. In such cases, proteinaceous or lipid-rich food waste was fed to improve methane yield. Similarly, sodium bicarbonate buffer was added to the reactor when there was a pH drop in the real-time data obtained. Likewise, whenever the intrusion of oxygen was detected inside the digester, steps such as checks for any leakage in the system and/or nitrogen sparging were taken. Access to real-time data aided in immediately resolving the oxygen presence, which otherwise could inhibit sensitive anaerobes inside the digester. Therefore, high quality of biogas was ensured in the anaerobic digesters through online monitoring and control in this study.

The UK system facilitated off-site assessment of both the running costs and the effects of novel design features. With the UK reactor, this was specifically the design of the re-circulation pump plus heat retention within the reactor. The auditing of each component's energy use, compared against contemporary biogas production, revealed that during winter months, the immersion heater and heat transfer pump were consuming approximately nine times the energy value of the total biogas produced (this was based on a biogas calorific value of 22 MJ/m$^3$, and an average immersion heater daily energy consumption of 9 kWh, which varies dependent on day degrees at the site). Though not widely disclosed, similar negative efficiencies have previously been reported for AD systems in temperate regions [24]. When the re-circulation pump was activated, the energy consumption of the system doubled, and calculations predicted that 385 times increase in biogas production would be required for the system to operate at positive net efficiency. Further studies are planned to test the effect of the re-circulation pump on biogas composition and volume as a function of re-circulation pump flow rates.

For AD reactors operating at positive efficiency, the system permits the easier assessment of similar process economics such as payback time, etc., along with data on how these are affected by feedstock variations. This could be done off-site, and on a dynamic basis, for a suite of AD installations.

Process loss prevention and operator safety was also improved with the system through its ability to continuously and remotely monitor pressure build-up in the digester headspace of both reactors. Despite pressure relief valves being standard features, explosions from biogas plants are not uncommon [25, 26]. So, such a remote-monitoring adaptation provides supplementary safety features and ones that are currently absent from small-scale systems. Furthermore, extra benefits come from its ability to provide both early warning detection and to greatly minimize the potential for placing on-site operators at risk.

By providing information on key process parameters in real-time (as can be seen from Figure 3 and Figure 4), the Thailand system ensured that process stability, and therefore optimization could be monitored as feedstock composition varied. This was found to reduce operation and maintenance costs by alleviating the burden of frequent reactive interventions, some of which would otherwise have involved complex procedures that are not always easy to procure due to their cost and lead times. This benefit comes from the system's ability to identify potential parameter changes and process instability at an early stage, thereby reducing response times. For example, the optimum pH for high biogas yield and a stable AD process is 6.5-8.0 [12, 19, 27] outside of which remedial measures such as increasing the retention time of feedstock or adding buffer can be adopted, followed by careful observation until the complete recovery of the system. This obviates the need for ex-situ analysis such as determination of the ratio of Volatile Fatty Acids to Total Alkalinity until a clear picture emerges. Similarly, sensors provided data on Oxidation-Reduction Potential (ORP), which for process stability is recommended to be less than -200 mV [18].

Calibration drift is a concern with any remote gas analyser and so the accuracy of the GasfluX unit was monitored. Figure 5 shows the results of our independent study comparing this instrument's outputs alongside manually taken measurements of $CH_4$ production using a calibrated Gas Data UK GFM-416 gas analyser for validation. Note that data for $O_2$ is available but omitted from Figure 5 as most of the readings from both devices overlap at the value of zero. Although GasfluX measured values every four hours, seven days per week, manually obtained values (by Gas Data) were only sampled once per day (excluding weekends). Through the experimental period, with the exception of day 2, the two sets of measurements from the remote monitor and the laboratory analyser only differed by 3-7%. This indicates a good correlation and justifies the choice of the GasfluX device as an effective remote monitoring device for smaller-scale AD systems. The manufacturer's recommended interval between calibrations for the GasfluX is every 6 months.

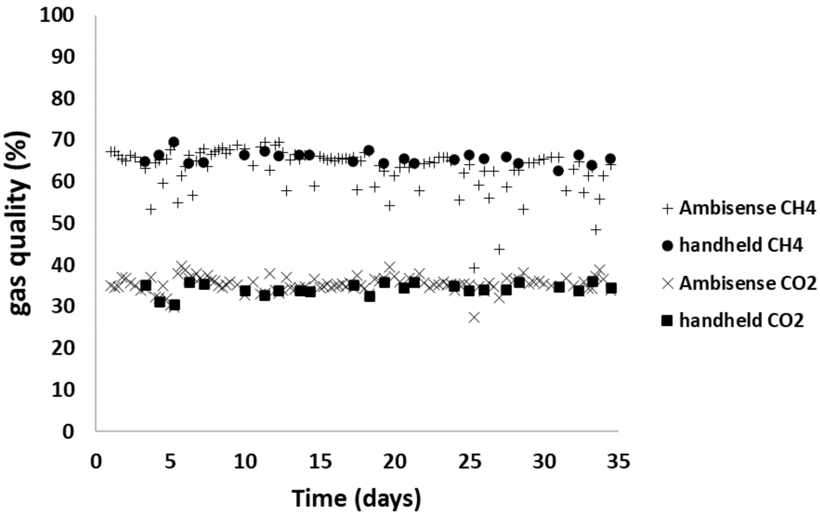


**Figure 5** Comparative gas analyses of $CH_4$, and $CO_2$ volumetric concentration from the UK AD unit. GasfluX values are shown with data obtained at the same time using a handheld gas analyser (Gas Data UK – GFM 416).

The purchase price of the Ambisense's GasfluX unit is £7000-£8500 per unit, depending on the specifications, and in addition to this the manufacturer's recommended service costs of currently £1000 p/a. Though expensive, this compares favourably to industrial control and monitoring systems of >£30,000 (estimate made by industrial scale operators). Designed primarily as an instrument for evaluating gas species composition of landfill sites the GasfluX units' standard 45 ml moisture filter proved inadequate for the high moisture-laden product gas from the reactors and was replaced by two in-series 310 ml composite filters (N771N, by Headline Filters, UK), supplemented by a two in-series silica gel traps. The composite filters had a self-draining mechanism, but required replacement fabric inserts approximately every four months, while the silica gel was refreshed weekly under continuous operation. Interestingly, $H_2S$ was found to permanently poison the silica gel during stages when it was produced in high concentrations. Hence the monitoring system was found to be useful for detecting high $H_2S$ that could be detrimental to digester stability and to pre-empt the requirement to replace the trap media.

Specific set points and thresholds have proved unsuccessful for AD process stability control purposes [11], as the parameters are interconnected and often specific to a set of operational parameters and the feedstock used. For example, a wide range of VFA concentrations of up to 4000 mg/l has been reported for stable AD reactors [15], making it very difficult to set a valid stability threshold value. On the other hand, apparent instability in the reactor may not immediately show in parameters such as methane in the gas phase, as lower methane production may often be masked and not detected if a headspace is of a very large volume [11]. Sudden changes in trends of a combination of parameters have been suggested as a more appropriate approach to predict the onset of process instability. Gas sensor data is a useful low-cost proxy indicator of AD process stability in the absence of more expensive direct measurement techniques such as VFA and spectrography. Future research would focus on improving the quality of process stability control information using machine learning techniques [28] where dynamic and non-linear system factors would be taken into account when judging the stability of a reactor.

Research monitoring of biogas plants is less controllable than laboratory experiments but has applications in the real-world [11]. Although currently cost prohibitive, when manufactured and deployed at scale it is anticipated that the capital and operational cost of the GasfluX equipment could reduce significantly. In addition, further studies should investigate how the costs of monitoring systems can be controlled through the development of simple but robust sensors [11], IoT communication, although this should also include manufacturing and commercialization costs of new monitoring devices. Recent developments in open-source standard electronic platforms, such as RISC-V and sensors to monitor AD variables offer solutions to the high costs associated with commercial instrumentation [29] This has the potential to make real-time AD monitoring economically and technically sustainable [30], and ensure stable biogas production; the rationale for this monitoring study.

## 4. Conclusions

To address the need for lower-cost methods of AD control and management at the community scale, the implementation of a de-centralised network of two AD plants linked by a central monitoring system has been studied. The aim of the study was to design, develop and assess a novel de-centralised IoT-based remote monitoring AD network. The specific objectives were to design and develop two independent community-scale AD systems, to test and commission the AD systems, to set up a networked lower-cost remote monitoring network, and to validate the performance of the remote monitoring against standard laboratory analytical techniques. The network comprised of two sites, one in the United Kingdom and one in Thailand, with each system being designed independently and having its own bespoke on-site control and monitoring equipment that meets the aim of the study.

Both AD systems were designed for the country context and operated successfully during the study producing levels of biogas comparable with the literature. The GasfluX device has proven to be reliable by giving comparable results to laboratory test equipment. Real-time, and simultaneously shared data of reactor parameters proved beneficial as it enabled off-site centralised monitoring of reactor status at multiple sites. In this case, it was useful for collaborative research purposes, but commercial applications can also be envisaged such as managing a multi-site network of AD reactors from a central station where expertise is located. This would negate the need for permanent skilled staff on site.

The off-site monitoring of biogas and other process variables enabled a rapid reactive response to maintain reactor stability and consequently biogas quality. $H_2S$ has a fast response to loading perturbations compared with methane which lags behind when changes in the reactor conditions occur and is a good indicator of reactor health. Measurements of biogas yield, along with comparable unit-specific power consumption facilitated dynamic economic appraisal of the systems. This automated data collection on biogas production is also seen as being attractive for countries where auditing is required to claim renewable energy subsidies.

Total system costs compared favourably with large-scale industrial alternatives. The IoT-based centrally monitored decentralised anaerobic digesters have higher performance in terms of stability, productivity, and efficiency, but lower cost. The IoT-based reactor configuration presented in this study can be applied by retrofitting existing decentralised biogas plants with only minor modifications. The future prospect of developing this research would have to integrate monitoring of both process characteristics (loading rate, hydraulic retention time, temperature, reactor size, gas quality, and quantity) and parameters indicating imbalance (VFAs, alkalinity, redox potential). Also, combining knowledge of the site-specific parameters (e.g. feedstock composition and variability, scale of the reactor, temperature) with machine learning would enable the development of tailored monitoring systems targeting only parameters relevant to a particular reactor.

The study recommends future research to realise the immense potential of online remote monitoring and control in anaerobic digestion systems.

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**Competing Interests**

The authors have declared that no competing interests exist.

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