CHAPTER 4

IoT FOR MANAGEMENT OF HOUSEHOLD BIOGAS SYSTEM: A FEASIBILITY ANALYSIS

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4.1 Introduction

The status of Household Biogas Systems (HBS) has been analyzed and presented in the previous Chapters. Several factors, including feedstock quality, microbial activities, and climatic conditions, critically influence the performance of biogas production. Effective management of these factors presents ongoing challenges. The importance of technology-integrated monitoring systems for providing management support has been discussed in previous chapters. These systems can offer real-time data and analytics to optimize biogas production processes, ensuring better performance and sustainability of HBS. This Chapter investigates the feasibility of integrating an Internet of Things (IoT) system for the management of household biogas plants. The aim is to explore how IoT can enhance monitoring and control capabilities, thereby improving the overall efficiency and effectiveness of HBS operations.

4.2 Materials and Methods

The methodology used to investigate the feasibility of the application of IoT for the management of household biogas systems is presented in **Fig. 4.1** and discussed below.

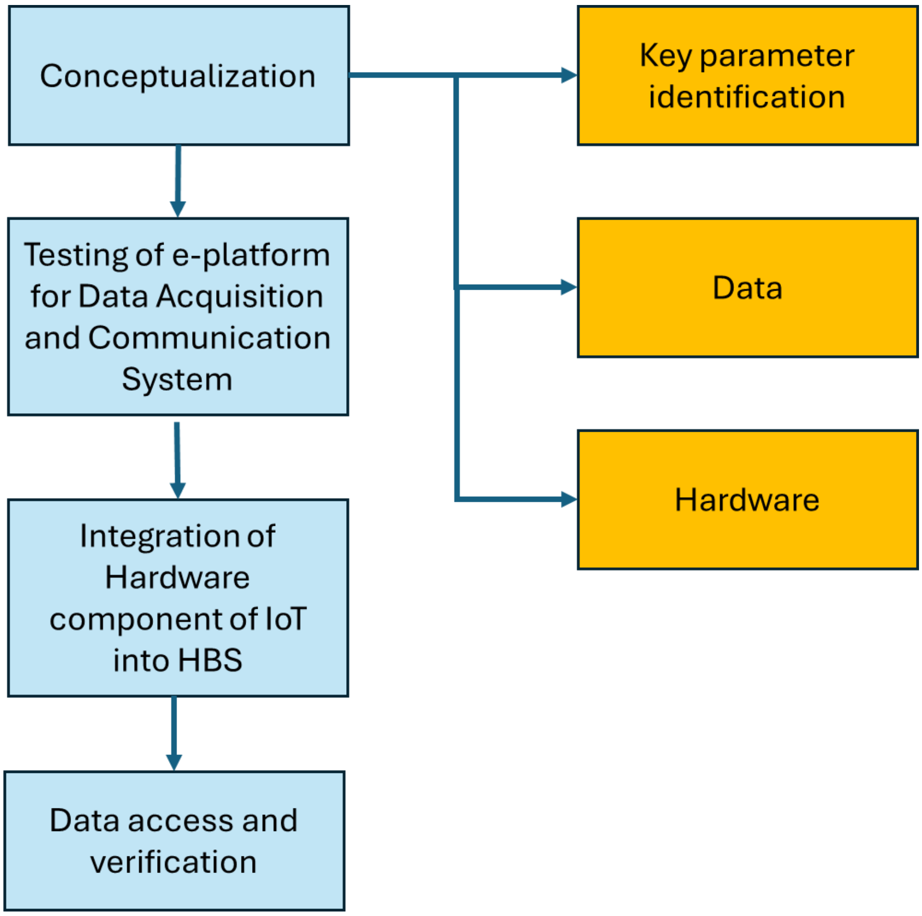


Fig. 4.1: Methodology to investigate the feasibility of the application of IoT for the management of HBS

Conceptualization of IoT in biogas system

The anaerobic reactor of a biogas system is the central unit where the conversion of solid biomass particles into a gaseous mixture with methane as a major component is achieved through a series of complex biochemical reactions through the involvement of a microbial consortium. The instantaneous data regarding the reaction conditions can provide useful information about the performance of the bio-methane conversion [1]. The major variables of the system that result in uncertainty are (i) feedstock characteristics (elemental composition, particle size, physical composition), and (ii) ambient conditions (temperature). Under such variable conditions, a specific reaction condition is maintained resulting in the conversion of biomass hydrocarbon into methane and other gases. There has been elaborate research describing the theory of bio-methane conversion from biomasses. It is known that the pH of the reaction medium is an important parameter reflecting the reaction conditions [2-4]. Again, the series of reactions require a given thermal environment i.e. specific temperature conditions which have to be met [5-7]. Thus, for a particular input of feedstock with known loading rate and characteristics, the instantaneous data of temperature and pH of the reaction environment can provide the status of the bio-methane conversion. For accurate and precise monitoring and management of the biogas system, an access to these parameters gives a comprehensive understanding of the health of the biogas system. In a typical biogas system, the digester provides the space for reaction whereas the gas holder provides the space for the storage of the gas before being released for consumption (**Fig. 4.2**). Further, data concerning the composition of the product gases (CH_4%, CO_2%, H_2S%) will provide information about the performance of the biomethane conversion of the feedstock.

The IoT system requires a provision for capture of data (ambient temperature, ambient RH, temperature of the reaction zone, pH of the reaction zone, pressure of the gas and gas composition viz. CH_4%, CO_2%, H_2S%) using appropriate sensors as shown in **Fig.4.3**. Data acquisition, processing integrated with suitable communication hardware and display unit (computer and smartphone) are core units of the IoT system, graphical representation of which is provided in **Fig. 4.3**.

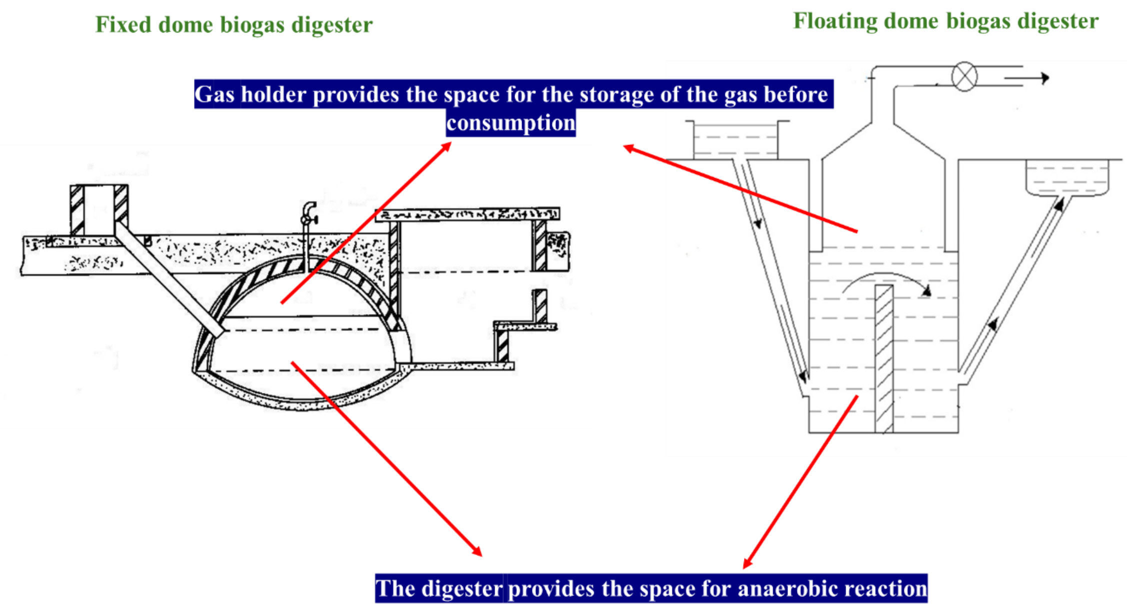


Fig 4.2: Gas holder and digester providing spaces for gas storage and gas consumption respectively in a Fixed dome and Floating dome-type biogas digester

Testing of e-platform for Data Acquisition and Communication System

In the current study, an experimental biogas reactor (Make: Shakti Surabhi 0.25 m^3) is used for integration of an available IoT system as shown in **Fig. 4.3**. Further, the server available in the AdaptNET laboratory of Tezpur University is used for data communication.

The control system for the designed IoT based biogas monitoring system consists of the ESP 32 microcontroller and the sensors (BME280, DS18B20, pH electrode). The description of the control system is done below and the schematic of the IoT-based biogas monitoring system is shown in **Fig 4.3**. The system is built using an ESP32 microcontroller, which acts as the brain of the system. The ESP32 is a powerful microcontroller that provides Wi-Fi connectivity to be used for IoT applications. The system consists of several sensors, including a BME280 sensor for measuring ambient temperature, pressure, and humidity. This sensor is used to monitor the conditions inside the biogas plant, which can affect the production of biogas. The system also includes a DS18B20 temperature sensor, which is a waterproof sensor used to measure the temperature of the slurry inside the biogas plant. This sensor is critical as it ensures that the temperature inside the biogas plant is optimal for the production of biogas. The system also includes a pH sensor, which is used to measure the pH value of the slurry inside the biogas plant. The system is powered using a power bank, which is continuously charged using a 5-volt adapter. All the sensors were calibrated using standard protocols. The data acquired by the sensors is sent to the server at an interval of 15 minutes. This data is used to monitor the conditions inside the biogas plant. The server receives the data from the ESP32 microcontroller and stores it in a database. The data can then be analyzed to identify any anomalies that may be affecting the production of biogas. The system can be accessed remotely using a web interface or a mobile application. This allows users to monitor the conditions inside the biogas plant from anywhere. Overall, the system provides a reliable and efficient way to monitor the conditions inside a biogas plant. The list of components of the IoT system and their location of installation is provided in **Table 4.1**.

Integration of Hardware component of IoT into HBS

The functionality of the outdoor and indoor IoT components installed are periodically checked and reported to assess the performance of the IoT system during the observation period. Simultaneously, data acquired through the system is also verified and analyzed.

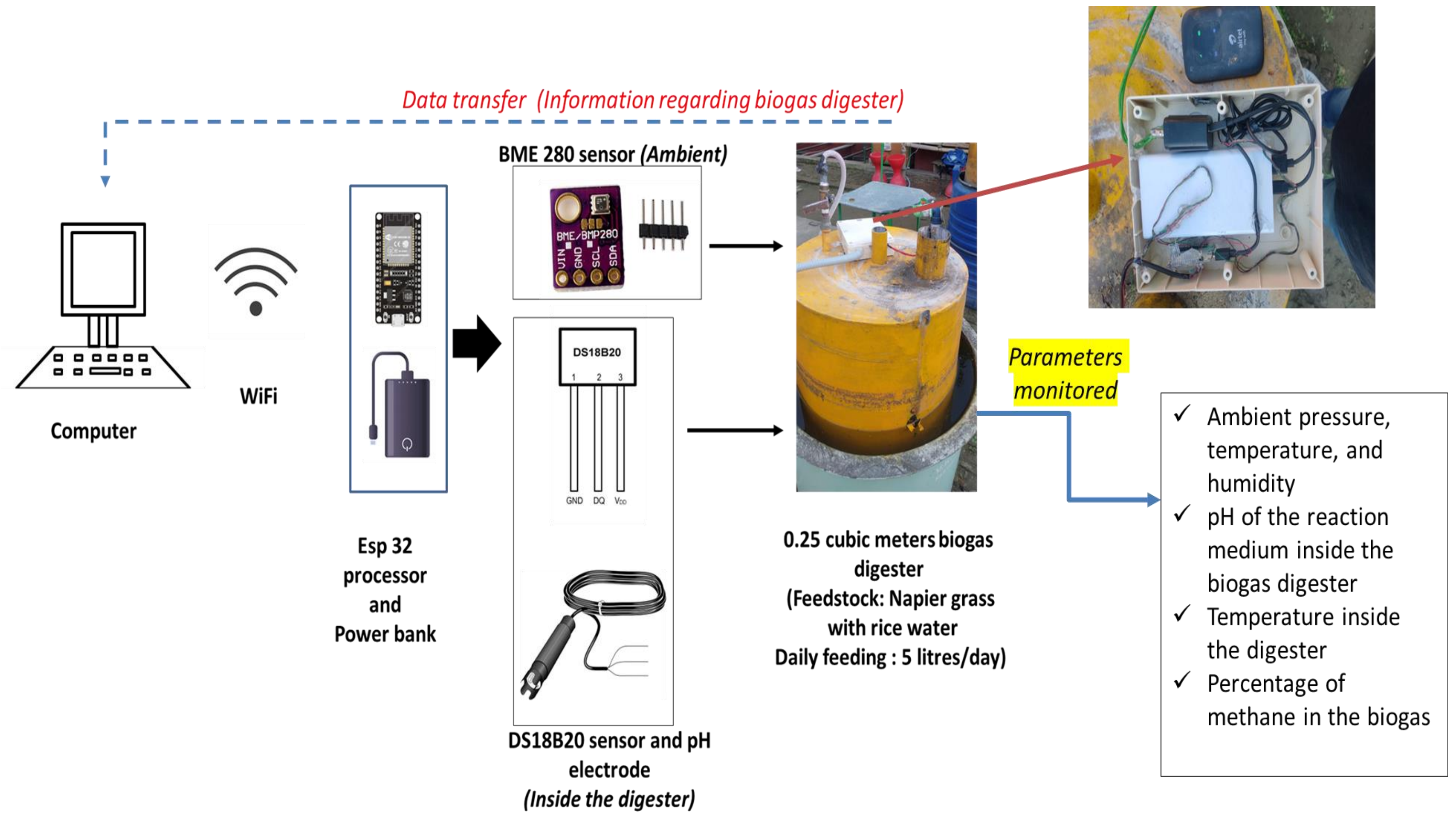


Fig 4.3: IoT-based biogas management system

Table 4.1: Table of Components, Specification, Installation Location, Remarks of the IoT system

S.No.	Components	Specification	Installation Location	Remarks
1	ESP 32 processor	• Wireless Connectivity: Wi-Fi, Bluetooth • Memory: Internal RAM (520 KB) • Operating Voltage Range: 2.2V to 3.6V • Security Features: Encryption, Secure Boot, Flash Encryption	Outside the digester	----------
2	Power bank	• Capacity: 20000 mAh • Battery Type: Lithium-polymer • Fast Charging	Outside the digester	----------
3	BME 280 sensor	• Voltage range: 1.8 to 5 volts DC. • Temperature: - 40 °C to + 85 °C (accuracy± 1°C) • Humidity: 0 % to 100 % (accuracy: ± 3%) • Pressure: 300 hPa to 1100 hPa (accuracy: ± 1Pa)	Outside the digester	----------
4	DS18B20 sensor	• Waterproof • Operating Voltage Range: 3.0 V to 5.0 V • Temperature range : 55 ° C to +125 ° C	Inside the digester in contact with the reaction media	• Pre-wired, • Particularly useful for measuring distant or wet conditions • Can be easily integrated with

				any microcontroller
5	pH electrode	• Operating Voltage: 5-volt DC input power • Accuracy: ±0.01pH	Inside the digester in contact with the reaction media	----------
6	Server	• Hewlett Packard Enterprise • Operating System: Linux	Outside the digester, not in the vicinity of the digester	----------

Data access and verification

An application software was developed for remote access of the sensor data as well as for its storage and display through a computer or a smartphone. The wireless network and server available in the Tezpur University campus are used for the above purpose.

In addition to understanding the technical feasibility the approximate cost of the system is also assessed from the prevailing market rate of the required components with realistic assumptions. Costs involved in the fabrication of the IoT-based biogas management system have been shown in **Section 4.5**. Based on these costs, the economic analysis of the IoT-based biogas management system with some selected rural enterprises has been carried out in **Chapter 5.**

4.3 Results and Discussion

4.3.1 Testing of e-platform for Data Acquisition and Communication System

As discussed in the previous section, an application software is used to acquire the data of the biogas system pertaining to (i) reaction zone (temperature, pH), (ii) ambient conditions (temperature, relative humidity) (iii) output gas composition (CH_4, CO_2, H_2S) using the relevant sensors, microcontroller and communication network. The results obtained from the test are presented and discussed below.

Acquisition of data from the reaction zone of the biogas system

The temperature and pH of the reaction zone are important indicators of the performance of the biogas system. A neutral pH and suitable temperature to support the anaerobic reaction taking place in the Mesophilic (20 ºC – 45 ºC) and Thermophilic conditions (60 ºC -80 ºC) are desired. The temperature and pH sensors in the current investigation were mounted within the reactor, which are connected using a communication cable with the microcontroller kept outside of the biogas system.

Working of the IoT system corresponding to the capture of data (temperature and pH), transmission, and display at the user end have been tested successfully, as shown in **Fig. 4.4 (a, b).** The system has the provision of setting the interval of data acquisition, whereas, for the test, 15-minute intervals were considered.

Fig 4.4 (a): Installing the circuit inside the digester

Reaction zone temperature is influenced by the ambient temperature. Moreover, the humidity of the biogas at any given point in time is related to the relative humidity of the ambient air. Thus, information related to ambient temperature and ambient relative humidity is important to understand the performance of the biogas system in terms of the reactions and quality of the biogas. The instantaneous status regarding the ambient temperature and humidity was also successfully captured, transmitted, and displayed in the system.

Several attempts were made to capture the gas composition data by installing gas sensors inside the gas holder (**Fig. 4.5**).

Fig 4.4 (b): Slurry in contact with the circuit

However, the sensors were found damaged (**Fig. 4.5 (b)**) and therefore composition data could not be accessed through the IoT system. Erroneous results were displayed, and upon further analysis, it was determined that the sensors were damaged, leading to inaccurate readings. For example, the pH sensor showed a reading of 19, which is beyond the expected range. This confirmed that the sensors were compromised. This is being further investigated through a thorough inspection. The sensors were damaged probably due to humidity and acid vapor inside the biogas digester.

The interpretation of data collected from corrosion sensors is critical. The data must be analyzed in the context of the specific environmental conditions and the sensor's operational limits. Monitoring of sensor performance was implemented to minimize these effects. If corrosion significantly impacted sensor functionality, the data collected during periods of malfunction would have been flagged and either corrected or excluded from analysis.

An example of the degradation in the components can be observed from **Fig. 4.5** in which the status of a circuit component is shown before and after placing it inside the gas holder of the household biogas plant. Two major kinds of degradation are observed.

a) *Corrosion of solder mask layer*: Solder mask layers are protective layers on printed circuit boards, which provide the desired insulation between the different components. Removal of this layer is undesirable and may lead to unwanted

connections arising out of conductive layer deposition or short circuits. Identifiable by its green or blue color, this solder mask layer can be usually removed through processes of mechanical stripping and chemical stripping. In the case of the household biogas system, the only possibility is the chemical stripping of the solder mask layer. It is established that such corrosion in electronic components is caused due to humidity and temperature over a continuous number of cycles [8,9]
Processes like oxidation or hydration of the solder flux resin can lead to such events of corrosion. As reported in [8], water film formation may lead to leakage current and subsequent degradation of the components. Hydrogen sulphide, one of the gaseous products in a biogas system, in a humid environment is corrosive for printed circuit boards (PCBs) [10].

b) *Deposition of residue on metal bodies*: Another observation from **Fig. 4.5** is the deposition of residue (gaseous or moist) on the circuit components. Although this is less severe than the observation of (a), it must be noted that over 6 months, the structure of the circuit components have considerably aged. The metal bodies and contacts are largely affected by these depositions. Over a satisfactory period in which an IoT system is expected to be operational, such aging may be detrimental in affecting the performance of the electronic components.

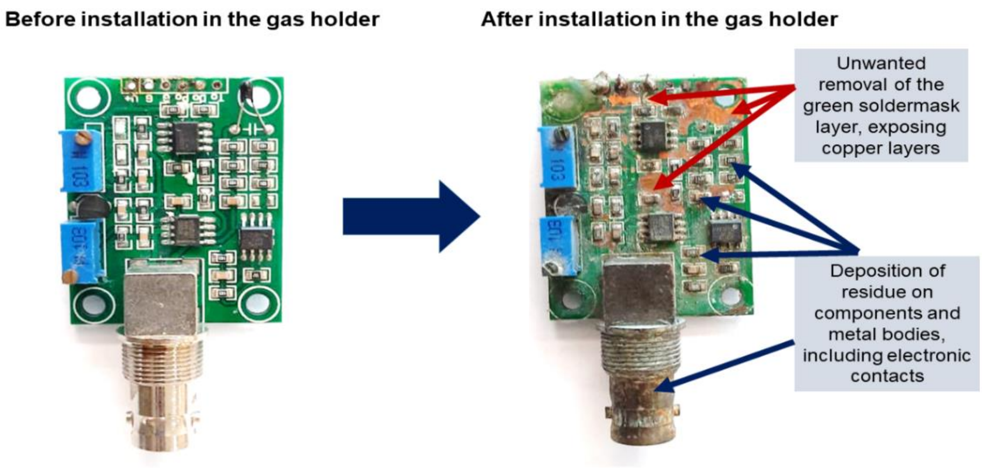
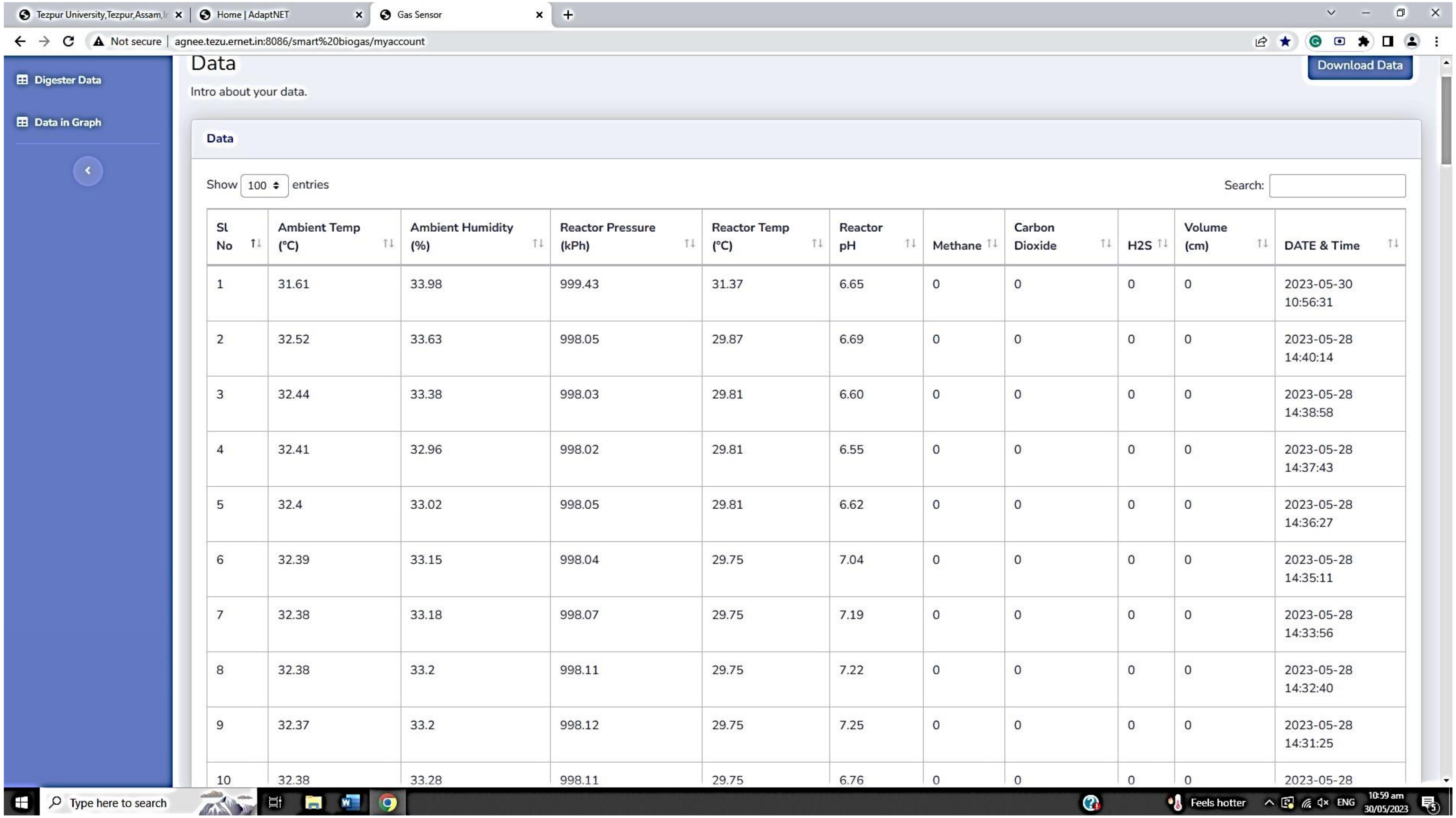


Fig. 4.5: Status of a circuit component before and after installing it in the gas holder of the household biogas system

To reduce the likelihood of corrosion affecting the solder mask layer, protective coatings, such as polymer-based or epoxy coatings, can be applied. These coatings act as a physical barrier, shielding the solder mask from environmental factors like humidity and temperature. In addition to extending the lifespan of the components, these coatings will help maintain accuracy by preventing interference from external conditions. They will also protect the circuit components from aging caused by the deposition of sludge or other contaminants.

The relative humidity and the ambient temperature as seen in **Fig 4.6 (b)** have been recorded by the BME 280 sensor. The relative humidity was around 70% and the ambient temperature was around 4-5 °C more than the temperature inside the digester.

The ambient temperature and relative humidity can be considered as reference points for maintaining optimal anaerobic conditions inside the digester. If the ambient temperature is consistently higher, it can help sustain the digester's temperature without the need for additional heating. On the other hand, if the ambient temperature drops significantly, additional heating may be necessary to maintain optimal digestion conditions. Higher relative humidity is crucial for the anaerobic digestion process. Insufficient moisture can retard microbial activity and may lead to lower biogas yields.



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Digester Data

Data in Graph

Data

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Sl No	Ambient Temp (°C)	Ambient Humidity (%)	Reactor Pressure (kPh)	Reactor Temp (°C)	Reactor pH	Methane	Carbon Dioxide	H2S	Volume (cm)	DATE & Time
1	31.61	33.98	999.43	31.37	6.65	0	0	0	0	2023-05-30 10:56:31
2	32.52	33.63	998.05	29.87	6.69	0	0	0	0	2023-05-28 14:40:14
3	32.44	33.38	998.03	29.81	6.60	0	0	0	0	2023-05-28 14:38:58
4	32.41	32.96	998.02	29.81	6.55	0	0	0	0	2023-05-28 14:37:43
5	32.4	33.02	998.05	29.81	6.62	0	0	0	0	2023-05-28 14:36:27
6	32.39	33.15	998.04	29.75	7.04	0	0	0	0	2023-05-28 14:35:11
7	32.38	33.18	998.07	29.75	7.19	0	0	0	0	2023-05-28 14:33:56
8	32.38	33.2	998.11	29.75	7.22	0	0	0	0	2023-05-28 14:32:40
9	32.37	33.2	998.12	29.75	7.25	0	0	0	0	2023-05-28 14:31:25
10	32.38	33.28	998.11	29.75	6.76	0	0	0	0	2023-05-28

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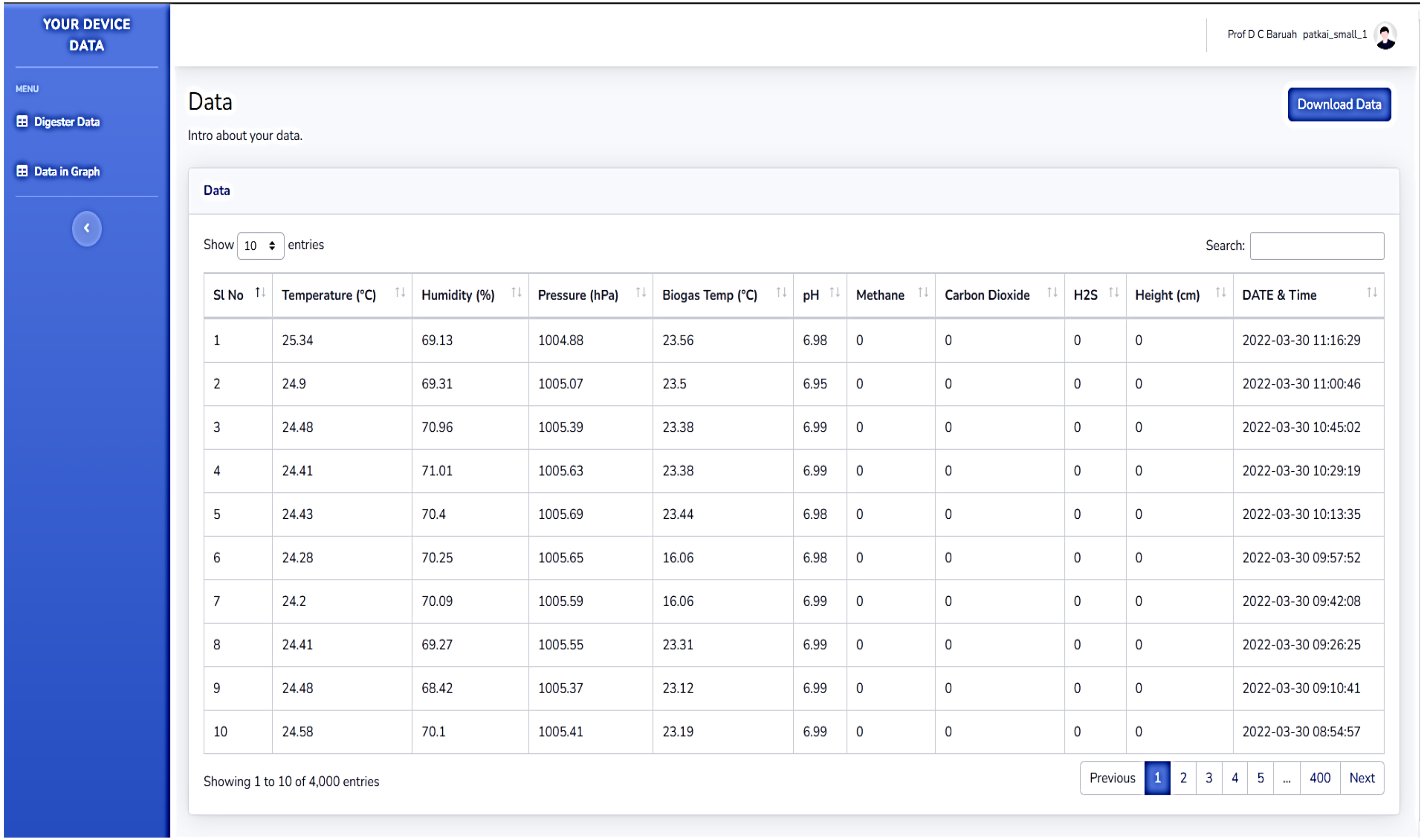

YOUR DEVICE DATA

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Digester Data

Data in Graph

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Data

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Sl No	Temperature (°C)	Humidity (%)	Pressure (hPa)	Biogas Temp (°C)	pH	Methane	Carbon Dioxide	H2S	Height (cm)	DATE & Time
1	25.34	69.13	1004.88	23.56	6.98	0	0	0	0	2022-03-30 11:16:29
2	24.9	69.31	1005.07	23.5	6.95	0	0	0	0	2022-03-30 11:00:46
3	24.48	70.96	1005.39	23.38	6.99	0	0	0	0	2022-03-30 10:45:02
4	24.41	71.01	1005.63	23.38	6.99	0	0	0	0	2022-03-30 10:29:19
5	24.43	70.4	1005.69	23.44	6.98	0	0	0	0	2022-03-30 10:13:35
6	24.28	70.25	1005.65	16.06	6.98	0	0	0	0	2022-03-30 09:57:52
7	24.2	70.09	1005.59	16.06	6.99	0	0	0	0	2022-03-30 09:42:08
8	24.41	69.27	1005.55	23.31	6.99	0	0	0	0	2022-03-30 09:26:25
9	24.48	68.42	1005.37	23.12	6.99	0	0	0	0	2022-03-30 09:10:41
10	24.58	70.1	1005.41	23.19	6.99	0	0	0	0	2022-03-30 08:54:57

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Fig 4.6 (a): Computer display of the biogas monitoring system showing ambient pressure, temperature, humidity; temperature, and pH of the reaction media inside the digester

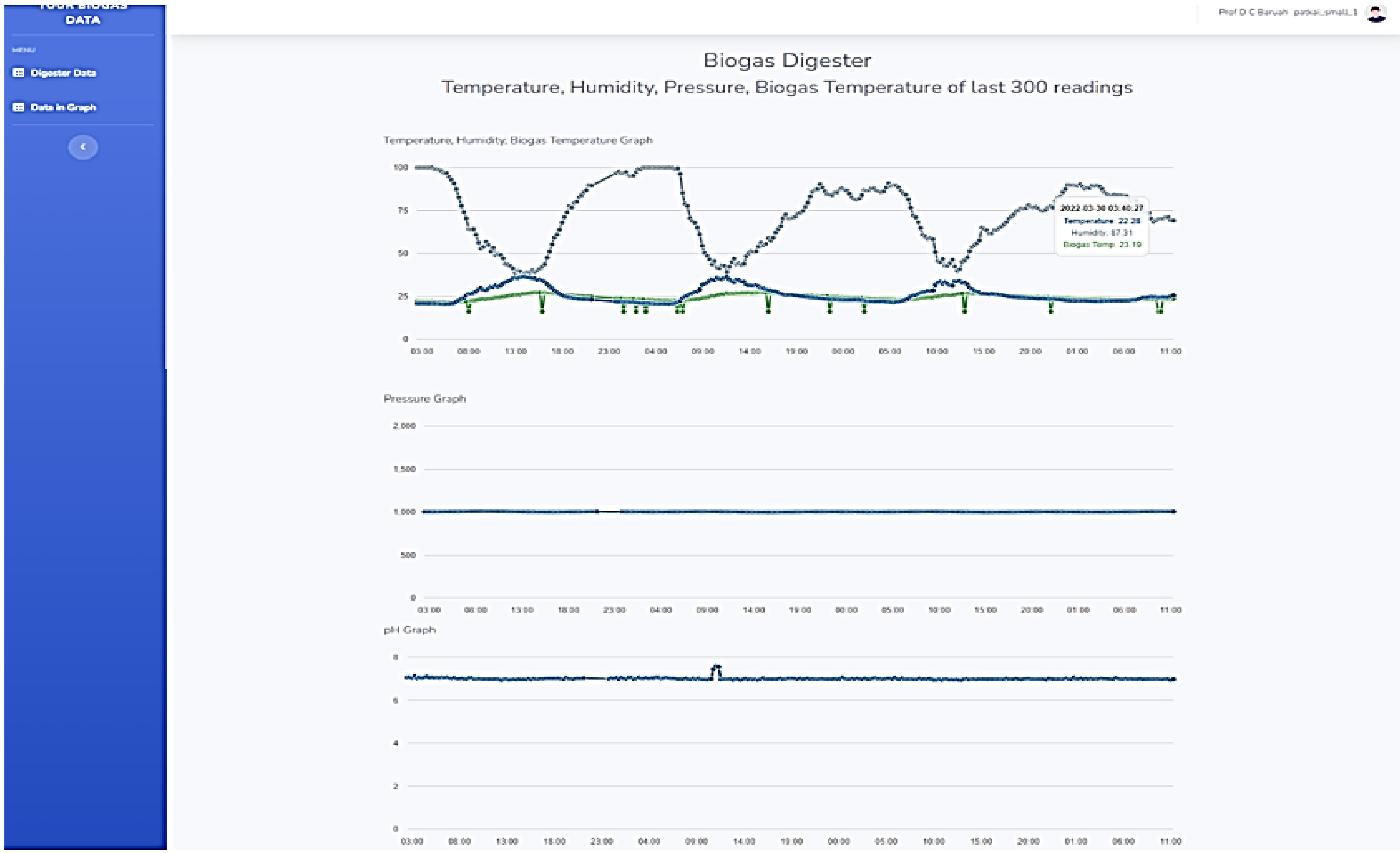

Fig 4.6 (b): Graph representing ambient temperature, pressure and humidity, slurry temperature, and pH of the biogas

4.3.2 Integration of Hardware component of IoT into HBS

Though the gas composition data could not be accessed in the current investigation, the functionality of the IoT system could be tested for the remaining parameters. The operational features of the test biogas system were ascertained by collecting the gas composition data using a conventional gas analyzer (Portable Gas Analyzer Combimass ®GA-m, measuring range of methane = 0 to 100 % of the volume, accuracy = ± 0.5% volume, measuring time = 50 to 120 seconds). Variation of the temperature and pH data of the reaction zone (**Fig. 4.6 (b)**) as recorded in the test period is indicative of the reaction condition which is found in line with the production of biogas.

Any notable deviations in pH will be useful for the biogas operator to make appropriate interventions at the site. Moreover, such information will also be known to a remotely located person or a manager to understand the operational status of the biogas system. Thus, the system designed is found useful.

The temperature profile as recorded by the IoT system (**Fig. 4.6 (b)**) at two specific locations (a) ambient (outside of the reactor) and (b) reaction zone temperature indicates thermal management of the biogas system. The available heat of the ambiance can be transferred to the reaction zone to ensure better performance during some periods of the day as noticed from the plot. Around 72 hours period of operation, the reactor zone remained cooler than the outside whereas a higher temperature would have been better for efficient gas production. The ambient temperature and relative humidity can serve as reference points for maintaining optimal conditions within the digester. If the ambient temperature is consistently higher, it can help sustain the digester's temperature without the need for excessive heating. Conversely, if the ambient temperature drops significantly, additional heating may be necessary to maintain optimal digestion conditions.

4.3.3 Data access and verification: Critical challenges for IoT applications

The stability of the electronic components used for the IoT system installed in an outdoor ambiance has remained a major challenge. Similar experiences were also reported in earlier literature [8,9,10, 11]. Probable solutions for system stability, protection from high humidity, chemical contamination, etc. are obtained through review and presented below.

Similarly, the concerns regarding software, reliable power supply, and consistent performance of sensors with expected data accuracy are also elaborated below.

Issues for hardware integration with existing biogas plants

The possibility of integration of the IoT system in an existing biogas system was also explored (**Fig. 4.7 (a) and (b)**), however, without substantial success. Access to installing the sensors for reactor data has remained a major challenge in the existing biogas system. However, data pertaining to some of the parameters were accessed through traditional gadgets for the biogas system and were successful. The absence of instantaneous data-capturing capability of the manual method is evidenced as a limitation of the manual method.

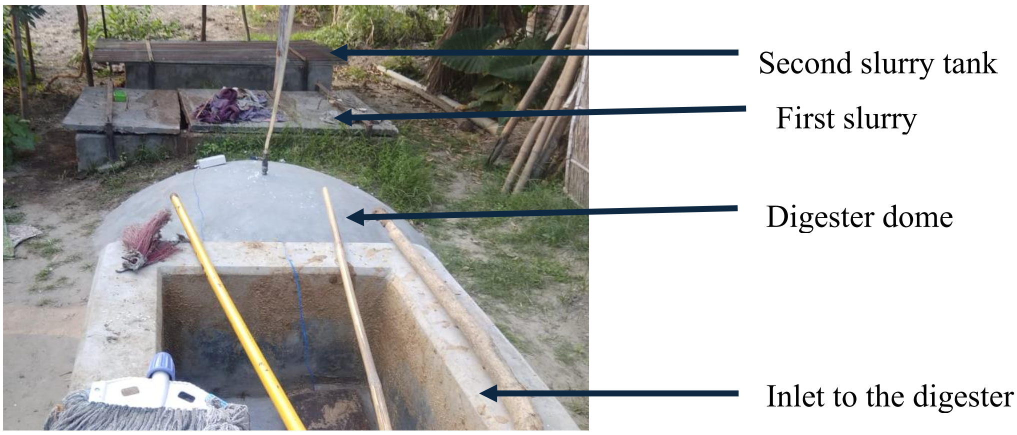

Fig 4.7 a: 2 cubic meters *Deenbandhu* biogas system

Fig 4.7 b: Installing of IoT based biogas monitoring system in 2 cubic meters *Deenbandhu* biogas system

Structural reliability of electronic components

Corrosive effects of humidity, temperature, and gases on commercially printed circuit boards are major concerns for an IoT-integrated biogas system. The different electronic modules that make up the IoT system comprise of electronic components embedded in the PCBs based on the manufacturer's placement and routing strategies. Exposure of the solder-masked copper interconnect layer in a PCB to products like H_2O and H_2S in the presence of temperature could lead to degradation of the performance of the electronic system over a long period. Although smart systems equipped with IoT are prospective in addressing the monitoring and diagnosis of a biogas plant, the reliability of the electronic components (microcontrollers, sensor modules, and connecting wires) is a major problem. Electronic components with desired performance at room temperature may exhibit high leakage current inside the household biogas system, indicating lesser reliability of these components. Such degradation leads to erroneous data, largely deviating from the calibrated values. There are indeed mistakes and uncertainties in the instruments used to measure pH and temperature, which can affect how accurate the readings are. Even though an uncertainty calculation was not specifically included in this study, we made sure the data were accurate by routinely calibrating the instruments according to the manufacturer's instructions. To reduce random mistakes, measurements were also made several times, and any notable variations were recorded.

Calibration of commercial sensor modules

Sensors make an IoT system intelligent. There are a large number of commercial sensors available. However, one of the major challenges is that the calibration of these sensors, which is carried out in the laboratory in a confined environment is not sufficient to make them system-ready in terms of accuracy. Although the proportionality between laboratory measurement and real-world measurement is maintained, there are deviations in absolute values.

Outdoor power supply management

Since a smart IoT system integrated with the household biogas system is supposed to acquire data continuously throughout the day, therefore, one of the fundamental requirements in an IoT set-up is the power supply which is required to keep the system live. Direct current batteries or energy storage devices are the solutions; however, the depletion of voltage in batteries needs to be constantly monitored. Since an IoT system consists of electronic components for different purposes such as sensing, driving circuits, analog-to-digital converters, and memories, the power specifications for every one of them are highly likely to be different. Therefore, depletion of voltage at any point in time may lead to erroneous data. For a biogas system, provision and monitoring of a consistent outdoor power supply are quite important.

Automated error-detection

An online IoT system consisting of sensors is expected to be a diagnostic mechanism for the household biogas system. It is embedded with different electronic components including sensors, driver circuits, and microcontrollers. The data that is received on the server from the remote IoT system is the only source of information on which the clients or users rely for the operation of their biogas plants. However, there is a lack of an automated server-integrated error-detection mechanism that can detect if there is an error in the data acquisition by the sensors, which may arise out of events like interrupted power supply, sensor degradation, and short circuits between two components. This concern is one of the greatest challenges in IoT-integrated household biogas systems considering the fact that the data size is huge and the errors may be undetectable at times owing to the complex dependence on several variables.

Estimation of system cost and affordability

An attempt has been made to estimate the potential cost of the IoT system from several cost components which is presented in **Table 4.2**.

Table 4.2: Costs involved in the fabrication of the IoT-based biogas management system

S.No.	**Item**	**Cost (INR)**	**Replacement time (years)**	**Depreciation value (INR)**	**Total Cost (INR)**
1	ESP 32 processor	250	4	56.25	306.25
2	Power bank	1120	4	252	1372
3	BME 280 sensor	650	4	146.25	796.25
4	DS18B20 sensor	73	4	16.5	89.5
5	pH electrode	2500	2	1125	3625
6	Server	58958	4	14850	73808
7	Microcontroller	742	2	371	1113
Total cost					**81110**

4.4 Summary including limitations

The absence of remote monitoring has been identified as one of the key limitations hindering the promotion and effective management of Household Biogas Systems (HBS). Implementing technology-integrated solutions, such as IoT, can provide significant benefits in terms of monitoring and optimizing biogas production. However, several challenges and limitations must be addressed to ensure successful implementation.

The integration of IoT systems into HBS aligns with broader national initiatives such as Digital India, which aims to enhance digital infrastructure and connectivity across the country. This initiative can foster entrepreneurship opportunities by enabling local businesses and startups to develop and deploy IoT solutions tailored for rural and semi-urban settings where HBS are commonly used. Enhanced monitoring and management capabilities can improve the reliability and efficiency of biogas systems, encouraging wider adoption and supporting sustainable energy goals.

Implementing IoT systems introduces potential security vulnerabilities. Ensuring data privacy and protecting the system from cyber-attacks is crucial for maintaining user trust and system integrity. Additionally, the physical security of IoT components is a concern, as devices installed in remote or rural areas may be susceptible to theft or vandalism. Measures must be taken to safeguard these components and ensure their continued operation. The IoT devices and sensors used in HBS must be designed to withstand harsh environmental conditions. These systems should be durable and capable of functioning effectively in rural areas where conditions may be less controlled. The reliability of IoT systems is essential for continuous and effective monitoring. Any downtime or malfunction can disrupt the biogas production process and lead to inefficiencies. Therefore, the IoT solutions must be tested rigorously to ensure consistent performance.

Despite the potential benefits, there are limitations to the integration of IoT in HBS. The upfront investment required for IoT devices, installation, and training can be a barrier for many households, especially in rural areas with limited financial resources. The successful deployment and maintenance of IoT systems require technical knowledge and skills, which may not be readily available in all regions. Providing adequate training and support is necessary to overcome this limitation. Reliable internet connectivity and power supply are essential for the functioning of IoT systems. In many rural areas, infrastructure limitations can pose significant challenges to the continuous operation of these systems.

Proper calibration of key components in the IoT-based biogas monitoring system is essential for correcting malfunctions and ensuring reliable performance. This requires regular monitoring and maintenance of elements such as sensors, valves, and digesters to prevent failures. Any irregular readings should be promptly diagnosed, with immediate recalibration or replacement of damaged sensors as needed. Additionally, any deviations from optimal biogas conditions should be addressed promptly by operators to minimize malfunctions and ensure the smooth operation of the system.

Addressing these challenges and limitations is critical for the successful adoption of IoT-based monitoring in HBS. By overcoming these obstacles, the potential for improved management, increased efficiency, and broader promotion of biogas systems can be realized, contributing to sustainable energy solutions and rural development.

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