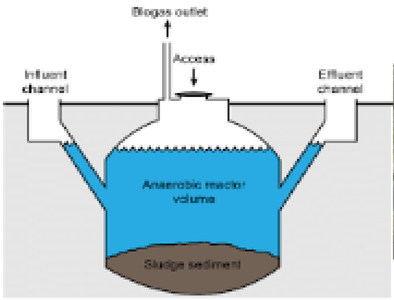
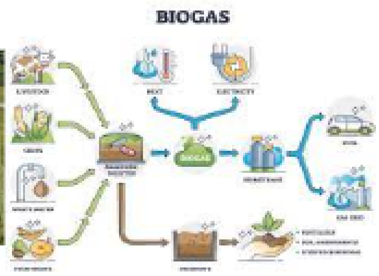
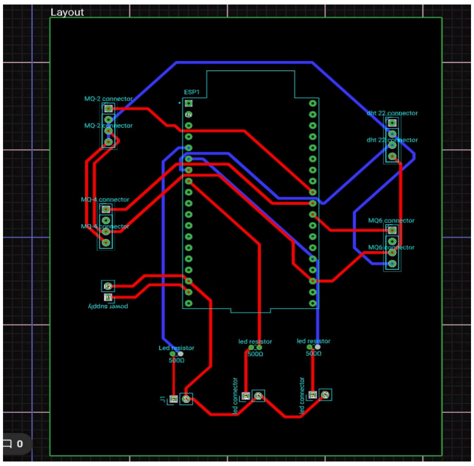
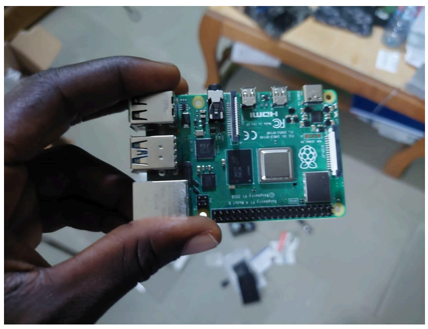
SCIENTIFIC DOCUMENTATION

GO GREEN Smart Biogas Technology (SBT) Project









Abstract

This research project aims to develop and evaluate an Internet of Things (IoT) system (device) to monitor biogas plants, specifically small-scale and domestic biogas plants. The primary research question guiding this study is: How can an IoT system (device) be designed and implemented to effectively monitor key parameters of biogas plants to improve both operational and environmental efficiencies and safety (OEES)? This question addresses research and development (R&D) gaps that exist for biogas technology adoption, utilization and durability, emphasizing the importance of real-time monitoring and data analytics in optimizing biogas production, and ensuring both operational and environmental efficiencies and safety (OEES). The ultimate outcome is to increase the adoption and utilization of environmentally conscious and user-friendly smart biogas technology for organic waste management whilst reducing to the barest minimum, greenhouse gas (GHG) emissions and the abandonment of biogas plants shortly after they are operationalized in Ghana. This is critical for sustainable and optimized organic waste management, especially for farmers, other non-technical individuals, and more. Moreover, this is crucial in reducing to the barest minimum the frequency of abandonment, as some abandoned biogas plants, neither decommissioned at all nor properly decommissioned are environmental threats. These environmental threats include breeding grounds for mosquitoes (potential for malaria), and reptiles (such snakes), amongst others.

Herewith, the scope of this research project starts with a literature review to understand the landscape of biogas technology in Ghana, its sub-region, Sub-Saharan Africa, the continent Africa, and across the world. This landscape encompasses a brief about understanding and adopting biogas technology, the evolution of biogas technology together with initiatives and projects that have been executed, challenges and opportunities for sustainable development in the aforementioned geographical contexts. In the sub-context of challenges and opportunities for sustainable development, this research project delves into how the development, deployment for testing and evaluation of an Internet of Things (IoT) system (device) enhances effectively and efficiently the monitoring of biogas plants, specifically small-scale and domestic biogas plants. Our methodology embraces a step-by-step approach and framework on how we developed, deployed for testing and evaluation, the results and discussion of an Internet of Things (IoT) system (device) for small-scale and domestic biogas plants in Ghana.

After several months of hard work, the first prototype of the smart biogas technology (SBT) was ready. During testing, the smart biogas system reliably measured biomethane gas concentrations and other parameters, with few recommendations for further improvement including moisture control, pH component integration, signal enhancement, extended monitoring, and system scalability. There was limited testing, due to time constraints, however, there is a commitment to rectify this in the next phase of this project. Also, the software component for user experience will be further improved through testing and continuous enhancement by a skilled team.

Overall, this project was a success.

Table of Contents

1. Introduction

1.0. The Origin: A Historical Journey of Biogas Technology Through Time

In seeking the pursuit and development of anything, it is critical to understand the origin of such a thing in the limelight, so does biogas technology. Today, biogas technology to the majority is seemingly, a modern technology: This is quite not right. Evidence of the use of biogas goes back to as early as 900 BC (the 10th century BC), where its combustion was used to heat the bathwater of the ancient Assyrians. It is also established as an anecdotal evidence of the use of this technology by the Persians in the 16th century BC.

Progressively, in the 1600s (the 17th Century), the Flemish scientist Jan Baptista van Helmont recorded the discovery that flammable gases are produced from decaying organic matter. This work helped shape our knowledge of the anaerobic digestion process as it is today and Van Helmont is credited with coining the word "gas" from the Greek word chaos. Following this, the next historical event was by the works of Count Alessandro Volta, known for his invention of the battery, concluded in 1776 (the 18th century) that there was a direct correlation between the amount of decaying organic matter and the amount of flammable gas produced.

Then, at the beginning of the 1800s (the 19th Century), Sir Humphry Davy, the creator of the first electric light, determined that the flammable gas being produced from the decaying organic matter was methane. This was determined in 1808, as Sir Humphrey Davy established that cow manure produced methane, during the AD of cattle manure. Not too soon after, in 1859, the first known anaerobic digester plant was built in Bombay, India, and by 1895, biogas recovered from a sewage treatment plant in Exeter, England was used to fuel streetlamps.

Following the above, the early 1900s (the 20th Century) saw the development of anaerobic digestion tanks, which replaced anaerobic lagoons. The first of this was in 1906, when Karl Imhoff invented the Imhoff Tank, a two-chambered anaerobic digestion (AD) tank to receive and process sewage. His design would become an early form of anaerobic digestion (biogas) plants in operation today. Anaerobic digestion tanks are essential for the controlled biological process that converts organic waste into biogas. The next few years, from 1914 to 1918, saw a decline in interest in biogas as petroleum became the dominant fuel in World War I. However in the 1930s, the development of microbiology became a recognized scientific discipline, which led to a massive amount of research taking place on anaerobic digestion, bacteria, and methane. This scientific discipline led to research by Buswell and others in the 1930s to identify anaerobic bacteria in anaerobic digestion as the generators of biogas and found the ideal conditions that promote methane production. Buswell is recognized for the Buswell's Equation, a chemical model used to calculate the theoretical amount of biomethane produced from the anaerobic digestion of organic materials. This stoichiometric equation is used to predict the composition and production rate of biogas as anaerobic digestion is a complex biochemical process.

From 1939 to 1945, the interest in biogas increased due to widespread petroleum shortages during World War II. When the war ended, the interest in biogas again dwindled as petroleum availability returned to normal levels. Following this, in the 1950s, further developments led to activated sludge systems becoming established as a way to apply anaerobic digestion to solid waste.

In the 1960s, both India and China began developing small biogas digesters for farmers. Then, the Energy Crisis of 1970, caused by disruptions to the supply chain via wars in the Middle East, renewed interest in anaerobic digestion (AD). This period also saw the establishment of the International Energy Agency (IEA) in response to the major oil disruptions in 1974. It promotes international energy cooperation and is made up of 31 member countries. During this period, China adopted anaerobic digestion technology on a massive scale in the form of small household digesters. Thus, modern anaerobic digestion only began to make traction in the 1970s, where the drive for alternatives to fossil fuels drove the innovation and widespread development of the biogas industry. This period witnessed industrial anaerobic digestion plants and anaerobic digestion gaining popularity and efficiency. Following this, Germany in 1991, became the first country in the world to implement feed-in tariffs (FIT) to support the expansion of anaerobic digestion technology. Undoubtedly, the 1900s (the 20th Century) brought a renaissance of industrial and small-scale biogas systems.

What is going to be of the 21st century? Since 2000, biogas has been part of mainstream energy with the dramatic increase in demand for renewable energy in the 21st century, as anaerobic digestion emerged as a solution to meet the growing decarbonized energy demand and national and global methane reduction targets. This has led to global production increasing more than five-fold, from 0.29 to 1.46 exa (10^{18}) joules between 2000 and 2022, and over 7 billion cubic meters in 2000 to over 38 billion cubic meters in 2020. Europe, China, and the United States accounting for 90% of global biogas production are the well-established world leaders in biogas, with some African countries more recently scaling up their biogas industries (IEA). This has been possible given a focus on developing biogas technologies and expanding biogas to more rural areas, especially as clean cooking technologies in African communities. Currently there are over 50 million micro-biodigesters, 132,000 small/medium/large scale biodigesters, and 700 upgrading plants (to produce biomethane) in operation worldwide (according to the World Biogas Association, 2019). However, there has been an uneven distribution of biogas technologies due to the disproportionate availability of materials, funding, and policies among countries.

The journey through the development of this technology has witnessed some coalitions such as:

- **2008 – World Bioenergy Association**: The World Bioenergy Association was founded to sustainably develop bioenergy globally and promote the business environment of bioenergy.
- **2009 – European Biogas Association (EBA)**: The EBA was founded to facilitate the deployment of sustainable biogas and biomethane production and use throughout Europe.
- **2009 – The International Renewable Energy Agency (IRENA):** IRENA was founded as a global intergovernmental agency focused on scaling renewable energy. It comprises 167 member countries as well as the European Union.
- **2010 – American Biogas Council (ABC)**: The ABC was founded to be the voice of the US biogas industry and today represents over 400 companies in the biogas supply chain.
- **2011 – African BioRenewable Association (ABA)**: Initially established as the African Biogas Association, the ABA was rebranded in 2011 to encompass the agriculture, waste and water management, recycling, and biomass industries.
- **2014 – Asia Pacific Biogas Alliance (APBA)**: The APBA was established to be the voice of the biogas industry in the Asia Pacific Region and to facilitate the growth and development of the biogas industry.

- **2016 – World Biogas Association**: The World Biogas Association was established as the global trade association for the biogas, landfill gas, and anaerobic digestion sectors.

The above coalitions have been vital to the continued existence of this technology and its expansion into other uncharted territories across the globe.

Despite the establishment and operation of the above coalitions, policies and their implementation have also been vital for the continued and enabling existence of this technology. The most well-known piece of legally binding, international climate mitigation legislation is the Paris Agreement, the goal of which is to limit global warming to below 2.0 degrees Celsius (℃), preferably to 1.5℃, compared to pre-industrial levels. In addition, the International Energy Agency's (IEA) Net Zero Emissions by 2050 Scenario is one framework for the global energy sector to achieve net zero CO2 emissions by 2050 and universal energy access by 2030. Another prominent piece of international legislation regarding biogas is the Global Methane Pledge (GMI). In 2021, over 100 countries pledged to reduce global methane emissions by at least 30% from 2020 levels by 2030. The GMI biogas subcommittee was established to manage the abatement, recovery, and use of methane that occurs when biogas is produced. Because of this, there are quite a number of global and country-specific biogas energy policies and organizations aimed at meeting the 2050 Net Zero Scenario (IEA).

In spite of the historical journey of biogas technology through time, there is little detail on how digital technologies which have been more profound in the 21st century is or could revolutionize biogas technology. Notwithstanding, it is still critical to understand the historical trends in biogas technology development in order to learn, strategize and improve for further developments and advancements, especially for our innovation and its untapped potential for the world. What will be the next breakthrough of this technology and how will it come? Certainly from the above, the future will be heavily influenced by ambitious government targets, productive and inclusive policy development and support, increasing competitiveness of biogas energy companies (most likely with digital technologies as a vital component), and decreasing the upfront costs associated with installing biogas technologies.

Given the above, the next section will dive into what is meant by biogas technology from a more scientific perspective.

1.1. What is Biogas Technology?

Biogas technology is basically a natural (green) biotechnology process where microorganisms in anoxic (anaerobic or without oxygen) environments break down organic matter (biomass) to produce biogas, a mixture of gases (containing bio-methane). This is only achieved in the presence of favourable conditions, the right amount of nutrients, pH, pressure and optimum temperature for life cycle processes such as growth, multiplication, anaerobic digestion of the microorganisms, inter alia.

To have an overview of the entire process for the conversion of biomass to methane, there is a four (4) tier multi-stage microbial process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Let us have a slight look at what is entailed in each process, however, the process remains the same, irrespective of the type of feedstock used:

- **Hydrolysis:** As the first tier of the multi-stage process, focuses on the decomposition of the organic matter (biomass), facilitated by the presence of water. Here, longer chain carbohydrates (such as fibers, sugars and other polymers) are broken down into shorter chains (monomers);

- **Acidogenesis:** In this tier, the aforementioned, shorter chains (monomers) are converted into fatty acids;
- **Acetogenesis:** At this stage, the fatty acids are converted into acetic acid, along with carbon dioxide and hydrogen; and
- **Methanogenesis:** At the apex of the multi-stage process, the acetic acid and hydrogen are metabolized, giving the final products of the reaction as methane, carbon dioxide, and other gases.

The fragmental composition of the biogas, a mixture of gases are biomethane (CH_4, 50 - 70%), carbon dioxide (CO_2, 25-50%); other gases such as nitrogen (N_2, less than 5%), hydrogen (H_2, less than 1%), and oxygen (O_2); and trace gases such as hydrogen sulphide (H_2S, less than 3%), water vapour ($H_2O_{(g)}$, less than 10%), and ammonia (NH_3, less than 3%). Along with the end products of the bio-methane and carbon dioxide, varying amounts of impurities are often found. These may include sulphuric compounds, heavy metals, or other toxins, depending on the types of wastes utilized and their sources. These could result in a number of risks, including the disruption of the process, destruction of digester biota (resulting in a useless toxic sludge) or make the gas product unsafe and unusable. To prevent this, it is key to ensure that all feedstock that enters a digester is of sufficient quality and safety.

Despite the aforementioned compositional percentages, the composition of biomethane to carbon dioxide in biogas is influenced by the substrate used and the Symons and Buswell's equation can predict this relationship, and deduce respective compositional percentages. From previous research, carbohydrate-based feeds typically have gas compositional percentages around 55% biomethane and 45% carbon dioxide, whilst fats, can contain as much as 75% biomethane and 45% carbon dioxide in biogas compositions.

In running biodigesters, below are some major factors that are variable and considerable:

- **Water content:** Water is essential for natural decomposition, and therewith for an anaerobic digestion process. Given this, an appreciable amount of water is required for the multi-stage process to be successful, and the water content can vary from a 60% "dry" mix to a 98% "wet" slurry. Depending on the type of biodigester being used, low water content could make the mixing and pumping of materials more difficult, thus a wet mixture is mostly preferred. Following the laws of thermodynamics and the type of water used, a high water content (for relatively cool water), more heat must be added to maintain the digester's temperature, and more.
- **Operational temperature range:** Appreciably, biodigesters operate in system-temperature ranges classified as thermophilic (50-60 degrees Celsius), mesophilic (30-40 degrees Celsius), or, rarely, the psychrophilic (10-20 degrees Celsius) range. Of all these ranges, thermophilic systems are generally more efficient, and it is known that most large digesters operate in this range, while most mid-sized systems run in the mesophilic range. Having acknowledged this, it should be noted that anaerobic reactions are largely endothermic, meaning they require heat to be added to the system to prevent system dysfunction, inter alia. Moreover, heat losses can

be substantial, especially in colder or cooler weathers. In colder (temperate zones), additional heat is usually provided from a genset, as in cold climates there is a potential challenge in ensuring systems maintain a system-preferred and appropriate operating temperature. This suggests unique system designs for biogas plants and/or biodigesters to cater for heat losses, especially from a comparative view of variable climatic and meteorological determinants. This could be a changing narrative for the tropics, given the climate change turmoil in our world - With Africa as a major geographical location that needs to be studied despite several unsuccessful attempts in harnessing the true potential of biogas technology.

- **Cycle times:** Cycle time in this context, basically refers to the sequence in which biodigesters are fed with feedstock, varying from a day to a month. Warmer temperatures generally accelerate this process. Feedstocks can be fed in a continuous or batch-based approach. In some plants, these processes are separated, allowing for a wider range of feedstocks and potentially higher efficiencies if managed correctly.
- **System efficiency:** Efficiency for a biogas plant tends to improve with necessary heat, inter alia, and scale. Studies show a correlation between methane production and the types of bacteria present, and it can take a year or more for a digester to work optimally. This is related to the variable populations and activity levels of these bacteria. The science surrounding these digestive bacteria is an ongoing area of research, with many interesting questions about digestion processes and bacterial strain performance. These factors can vary with other system parameters such as pressure, pH, and temperature. Therefore, a combination of these parameters is critical for achieving system efficiency. Having real-time system data with actionable insights could be significantly meaningful.
- **Operational manoeuvrability for efficiency and optimization:** While this wording may seem complex, it essentially focuses on how elements within the system work together, guided by the knowledge and insights of the users/operators. It is crucial to build a system that is both operator-friendly and operation-friendly for the end user, and of course environmentally friendly as well. Operational manoeuvrability for efficiency and optimization in biogas entails having the agility and flexibility to adjust various aspects of the biogas production process at any point in time. This includes temperature control, feedstock composition, mixing intensity, and other parameters to ensure the process runs as efficiently as possible and maximises output. Implementing both preventive and adaptive strategies helps in overcoming challenges like heat loss in colder climates (and even climate resilience) or fluctuations in feedstock quality. These strategies optimize the entire biogas production system for better overall performance without compromising on operational, environmental, and operator safety.
- **Monitoring:** Monitoring? Yes, monitoring it is. Monitoring can be active or passive, depending on the systems in place and the level of technical awareness and know-how of the user or operator. This critical factor is often neglected or improperly handled, yet it is essential for achieving operational manoeuvrability for efficiency and optimization, as discussed. Empirically, attaining operational manoeuvrability for biodigesters is intrinsically linked with efficient and effective monitoring. This involves honing easy, friendly, agile, and scalable user or operator capacities. At a higher level, this helps the end user/operator gain practical insights and understanding of both how and what works for a biogas plant. It is crucial in building user confidence in this nature positive technology and could be a strategic

and practical way to change negative and ageing perceptions of this technology, especially in Africa. But how do we do this in a safe, cost-effective, affordable, efficient, and scalable way? Worry not, for that is what this report is all about.

With the above, below are different pathways or technologies used to produce biogas:

- **Biodigesters:** Includes either wet or dry digesters. Wet digesters are the most common style of anaerobic digestion. The substrates are moved around as liquid slurries, the consistency of the contents is 3-15% solids, and retention times range anywhere from 20-40 days. For dry digesters, the substrates are kept in a stackable form and remain in a pile during the anaerobic digestion process;
- **Landfill gas recovery systems**: The decomposition of municipal solid waste at landfill sites produces biogas which is captured by pipes and extraction wells; and
- **Wastewater treatment plants**: Organic matter, solids, nitrogen, and phosphorus can be recovered from sewage sludge and turned into an input material for producing biogas.

To a deeper level, it is necessary to appreciate the different types of feedstocks that can be used to produce biogas and these include:

- **Crop residue** from wheat, maize, rice, other coarse grains, sugar beet, sugar cane, soybean, and other oilseeds;
- **Animal manure** from cattle, pigs, poultry, and sheep;
- **Municipal solid waste** from food, leaves, grass, cardboard, wood, and industrial waste from the food processing industry; and
- **Wastewater sludge** from wastewater treatment plants.

Biogas technology has multiple applications, including heating, power generation (mostly independent), and upgrading to biomethane for transport fuel or natural gas grids in some instances, inter alia The anaerobic digestion produces valuable by-products like digestate for soil amendment and biogenic CO_2 for various bioeconomy sectors. For rural communities in Africa, the biogas component offers a sustainable alternative for power generation and clean cooking.

Assuredly, biogas technology is a nature-positive technology, but when managed effectively and efficiently to realize its full potential. For the course of this project, the emphasis is on biodigesters.

1.2. Background of Biogas Technology in Ghana

Biogas technology started in the 1960’s in Ghana and till date the main motive has been to manage waste (sanitation). Despite this, biogas generated is mostly utilized for cooking in domestic settings, industrial heating and electricity generation for industrial plants. The technologies that have most been used are the fixed dome and the floating drum biogas digesters, especially for small-scale and domestic purposes.

In Ghana, biogas plants in industrial settings are highly developed with almost all the needed digital tools to ensure successful operation. A typical example is the Waste to Energy Project (Hybrid PV-Biogas-Pyrolysis Plant) at Gyankobaa; It is a state of art 400 kW Plant consuming 12 tons of municipal solid waste (plastics & organic waste) per day. Despite this technological advancement in industrial settings, we cannot read the same or even similar in domestic or small-scale biogas plants.

Furthermore, some challenges of biogas plants included failing to operate few months after construction, issues on untrained (quacks) biogas plant installers, "myths about biogas plants" where some biogas plant owners are made to believe that the biogas would come after twenty (20) years, amongst others. Over the years, especially after 2010 in Ghana, a number of biogas plants have been developed by trained (expert) biogas plant installers and research organizations like CSIR-IIR (Center for Scientific and Industrial Research - Institute of Industrial Research). Basically, the floating drum and fixed-dome bio-digesters have been in existence for quite some time, with traditional fixed-dome bio-digester (FDBD) being more prominent.

With the Center for Scientific and Industrial Research - Institute of Industrial Research (CSIR-IIR), three (3) types of bio-digesters have been developed. In 2014 they designed and constructed the Anaerobic Baffled Bio-Digester (ABBD). This was to address the challenges of cost and constructional skills that came along with the traditional fixed-dome bio-digesters (FDBDs). Next, in 2019, the Portable Anaerobic Baffled Bio-Digester (PABBD) was also designed for small scale domestic effluent treatment and biogas production. This design is similar to ABBD but the only difference is that the components of the digester are pre-fabricated in the form of concrete slabs and transported for installation on-site. Most recently, in 2020, CSIR-IIR has designed and constructed an Integrated Bio-digester (IBD). This was designed and constructed to resolve problems associated with FDBDs, both the costs of construction and identifying and repairing digester leaks. As seen in the development by CSIR-IIR, there has been a major advancement in eliminating the problem of untrained/unskilled artisans in the biogas plant construction space. Despite these advancements in technology, a number of other technologies by artisans are unaccounted for, thus unknown as there is no reported research and technical papers capturing them.

Moreover, till date, there is not a single policy in our country concerning biogas plants. Though in a Digital Global Biogas Corporation (DiBiCoo) event last year, Mr. Seth Mahu who happens to be the Director of Renewable Energy under Ghana's Ministry of Energy said, "My search at the Energy Commission indicates that the Commission has already taken measures to draft the first biogas regulatory framework and after this event, we are going to escalate it and get the Minister to communicate to the Executive Secretary to expedite action in developing and completing the framework for the industry." "I want to give you the Minister's assurance that we are going to work with the Energy Commission to ensure that the regulatory framework for biogas is developed as quickly as possible," he concluded. This proves the need to also look into policies on biogas technology.

With the pursuit of resolving challenges in the biogas industry, the Biogas Association of Ghana (BAG) has been formed at a practitioners meeting in Accra (in 2016) to promote biogas technologies, improve capacity of practitioners and standards in Ghana. Institute of Sustainable Energy and Environmental Solutions (ISEES) was part of the inauguration of the Ghana Biogas Association which was under the auspices of the Environmental Protection Agency's Center for Clean Production Technologies and the Switch Africa Green Project. The Biogas Association of Ghana consists of firms, organizations, institutions, companies and individuals who are deeply engaged in the design and construction of biogas plants, research and development activities in the biogas technology, sale of biogas accessories, advocates of renewable energy technology and users of the technology. Furthermore, the need to form the association was key because of the challenges being faced in the biogas sector in Ghana, including failing digesters, lack of standards, low capacity of some practitioners as well as the high need to create awareness on the benefits of and efficient utilization of biogas systems for waste management, improved sanitation and energy and organic fertilizer generation.

Following the above development, in June 2024, the Ghana Standards Authority (GSA) constituted a National Technical Committee for Renewable Energy Resources - Biogas Sub-sector. Two Fellows of the Brew Hammond Energy Center at the Kwame Nkrumah University of Science and Technology (KNUST), Prof. Lawrence Darkwah and Prof. Francis Kemausuor, as experts are members of the aforementioned technical committee. These experts would support the Ghana Standards Authority to develop and implement standards to promote international compatibility and harmonization in the production and use of biogas. Since our research emanated from KNUST with our linkages to relevant institutions such as the Biogas Association of Ghana (BAG), the Strategic Youth Network for Development's (SYND's) Young Green Entrepreneurs (YGE) Cohort II, it is strategic and appreciable to track and make inputs to the standards being developed. Moreover, our strategic connection to the technical committee would also drive our innovation with compliance to the standards being worked on.

Herewith, above is the condensed trajectory on the evolution of biogas technology in Ghana. There still remains not a single digital technology incorporation footprint for small-scale and domestic biogas plants, despite the transformation over time. To achieve process optimization, reduction in the abandonment of biogas plants shortly after they are operationalized, amongst other environmental parameters, digital technology incorporation for small-scale and domestic biogas plants needs to be investigated.

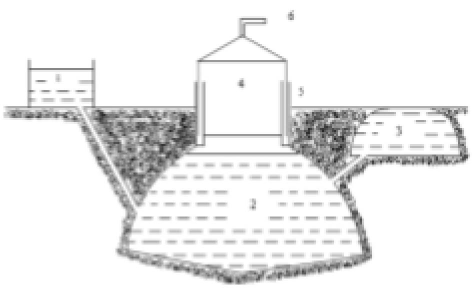
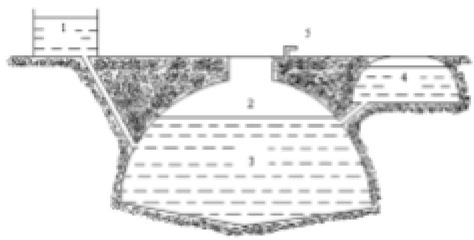


Fig. 0.1. An image of a fixed dome digester



Fig, 0.2. An image of floating drum digester

2. Literature Review

2.1. Biogas Technology in the African Context (inclusive of Ghana)

Biogas technology: A misunderstood invention or a game-changer for Africa?
Intriguing question, indeed. The answer requires a deep dive into its history, current adoption, bottlenecks, and future potential. There is no denying the hurdles, but the promise it holds is equally undeniable.

In relation to the above, there is no concrete evidence of when biogas technology was first attempted in Africa. However, it is known that the first commercial biogas plant was established in South Africa in 1957 by L. John Fry, who developed an anaerobic digester to generate energy from pig manure. Since then, the adoption of biogas technology has been gradually increasing across the continent, with countries like Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin, and Burkina Faso implementing national biogas programs.

Mentioning this brings into the picture SNV, an organization committed to the adoption and application of biogas technology on the African continent, establishing 114,064 biodigesters as of 2022 in nine African countries. SNV's work started in 1992 on a transformative journey in rural Nepal, introducing biodigesters - a technology that has since scaled to 27 countries globally, reaching a milestone of one million units as of 2022. Currently, SNV is making headways with unlocking climate finance to promote the use of bio-digesters through a digital innovation.

From April 5 to 7, 2016, in Addis Ababa, Ethiopia, Hivos, SNV Netherlands Development Organisation, and the Ministry of Water, Irrigation and Electricity in Ethiopia hosted the Africa Biogas and Clean Cooking Conference. This conference brought together businesses, knowledge institutes, government policymakers, local and international experts, and academia from the energy sector to discuss challenges and opportunities in the biogas industry and to exchange solutions. The conference highlighted:

- Household biogas technology and the multiple benefits associated with the use of biogas and bioslurry;
- Creation of vibrant clean cooking markets in Africa;
- Reduction of greenhouse gas emissions and sale of carbon credits; and
- Financing the biogas and clean cooking sector to enable affordability and access for small-scale farmers.

The conference presented the opportunity to highlight the Africa Biogas Partnership Programme (ABPP), a partnership between the Netherlands Ministry of Foreign Affairs, Hivos, and SNV in support of national biogas programmes in Ethiopia, Kenya, Tanzania, Uganda, and Burkina Faso. This partnership was geared towards constructing 100,000 biogas plants that would enable half a million people to access a sustainable source of energy by 2017. The overall objective of the ABPP was to work towards achieving the Sustainable Development Goals by developing a commercially viable, market-oriented biogas sector that will support the use of domestic biogas plants as a local, sustainable energy source.

The Africa Biogas Partnership Programme (ABPP) was a success in the five African countries. Key reasons behind the ABPP's achievements, according to ABPP's Fact Sheet include:

- Thorough, participatory, and context-specific preparation as the basis of the design of its country programmes;
- The ultimate goal of establishing sustainable biodigester markets in the countries of intervention;
- Promoting a market-oriented approach where both local and international enterprises can grow their businesses with the construction, installation, and servicing of biodigesters; and
- Developing sector support functions in close partnership with multiple stakeholders (private and public sector organizations and institutions).

With these commitments, among others, biogas technology in Africa has been evolving over the past few decades. Its growth is driven by the need for sustainable energy solutions, effective waste management, and socio-economic benefits. However, adoption is still in its early stages in different parts of the African continent, with challenges such as initial capital costs, lack of awareness, and the need for enabling technologies for improved usability and user experiences. Additionally, the types of bio-digesters used in Ghana are relatively similar to those used elsewhere on the continent. However, there are several modifications that are not accounted for, given the limited scope of work in this technological niche.

Amidst the climate change challenges of vulnerability, mitigation, adaptation, and resilience, biogas technology stands out as an untapped potential for empowering rural and underserved communities. It offers equitable energy access and socio-economic benefits. Climate change challenges, like the impact of solar radiation modification (SRM) or solar geoengineering on solar installations, make biogas a resilient alternative. SRM could limit the solar intensity for solar plant installations, raising questions about their efficiency and effectiveness. What about the millions of dollars invested, especially from development and aid organizations? How will the quality of life improve for people in rural and underserved communities? What about the high cost of batteries that come with these solar installations? The effectiveness of these technologies and investments remains debatable. However, biogas technology requires substantial capacity-building from scenario-based and result-oriented management approaches to maximize its potential. This is achievable, sustainable, scalable, and cost-effective.

Subsequent sections of this document will delve into the essence and challenges of bringing this technology out of the tunnel or well to harness its potential.

2.2. Why Biogas Technology is Crucial for Ghana and Africa

Biogas technology is such a vital technology for Ghana and Africa given the reasons below. With little to no processing, biogas can be used for:

a. clean cooking, lighting, or electricity generation, and has therefore is recognized as crucial pathway to sustainable energy production (Ali et al., 2020; Funmi et al., 2021; Msibi and Kornelius, 2017; Sur- roop et al., 2019);

b. local economic development (Lietaer et al., 2019; Mengistu et al., 2015);

c. increased agricultural production and soil remediation (Ngumah et al., 2013; Smith et al., 2014);

d. climate change mitigation (Bruun et al., 2014; Funmi et al., 2021; Hoch et al., 2018);

e. decreased deforestation (Bär et al., 2021; Lietaer et al., 2019; Twinomunuji et al., 2020);

f. reduced household and ambient air pollution (Lietaer et al., 2019; Twinomunuji et al., 2020);

g. and as a waste management solution (Ali et al., 2020; Funmi et al., 2021; Ngumah et al., 2013; Owang et al., 2020a; Surroop et al., 2019).

Besides the above, this technology is vital for poverty reduction as well, inter alia

2.3. Challenges of Biogas Technology Adoption and Application in the African Context

Quite an extensive work has been done in this area by Marc Kalina, Jonathan Òlal Ogwang, and Elizabeth Tilley, in their paper titled 'From potential to practice: rethinking Africa's biogas revolution.' This section leverages on the in-depth work they have done and also in putting together several useful research from other researchers.

In their paper, they highlighted the immense amounts of money spent by African governments, private individuals, and most conspicuously, international aid agencies and donors, on countless biogas projects on the continent. Despite these investments, biogas in African countries has not met the expectations of the immense value it has for the continent, but rather is strewn with the ruins of hundreds of failed and abandoned biogas projects. Following this, they delved into the work they have done in two African countries, why biogas projects fail, and the role of social scientists in engaging with biogas owners and operators to bridge the socio-technical divide from potential to practice. They argue that although biogas has generated a tremendous amount of scholarly output, the bulk of the work that has been produced, especially on small-scale decentralized digesters, demonstrates an overwhelming tendency to focus on positives. Thereby referring to positives on biogas's unlimited potential to solve several pressing global issues, while generally ignoring why this has not yet happened. Moreover, they expressed that the bulk of biogas literature tends to take a high-level approach, often through reviews rather than with new empirical data, with very few case studies on specific interventions, and a tendency to focus on the limited success that has occurred with small-scale digesters, in specific contexts, with only brief speculation on why these limited successes remain so. These perspectives are compelling enough and the emphasis on empirical data, to an extent, calls for the integration of user-friendly and enabling technologies, inter alia.

Given the above and research done on the promise of small-scale biogas, there are several barriers that prevent its actualisation. They emphasized these are barriers that are continually discussed but rarely seem to get addressed. Additionally, these barriers are also in resonance with a research paper titled 'The Biogas Initiative in Developing Countries, from Technical Potential to Failure: The Case Study of Senegal' by Boucar Diouf and Ekra Miezan. Below are specific barriers that have received significant attention:

a. the high initial cost of technologies, as well as the constant cost of maintenance, especially for the poor (Bekchanov et al., 2019; Chen et al., 2017; Dyah, 2019; E. U. Khan and Martin,

 |

2016; Landi et al., 2013; Mittal et al., 2018; Puzzolo et al., 2016; Rupf et al., 2015; Taylor et al., 2019);

b. a lack of state or donor investment in biogas, for both research and to assist with funding (Bößner et al., 2019; Boyd, 2012; Ho et al., 2015; Mukeshimana et al., 2021; Nevzorova and Kutcherov, 2019; Patinvoh and Taherzadeh, 2019; Silaen et al., 2020);

c. as well as the inability for small plant owners to take advantage of international carbon credit schemes (Shane et al., 2015);

d. the difficulty of accessing biogas technology within some national contexts (Hamid and Blanchard, 2018; Parawira, 2009);

e. a lack of supportive public policy framework in certain nations (Bekchanov et al., 2019; Bößner et al., 2019; Boyd, 2012; Gao et al., 2019; Hasan et al., 2020; Ho et al., 2015; Patinvoh and Taherzadeh, 2019; Roopnarain et al., 2020; Yousuf et al., 2016) or;

f. low state or institutional capacity to implement a national biogas programme (e.g. Budiman, 2021; Landi et al., 2013; Nevzorova and Kutcherov, 2019; Rupf et al., 2015), as well as;

g. onerous regulatory barriers (Mittal et al., 2018; Taylor et al., 2019;), including potential political instability in some contexts (Kamp and Ber- múdez Forn, 2016);

h. a lack of sufficient or consistently available feedstocks (Chen et al., 2017; Glivin and Sekhar, 2020; Iqbal et al., 2014; K. Khan et al., 2018; Mittal et al., 2018; Nevzorova and Kutcherov, 2019; Roopnarain et al., 2020);

i. poor climatic conditions, including variable temperatures or water scarcity (Kampand Bermúdez Forn, 2016; Mittal et al., 2018; Rupf et al., 2015);

j. space for digester installations, especially in dense village or urban contexts (Akinbami et al., 2001);

k. labour intensity of daily operation for owners (Roopnarain et al., 2020; Silaen et al., 2020; Taylor et al., 2019);

l. the unpredictability of biogas production and yields, which may render small-scale commercial utilization unfeasible (Bensah et al., 2011; Owang et al., 2020b);

m. potential cultural stigma or taboos associated with handling faecal matter or animal waste (Budiman, 2021; Dyah, 2019 Mittal et al., 2018; Rupf et al., 2015; Shane et al., 2015);

n. market barriers which influence demand for the gas, such as competition with other available, potentially cheaper, fuel sources (Bensah et al., 2011; Mittal et al., 2018; Nevzorova and Kutcherov, 2019; Taylor et al., 2019; Zuzhang, 2013);

o. the poor monitoring and maintenance of existing digesters (Iqbal et al., 2014; Shane et al., 2015; Taylor et al., 2019), and finally;

p. a lack of knowledge, information, and training for potential biogas owners or installers (Bößner et al., 2019; Dyah, 2019; Hasan et al., 2020; Landi et al., 2013; Mittal et al., 2018; Patinvoh and Taherzadeh, 2019; Rupf et al., 2015; Taylor et al., 2019).

With the above challenges, this project is in relation with especially points **o** and **p**. Moreover in the paper, they went further citing Wamwea (2017), writing about Kenya, generally observed better outcomes, they also found that the leading cause of failure amongst sampled owners was technical issues. Other countries, though outside Africa but with similar technologies offer valuable insights as well. For instance, Mahdi et al. (2012) is known to have used a mixed methodological approach to examine 85 digesters in Bangladesh's Pabna District, finding that 65% were not operating or operating poorly, with most failure owing to technical complications linked to the digester or the associated appliances. Likewise, in a survey of 141 digester owners in central Vietnam, Roubík et al. (2016) found that one-third of owners had experienced serious problems, with technical challenges, such as leaks in the reactor or piping, malfunctioning of the stove, or breakdowns in anaerobic digestion featuring prominently. In all the above instances, technical challenges cut across, and the inability of the plant owner to identify and resolve them, often led to plant abandonment. Thus given a digital technology with the power for performance monitoring of biogas plants, these challenges would be identified in time and even prevented in some instances for continued operations.

In relation to the above, they also identified that engagement with owners, funders, and providers have suggested that the interplay and relationship between these three stakeholders is vital. These expressed that this is a key determinant of a project's success or failure, with the owner being the most important factor, as their willingness and ability to engage with the systems seems directly correlated to outcomes. The ability here is tied to the operationality of the biogas owners or operators as well. In their, preliminary, on-the-ground, engagement with projects in both Malawi and South Africa they noticed that owners who had better outcomes with biogas were the ones, who largely, sought it out for themselves, while owners who were more passive 'beneficiaries' within the intervention, generally experienced poor outcomes. However, the reasons for why some were passive are not established in the paper, but this could be tied to technical challenges in understanding and operating the plant. They further highlighted that technical post-mortems of abandoned or failed systems lead to a one-dimensional understanding of project success or failure. This is laudable as running post-mortems from different perspectives enables one to identify probable causes from multiple angles and co-create curated and productive solutions to address identified challenges - A design thinking approach. Thus, engaging with owners, through participatory, qualitative research, which centers and interprets the owner's experiences, and can identify potential points of friction between systems and users, may reveal understudied or systemic challenges within current models of biogas provision. It is for such a challenge that our digital solution was generated and have been working on since.

In South Africa, Dumont et al. (2021) discuss the 'yuck factor' within biogas, a strong negative emotion that may lead people to withdraw from participating in biogas interventions. This is in line with contamination beliefs, which have also been described as "the magical law of contagion" or the "intuitive contagion heuristic", which hold that "once in contact, always in contact." These beliefs have been shown to have substantial implications for people's acceptance of various sustainability practices. This is also a principal reason why some people neglect adoption of this technology in Africa.

Furthermore, some challenges of biogas plants included failing to operate few months after construction, issues on untrained (quacks) biogas plant installers, "myths about biogas plants" where some biogas plant owners are made to believe that the biogas would come after twenty (20) years, amongst others.

All the above cumulatively sum up the reasons behind the challenges of biogas technology adoption and application in the African context. A number of these especially **o** and **p** are what out innovation and this project focuses on. This comes with ripple benefits and these translate into helping solve a number of the other identified barriers.

2.4. What is the way out? Could it be a Smart Biogas Technology (SBT)?

Smart Biogas Technology (SBT) is a nature-positive and enabling technology that incorporates digital technologies such as Internet of Things (IoT), machine learning and artificial intelligence (ML/AI), inter alia, to improve the functionality, optimization, and monitoring of biogas plants and processes - (*A definition Sampson O. Bempah*). This achieves realistic and minimalistic operational and environmental efficiencies without compromising safety.

In an era where reducing greenhouse gases (GHGs) to the barest minimum is crucial, SBT plays a vital role, especially with the abundance of organic waste as potential feedstock. Internet of Things (IoT) enables the monitoring of biogas plants and process parameters such as pressure, pH, temperature, gas leakage, inter alia, using special sensors programmed into a system. This system, powered by machine learning and artificial intelligence (ML/AI) for optimization is accessible via user-friendly software applications (web and mobile apps) for easy visualization and informed decision-making (for both corrective and preventive actions) by an owner or operator of smart biogas systems.

A USSD option is also being explored. Assuredly, this innovative solution could be the way out.

2.5. Why is Smart Biogas Technology (SBT) Application in Ghana worth investigating?

Throughout the evolution of biogas technology in Ghana and to an extent Africa, there is not a single trace of integrating digital technology in the biogas sector for small-scale and domestic biogas plants. This is an existential gap and our research focuses on developing, testing, and implementing an Internet of Things (IoT) system (device) to effectively monitor key parameters of small-scale and domestic biogas plants, to improve both operational and environmental efficiencies and safety (OEES). This has ripple, sustainable and responsible impacts on biogas technology adoption, utilization and durability. It emphasizes the importance of real-time monitoring and data analytics in optimizing biogas production, and ensuring both operational and environmental efficiencies and safety (OEES). Moreover, this is highly beneficial, especially for farmers, rural community dwellers, amongst others in Ghana and Africa where energy access and clean cooking still remains a major concern. Our user-friendly system is hereby adaptable to the needs of farmers, especially vulnerable groups in rural communities. Herewith, the outcomes of this project is expected to not only bridge the digital-divide gap, but also enable farmers, especially vulnerable groups produce their own nutrient rich organic fertilizers (affordable), generate electricity for lighting (with biogas), leveraging on several tonnages of agricultural (organic) waste they produce. This embraces the circular economy model whilst monitoring and optimizing key parameters easily and efficiently with our smart biogas technology. This issue would be investigated and explored in detail in this document.

3. Methodology

This research project aims to develop and evaluate an Internet of Things (IoT) system (device) designed to monitor small-scale and domestic biogas plants. Internet of Things (IoT) can be defined as the integration of digital sensors, actuators, and communication technologies to monitor and control various aspects of the biogas production process remotely such as methane gas. The primary research question guiding this study is: How can an IoT device be designed and implemented to effectively monitor the key parameters of a biogas plant to improve efficiency and safety? This question builds upon existing literature that emphasizes the importance of monitoring of biogas plants. In view of this, our approach in this project focuses on real-time monitoring and data analytics in optimizing systems and ensuring operational safety. In this section, we would explore in detail how we went about building, deploying, and eventually testing the Internet of Things (IoT) system (device) for the realization of a Smart Biogas Technology (SBT) to answer our research question.

In the immediate section below is a description of the components selection process for this project.

3.1. Components Selection

Components selection was crucial and selective in this project, especially as it is an Internet of Things (IoT) system (device) and would be used for monitoring the performance of small-scale and domestic biogas plants and processes. The main components of any Internet of Things (IoT) system are the sensors, the main brain of the system, that is the microcontroller or the processor, and the wireless connectivity which makes this an Internet of Things (IoT) project. In view of selectivity in the components we used for the IoT System, below are the various components that were used and properties that were considered.

3.1.1. Sensors Selection

To effectively monitor a biogas system there are some parameters that are required to conclude the system is performing as it is supposed to and to be able to trace the output of the system. To do this, information about the system's temperature, humidity, pressure and the amount of methane gas that is produced is needed. To get this information, devices such as electronic sensors and transducers were the right components. Sensors are devices whose electrical properties change with respect to a specific environmental change. For instance, temperature sensors change their resistance with a respective change in temperature. Moreover, the temperature sensor's range of operation (or coverage) was crucial in order not to select a temperature sensor that operates outside the range of the temperature in the environment it is measuring. Below are the various sensors that were used in this project together with their criteria of selection.

3.1.1.0. Temperature and Humidity Sensor (DHT22)

The DHT22 was a low-cost digital temperature and humidity sensor with a single wire digital interface. It uses a capacitive humidity sensor and a thermistor to measure the surrounding air and spits out a digital signal on the data pin (no analog input pins needed). The sensor was calibrated and did not require extra components and enabled the accurate measurement of relative humidity and temperature. The sensor used here was (CITYOS AIR, n.d.) DHT22 output calibrated digital signal. It utilizes exclusive digital-signal-collecting-technique and humidity sensing technology, assuring its reliability and stability. Its sensing elements are connected with an 8-bit single-chip computer. Every sensor of this model is temperature compensated and calibrated in an accurate calibration chamber and the calibration-coefficient is saved in type of programme in OTP memory, when the sensor is detecting, it cites coefficient from memory. Small size, low consumption, and long transmission distance (20 m) enable DHT22 to be suited in all kinds of harsh application occasions (Aosong Electronics Co. Ltd).

The operating range of this temperature sensor is 40 to 80 celsius and humidity 0 to 100% RH (Aosong Electronics Co. Ltd). Temperature is a critical parameter in biogas production, affecting microbial activity and gas yield. The DHT22 provided reliable and precise measurements, essential for maintaining optimal operating conditions.

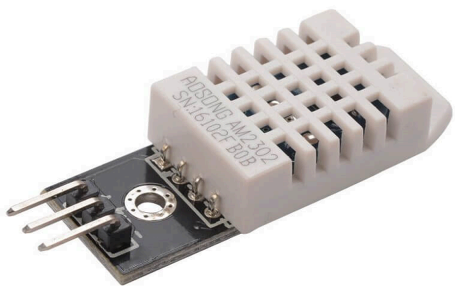


Fig. 1 DHT22 for temperature and humidity

3.1.1.1. Pressure Sensor (BMP180)

BMP180 is one of the sensors of the BMP XXX series. The BMP XXX series are all designed to measure barometric pressure or atmospheric pressure. BMP180 is a high precision sensor designed for consumer applications. Barometric pressure is basically the measurement of the weight of air molecules exerted at a given point on the earth. BMP180 sensor senses this pressure and provides that information in digital output. Also, the temperature affects this pressure and this requires temperature compensated pressure reading. To compensate, the BMP180 is equipped with a good temperature sensor.

Some features of this sensor include;

- Pressure range: 300 to 1100 hPa
- High relative accuracy of ±0.12 hPa
- Can work on low voltages
- 3.4 Mhz I2C interface
- Low power consumption (3 uA)
- Pressure conversion time: 5 msec
- Potable size

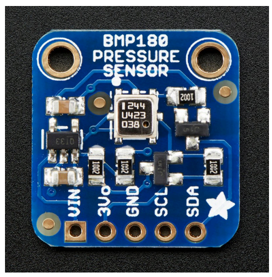


Fig. 2 BMP180 pressure sensor

Accurate pressure monitoring is vital for the safe operation of biogas digesters as pressure build up from the biogas could be a concern. The BMP180 is selected for its proven performance in industrial applications.

3.1.1.2. Gas Composition Sensor (MQ-4 for methane)

The MQ-4 is a highly sensitive biomethane gas sensor that detects biomethane concentrations in the air. It is commonly used in gas detection systems for industrial, environmental, and household applications.

Key Features;

- High sensitivity: Detects biomethane concentrations as low as 100 ppm
- High accuracy: ±5% of full scale
- Fast response time: <10 seconds
- Long lifespan: Up to 5 years
- Analog output: 0 - 5 V voltage output proportional to biomethane concentration (Hanwei Electronics)

Fig. 3 MQ-4 methane gas sensor

This sensor played a crucial role in the building of this system. The sensor monitored biomethane concentrations in the anaerobic digestion processes output, especially its biogas component. By monitoring biomethane levels, the sensor helped optimize the biogas production processes, such as anaerobic digestion and the type of feed the biogas plant was fed with, to maximize energy output as this is a function of the amount of biomethane produced.

Real-time monitoring of biomethane levels is critical to predict potential issues and enable proactive measures to be taken for maintenance and minimize downtime-A protective or preventive mechanism.

3.1.2 Microcontroller Selection

After selecting sensors for the system, the system needs to collect sensor data, organize them and transfer them to the cloud or a server before for analysis, analytics and visualization. Given this, the microcontroller helped us achieve this.

A microcontroller (MC, UC, or μC) or microcontroller unit (MCU) is a small computer on a single integrated circuit. A microcontroller contains one or more CPUs (processor cores) along with memory and programmable input/output peripherals. Program memory in the form of NOR flash, OTP ROM, or ferroelectric RAM is also often included on the chip, as well as a small amount of RAM. Microcontrollers are designed for embedded applications, in contrast to the microprocessors used in personal computers or other general-purpose applications consisting of various discrete chips.

Given the above, the selection of a microcontroller board for our project required adequate processing power, ease of programming, extensive support community, multiple I/O ports for sensor integration, and the ability to connect to the internet. Herewith, the ESP32 microcontroller board from Espressif, n.d. was selected for our system and its properties are described below.

3.1.2.0. ESP32 Microcontroller Board

ESP32 is capable of functioning reliably in industrial environments, with an operating temperature ranging from –40°C to +125°C. Powered by advanced calibration circuitries, ESP32 can dynamically remove external circuit imperfections and adapt to changes in external conditions (Espressif, n.d.).

ESP32 is highly-integrated with in-built antenna switches, RF balun, power amplifier, low-noise receive amplifier, filters, and power management modules. ESP32 adds priceless functionality and versatility to your applications with minimal Printed Circuit Board (PCB) requirements (Espressif, n.d.).

Engineered for mobile devices, wearable electronics and IoT applications, ESP32 achieves ultra-low power consumption with a combination of several types of proprietary software. ESP32 also includes state-of-the-art features, such as fine-grained clock gating, various power modes and dynamic power scaling (Espressif, n.d.).

ESP32 can interface with other systems to provide Wi-Fi and Bluetooth functionality through its SPI / SDIO or I2C / UART interfaces (Espressif, n.d.).

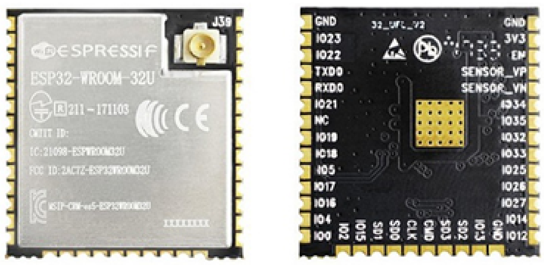


Fig. 4 ESP32 chip (front and back view)

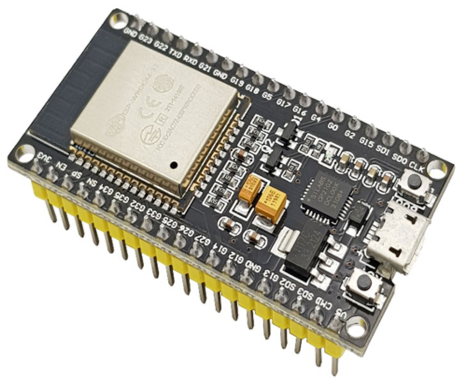


Fig. 5 ESP32 board

The ESP32 was chosen for its versatility and capability to handle multiple sensor inputs and real-time data processing. Its integrated Wi-Fi module facilitates seamless data transmission, and its low power consumption is ideal for continuous monitoring applications. Moreover, the ESP32's integrated Wi-Fi module or optional cellular modules (e.g. SIM800) for areas without Wi-Fi coverage.

Real-time data transmission is crucial for monitoring and analyzing biogas plant operations. Thus, the integrated Wi-Fi module of the ESP32 was used where internet access is available, whereas cellular modules were chosen for remote locations lacking stable internet connectivity.

3.2. Components Integration into an Internet of Things (IoT) System

3.2.1.0. Sensor Data Collection

One of the most important aspects of the project is to get the data from the biogas plant. What helps us to achieve this are the sensors and the microcontroller. This involves the acquisition of data from various sensors deployed within the biogas plant to monitor key parameters such as temperature, humidity, pressure, and methane concentration. The collected data provides real-time insights into the biogas production process, enabling efficient management and optimization.

In subsequent sections, are breakdowns of how each of the sensors collect data and communicate with the microcontroller (esp32).

3.2.1.1. Temperature and Humidity Sensor (DHT22)

Pertaining the temperature and humidity sensor, we would utilize the steps below to collect data and communicate with the microcontroller (esp32):

(1) Initialization: The ESP32 sends a start signal to the DHT22 to initiate data collection. This signal typically consists of pulling the data line low for at least 18 milliseconds and then high for 20-40 microseconds.

(2) Sensor Response: The DHT22 responds by sending a 40-bit data stream, which includes 16 bits for humidity, 16 bits for temperature, and 8 bits for a checksum.

(3) Data Readout: The ESP32 reads the 40-bit data stream. Each bit's duration determines whether it represents a 0 or a 1.

(4) Data Parsing: The 40 bits are parsed into humidity and temperature values. The checksum is used to verify data integrity.

The DHT22 outputs the temperature in degrees Celsius and humidity as a percentage relative humidity (RH).

Example output: Temperature = 25.6°C, Humidity = 60.5% RH.

3.2.1.2. Pressure Sensor (BMP180)

Pertaining the pressure sensor, we would utilize the steps below to collect data and communicate with the microcontroller (esp32):

(1) Initialization: The ESP32 communicates with the BMP180 via the I2C or SPI interface, sending initialization commands and setting the sensor to the desired mode.

(2) Pressure Measurement: The sensor measures pressure and temperature, applying temperature compensation internally.

(3) Data Readout: The ESP32 reads the pressure and temperature data registers. The BMP180 typically provides raw ADC values.

(4) Data Conversion: Raw values are converted to human-readable units (hPa for pressure) using calibration coefficients stored in the sensor's EEPROM.

The BMP180 outputs the atmospheric pressure in hectopascals (hPa) and the temperature in degrees Celsius.

Example output: Pressure = 1013.25 hPa, Temperature = 22.5°C

3.2.1.3. Methane Gas Sensor (MQ-4)

Pertaining the methane gas sensor, we would utilize the steps below to collect data and communicate with the microcontroller (esp32):

(1) Principle of Operation: The MQ-4 sensor detects methane gas (CH_4) concentrations using a thin dioxide (SnO_2) sensing layer. The resistance of the SnO_2 layer changes in the presence of methane gas.

(2) Data Collection Process:

(3) Preheating: The sensor requires a preheating period (typically 24 hours for first use, and a few minutes for subsequent uses) to stabilize its resistance.

(4) Gas Exposure: When methane gas is present, the sensor's resistance changes. The MQ-4 sensor's output is an analog voltage that varies with gas concentration.

(5) Data Readout: The ESP32 reads the analog voltage using its ADC (analog-to-digital converter) pin.

(6) Data Conversion: The analog voltage is converted to a digital value representing the methane concentration. Calibration is performed to convert the ADC value to parts per million (ppm).

The MQ-4 outputs the methane concentration in parts per million (ppm).

Example output: Methane concentration = 500 ppm.

3.2.2.0. Microcontroller (ESP32) Integration

(1) Sensor Initialization: Each sensor is initialized by the ESP32 using specific commands and protocols (I2C for BMP180, GPIO for DHT22, and ADC for MQ-4).

(2) Continuous Monitoring: The ESP32 is programmed to continuously monitor sensor data at defined intervals. Sensor data is read, processed, and stored in the ESP32’s memory buffer for further processing.

(3) Error Handling: The ESP32 includes error-checking routines to ensure data integrity. In case of communication errors or invalid data, the ESP32 retries the data collection process.

3.2.2.1. Data Aggregation

The ESP32 aggregates data from all sensors into a single JSON object for transmission.

Example JSON output;

```
{
  "timestamp": "2024-07-09T12:34:56Z",
  "temperature": 25.6,
  "humidity": 60.5,
  "pressure": 1013.25,
  "methane": 500
}
```

Below is code for the esp32 that collects the data from the sensors and prints the onto the serial monitor:

```
#include <Wire.h >
```

```
#include <Adafruit_Sensor.h>
#include <Adafruit_BMP085_U.h>
#include <DHT.h>
#include <DHT_U.h>

// Pin definitions
#define DHTPIN 2        // Pin connected to DHT22
#define MQ4PIN A0       // Analog pin connected to MQ-4

// Sensor type
#define DHTTYPE DHT22

// Initialize DHT sensor
DHT_Unified dht(DHTPIN, DHTTYPE);

// Initialize BMP180 sensor
Adafruit_BMP085_Unified bmp = Adafruit_BMP085_Unified(10085);

// Variables to hold sensor readings
float temperature;
float humidity;
float pressure;
int methane;

void setup() {
  Serial.begin(115200);
  Serial.println(F("Smart Biogas Monitoring System"));

  // Initialize DHT22 sensor
  dht.begin();
  sensor_t sensor;
  dht.temperature().getSensor(&sensor);
  Serial.println(F("------------------------------------"));
  Serial.println(F("Temperature Sensor"));
  Serial.print  (F("Sensor:       ")); Serial.println(sensor.name);
  Serial.print  (F("Driver Ver:   ")); Serial.println(sensor.version);
  Serial.print  (F("Unique ID:    ")); Serial.println(sensor.sensor_id);
  Serial.print  (F("Max Value:    ")); Serial.print(sensor.max_value);
Serial.println(F("°C"));
  Serial.print  (F("Min Value:    ")); Serial.print(sensor.min_value);
Serial.println(F("°C"));
  Serial.print  (F("Resolution:   ")); Serial.print(sensor.resolution);
Serial.println(F("°C"));
  Serial.println(F("------------------------------------"));
  dht.humidity().getSensor(&sensor);
  Serial.println(F("Humidity Sensor"));
  Serial.print  (F("Sensor:       ")); Serial.println(sensor.name);
  Serial.print  (F("Driver Ver:   ")); Serial.println(sensor.version);
  Serial.print  (F("Unique ID:    ")); Serial.println(sensor.sensor_id);
```

```
  Serial.print  (F("Max Value:    ")); Serial.print(sensor.max_value);
Serial.println(F("%"));
  Serial.print  (F("Min Value:    ")); Serial.print(sensor.min_value);
Serial.println(F("%"));
  Serial.print  (F("Resolution:   ")); Serial.print(sensor.resolution);
Serial.println(F("%"));
  Serial.println(F("------------------------------------"));

  // Initialize BMP180 sensor
  if(!bmp.begin())
  {
    Serial.print("Ooops, no BMP180 detected ... Check your wiring or I2C
ADDR!");
    while(1);
  }
  Serial.println(F("BMP180 Sensor initialized"));
}

void loop() {
  // Collect data from DHT22
  sensors_event_t event;
  dht.temperature().getEvent(&event);
  if (isnan(event.temperature)) {
    Serial.println(F("Error reading temperature!"));
  } else {
    temperature = event.temperature;
    Serial.print(F("Temperature: "));
    Serial.print(temperature);
    Serial.println(F("°C"));
  }

  dht.humidity().getEvent(&event);
  if (isnan(event.relative_humidity)) {
    Serial.println(F("Error reading humidity!"));
  } else {
    humidity = event.relative_humidity;
    Serial.print(F("Humidity: "));
    Serial.print(humidity);
    Serial.println(F("%"));
  }

  // Collect data from BMP180
  sensors_event_t bmp_event;
  bmp.getEvent(&bmp_event);
  if (bmp_event.pressure) {
    pressure = bmp_event.pressure;
    Serial.print(F("Pressure: "));
    Serial.print(pressure);
    Serial.println(F(" hPa"));
  } else {
```

```
    Serial.println(F("Error reading pressure!"));
  }

  // Collect data from MQ-4
  methane = analogRead(MQ4PIN);
  // Convert the analog value to a meaningful value (ppm) if you have a
calibration curve
  // For demonstration, we will just print the raw analog value
  Serial.print(F("Methane: "));
  Serial.print(methane);
  Serial.println(F(" (analog value)"));

  // Add delay before the next reading
  delay(2000);
}
```

Once data is collected on the ESP32 board, the data is temporarily stored in the Memory of the ESP32.

A circular buffer is used to manage the memory efficiently, ensuring that the latest data is available while older ones are overwritten as needed.

The code also includes an error detection handling mechanism. If a sensor fails to respond the system logs the error and re-read the sensor.

3.2.2.2. Data Transmission

Once the data was collected by the microcontroller, it was sent to the cloud to be stored and accessed by the mobile app and the web app. This provided the biogas plant owners realtime insight on the health status of the biogas plant.

Remember, one of the capabilities of the ESP32 microcontroller is its Wi-Fi capabilities. Given this, the data was transmitted over Wi-Fi to a cloud database, called influxDB. InfluxDB is an open-source time series database (TSDB) developed by the company InfluxData. It is used for storage and retrieval of time series data in fields such as operations monitoring, application metrics, Internet of Things sensor data, and real-time analytics.

Now, let us see how we configured and sent our sensor data to the influx database in the Arduino IDE;

3.2.2.3. WiFi Setup

The ESP32 was connected to a Wi-Fi network using the specified SSID and password.

```
#define WIFI_SSID "your_SSID"
#define WIFI_PASSWORD "your_PASSWORD"
```

3.2.2.4. InfluxDB Configuration

The ESP32 is configured to send data to an InfluxDB server using the specified URL, token, organization, and bucket.

```
#define INFLUXDB_URL "http://your_influxdb_server_address:8086"
#define INFLUXDB_TOKEN "your_influxdb_token"
```

```
#define INFLUXDB_ORG "your_influxdb_org"
#define INFLUXDB_BUCKET "your_influxdb_bucket"
```

3.2.2.5. Data Formatting

Sensor data is formatted according to the InfluxDB line protocol. This includes the measurement name, tags, and fields.

```
sensor.addField("temperature", temperature);
sensor.addField("humidity", humidity);
sensor.addField("pressure", pressure);
sensor.addField("methane", methane);
```

3.2.2.6. Data Transmission Process

Below are the data transmission process that was used in harness the intended results from the Internet of Things (IoT) System:

(1) Wi-Fi Connection: The ESP32 attempted to connect to the specified Wi-Fi network. When the connection was lost, it retried until the connection was reestablished.

(2) InfluxDB Client Initialization: The InfluxDB client was initialized with the server details and checked the connection to ensure the server was reachable.

(3) Sensor Data Collection: Sensor data was collected from various sensors (e.g., temperature, humidity, pressure, methane) at specified intervals.

(4) Data Transmission: Collected data was transmitted to the InfluxDB server using an HTTP POST request. When the transmission failed, the ESP32 retried until the data was successfully sent.

The following Arduino code demonstrates how data was collected from sensors and transmitted to an InfluxDB database over Wi-Fi:

```
#include <Arduino.h>
#include <WiFiMulti.h>
#include <InfluxDbClient.h>
#include <InfluxDbCloud.h>
#include <DHT.h>
#include <DHT_U.h>

// Project Macros
#define WIFI_SSID               "your_SSID"
#define WIFI_PASSWORD           "your_PASSWORD"
#define INFLUXDB_URL            "http://your_influxdb_server_address:8086"
#define INFLUXDB_TOKEN          "your_influxdb_token"
#define INFLUXDB_ORG            "your_influxdb_org"
#define INFLUXDB_BUCKET         "your_influxdb_bucket"

#define DEVICE                  "ESP32"

// DHT Sensor Configuration Macros
#define DHTPIN                  26
```



```
#define DHTTYPE               DHT22

#define DHT11_REFRESH_TIME    5000
#define INFLUXDB_SEND_TIME    10000

// InfluxDB client instance
InfluxDBClient client(INFLUXDB_URL, INFLUXDB_ORG, INFLUXDB_BUCKET,
INFLUXDB_TOKEN);

// Data point
Point sensor("Sensor_Data");

WiFiMulti wifiMulti;
DHT dht(DHTPIN, DHTTYPE);
const int gasPin = 33;
const int pressurePin = 32;
float gasVal;
float pressureVal;
uint8_t dht11_temperature = 0;
uint8_t dht11_humidity = 0;
uint32_t dht_refresh_timestamp = 0;
uint32_t influxdb_send_timestamp = 0;

void setup() {
  Serial.begin(115200);
  WiFi_Setup();
  dht.begin();
  pinMode(gasPin, INPUT);
  pinMode(pressurePin, INPUT);

  // Add constant tags - only once
  sensor.addTag("device", DEVICE);
  timeSync(TZ_INFO, "pool.ntp.org", "time.nis.gov");

  // Check server connection
  if (client.validateConnection()) {
    Serial.print("Connected to InfluxDB: ");
    Serial.println(client.getServerUrl());
  } else {
    Serial.print("InfluxDB connection failed: ");
    Serial.println(client.getLastErrorMessage());
  }

  dht_refresh_timestamp = millis();
}

void loop() {
  DHT11_TaskMng();
  InfluxDB_TaskMng();
}
```

```
void WiFi_Setup() {
  Serial.println("Connecting to WiFi");
  WiFi.mode(WIFI_STA);
  wifiMulti.addAP(WIFI_SSID, WIFI_PASSWORD);
  while (wifiMulti.run() != WL_CONNECTED) {
    Serial.print(".");
    delay(500);
  }
  Serial.println();
}

void DHT11_TaskMng() {
  uint32_t now = millis();
  if (now - dht_refresh_timestamp >= DHT11_REFRESH_TIME) {
    dht_refresh_timestamp = now;
    float humidity = dht.readHumidity();
    float temperature = dht.readTemperature();
    gasVal = analogRead(gasPin);
    pressureVal = analogRead(pressurePin);

    if (!isnan(humidity) && !isnan(temperature)) {
      dht11_humidity = (uint8_t)humidity;
      dht11_temperature = (uint8_t)temperature;
      Serial.print("Humidity: ");
      Serial.print(humidity);
      Serial.print("%  Temperature: ");
      Serial.print(temperature);
      Serial.println("°C ");
      Serial.print("Gas concentration: ");
      Serial.println(gasVal);
      Serial.print("Pressure: ");
      Serial.println(pressureVal);
    } else {
      Serial.println("Failed to read from DHT sensor!");
    }
  }
}

void InfluxDB_TaskMng() {
  uint32_t now = millis();
  if (now - influxdb_send_timestamp >= INFLUXDB_SEND_TIME) {
    influxdb_send_timestamp = now;
    sensor.clearFields();
    sensor.addField("rssi", WiFi.RSSI());
    sensor.addField("temperature", dht11_temperature);
    sensor.addField("humidity", dht11_humidity);
    sensor.addField("Gas concentration", gasVal);
    sensor.addField("pressure", pressureVal);
```



```
    Serial.print("Writing: ");
    Serial.println(client.pointToLineProtocol(sensor));
    if (wifiMulti.run() != WL_CONNECTED) {
      Serial.println("Wifi connection lost");
    }
    if (!client.writePoint(sensor)) {
      Serial.print("InfluxDB write failed: ");
      Serial.println(client.getLastErrorMessage());
    }
  }
}
```

3.4. UI/UX Component of the Software Application for Internet of Things (IoT) System

Fig. 6 A screenshot of the UI.UX Component of the Software Application for the Smart Biogas Technology (SBT)

For the purpose of testing our smart device, we need a reliable and efficient data management system. To this end, we have chosen InfluxDB as our data storage solution. InfluxDB is a time-series database that is specifically designed to handle the large volumes of data that are generated by IoT devices. It is also highly scalable, so it can easily accommodate the growth of our smart device fleet. In addition to InfluxDB, we are also utilizing Grafana for data visualization. Grafana is a powerful tool that allows us to create custom dashboards that display our data in a clear and concise way. This makes it easy for us to track the performance of our smart devices and identify any potential problems.

By using this data management process, we can ensure that our smart devices are operating efficiently and that we are able to quickly identify and resolve any potential problems.The component we are interested in serves as the bridge between raw sensor data and insights, ensuring we can interact with the system efficiently and easily.

The grafana user interface design prioritizes clarity, ease of use, and responsiveness. At its core, the dashboard in Grafana will provide real-time visualization of the key parameters: gas concentration, humidity, and temperature we are interested in. We can achieve this by integrating dynamic graphs, charts, and gauges that offer immediate feedback on the outputs of these variables. An example is, a line chart will be employed to show historical trends in gas concentration and temperature, and this will enable us to observe the patterns and identify anomalies over time. Also, real-time gauges for humidity will provide us with a snapshot of the current state with color-coding to highlight values that are within or outside of acceptable ranges.

Our ability to interact with the data output is very important and grafana allows us to filter data by time range, zoom into specific periods for a more detailed view, and set custom alerts that notify them of any critical changes in the sensor readings. This functionality will ensure that we are able to identify issues that are likely to cause a spike in gas concentrations.

The grafana visualiser supports reporting features that will enable us to generate and export reports that summarize the performance and status of the biogas system over selected periods. This can be invaluable for maintenance planning and performance evaluation.

3.5. Internet of Things (IoT) System Assembly, Site Selection, and Test Run

An in depth read into this document expresses the relevance of the potential a smart biogas technology is vital for revolutionizing the biogas industry, especially for small-scale and domestic biogas plants given the technical challenges and the abandonment of the plants. As a result, a smart biogas technology in the course of this project was built to resolve this challenge and run a test using the newly built system. This system basically functions by monitoring parameters such as methane concentration, humidity and temperature of the biogas generated as an approximation of what is in the biogas plant, and the received signal strength indicator (RSSI) of the smart system. These parameters as explained in this document are vital for the appropriate functioning and performance monitoring of biogas plants, thus the need to have them incorporated in our design; However the pH and pressure are crucial components as well. In order to have a better estimation, the system was located at approximately 1.2 meters within the line transmitting the gas from the biogas plant to the source of its usage, the kitchen. Below is a picture of the system that has been built:

Fig. 7. An image of the smart biogas technology (SBT) device built.

Following the completion of building the system, site selection was vital for running the test. Given this, DAS Biogas of Mr. Enoch Kofi Boadu at Juaben in the Ashanti Region of Ghana was selected, due to principal biogas construction and maintenance expertise, and the work done together for the ci=ourse of this project, worked with extensively on this project. At DAS Biogas, there are different variants of biogas plants: The fixed domes, the Chinese type of biogas plant, and their portable prefab designed tank here in Ghana. Proximity was of essence here given the selection of Juaben as the principal location, which is also at most an hour journey from the KNUST campus. These reasons, together with the expertise of DAS Biogas and availability to test the system together, at least under the care of an expert justified our selection of Juaben, where we ran the test of the new system.

Having selected the location, a day was selected and the tests were run. In the course of running the test, accurate and consistent data logging was critical; This is essential for long-term monitoring of biogas systems. In this test, data points were recorded at 10-second intervals, ensuring continuous monitoring without any significant gaps in the timestamps. Preferably, the system test was going to be extensive and left for a minimum of three (3) days to two (2) weeks to gather enough data points and understand how the system functions during different parts of the day and under different weather conditions. However, this was not possible given the short-term life span of the battery of the smart system built and the time available for completing the project. In our next phase, this will be significantly explored. To accommodate this and have an overview of the minute changes was then justified with the selection of the above discussed approach where data points were recorded at 10-second intervals. The results and discussion section will delve more into this.

3.6. Evaluation of the Chosen Method and its Limitations

Certainly no first prototype is ever a perfect and fit it all solution, but with continuous learning and improvement systems are adjusted to meet the needs and solutions expected of technologies. Such a kind is this project. Thus, below are some limitations of this project:

- **pH reading:** It is worth noting that the pH reading, a crucial component, is missing as part of the component for the smart biogas system. This was identified later after our design and for this reason, another digital model which would be a dip-rod is being developed as this is vital to be in the system to measure the internal pH of the biogas system. The dip-rod would also feature the pressure sensor as well. Despite not having these and the level of stability of the biogas plant, this was not a major concern for this test.
- **Test time:** From the test run, it is witnessed that the test spanned only a few hours instead of from several days to two (2) weeks and even beyond. Due to this the impacts of different weather conditions, how the plant and system works comparatively during the day and night, and in seasons in the year were totally absent in this test, and for that matter, this study. However, adjustments were made for shorter time stamps, but this is not enough. In our next phase, this will be significantly explored.
- **Battery life span:** It was also experienced that the battery's life span was pretty short, spanning only a few hours. Thus, there is a potential modification to include a small micro-solar panel to charge and sustain the battery to keep it running effectively and efficiently.
- **Multiple testing of the system:** To test robustness and other essential parameters, it is vital to run multiple tests on different biogas systems, and under varied levels of conditions to have an effective and efficient technology. This was a shortfall for this project given the time that was left at hand. However, in the next phase, this will be dealt with intensively for the continued operationality of the technology, technical robustness, efficiency, and effectiveness.

- **Software component for improved user experience:** Given the technical incapacity and time constraints, the software component for improved user experience was not completed for this phase of the project. Thus, reaching only the visualization of the data generated from the system at the highest level reached for this project. In the next phase, a talented and focused team, with the required technical expertise will focus on getting this aspect done and get this tested multiple times for efficiency, effectiveness, and robustness for improved user experience.

4. Results

4.1. Methane Concentration (in parts per million, PPM)

The diagram below express a graphical representation of the pathway of methane concentration of biogas generated from a biogas plant during the test of the newly built smart biogas technology (SBT) system for few hours:

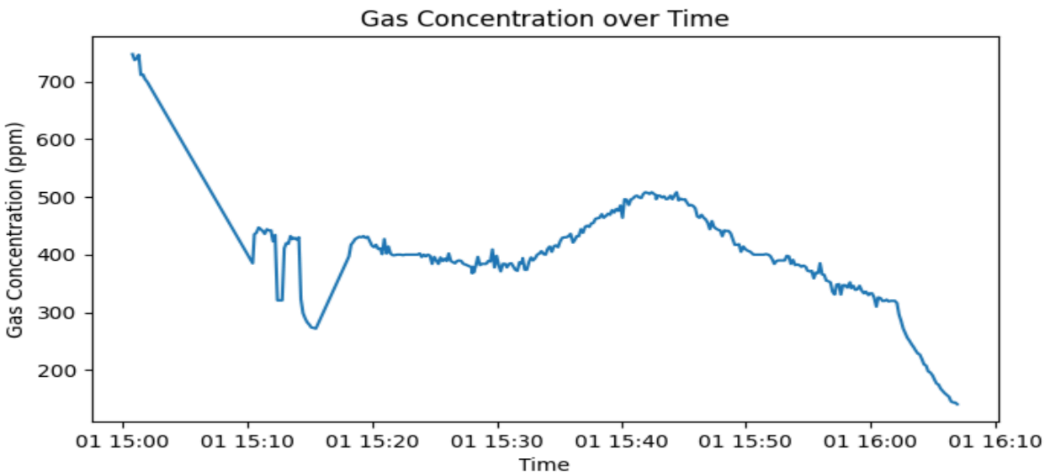


Fig. 8. A graph of methane gas concentration over time.

From the above graphical representation, the range of cleaned data points for the methane concentration is between 100 and 800 ppm. This rationale behind this result will be expressed in the discussion section.

4.2. Humidity (in percentages)

The diagram below express a graphical representation of the pathway of the humidity content of the gas from a biogas plant during the test of the newly built smart biogas technology (SBT) system for few hours:

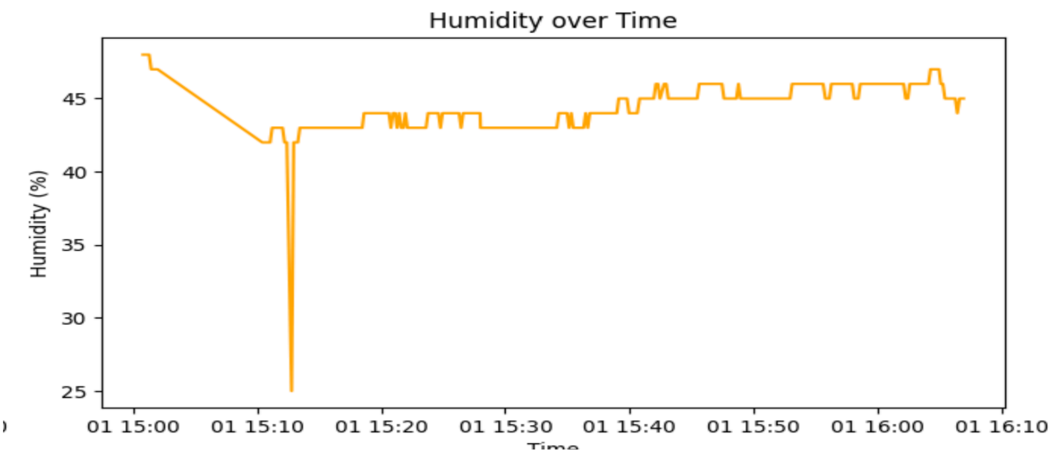


Fig. 9. A graph of humidity over time.

From the above graphical representation, the range of cleaned data points for humidity is between 20% and 70%. This rationale behind this result will be expressed in the discussion section.

4.3. Temperature (in ℃)

The diagram below express a graphical representation of the pathway of the temperature range of operation of a biogas plant, with an approximation of the temperature of the gas exiting the biogas system during the test of the newly built smart biogas technology (SBT) system for few hours:

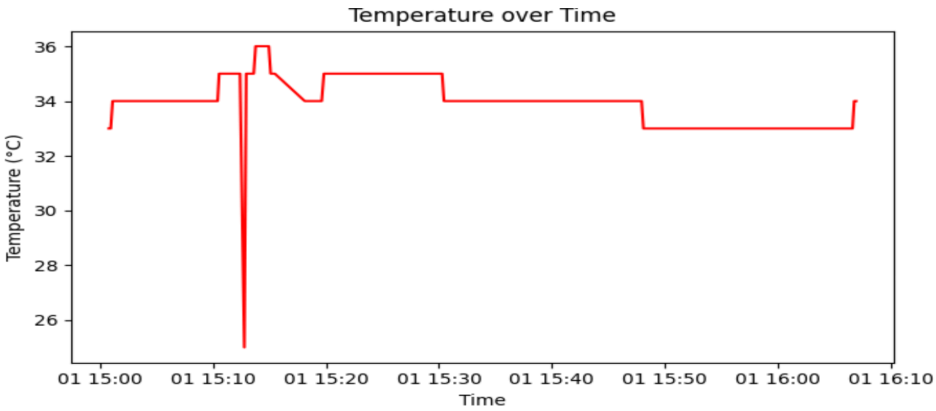


Fig. 10. A graph of biogas internal system temperature over time.

From the above graphical representation, the temperature range of cleaned data points of operation of the biogas plant is between 25 ℃ and 36 ℃. This rationale behind this result will be expressed in the discussion section.

4.4. Received Signal Strength Indicator, RSSI (in dBm)

The diagram below expresses a graphical representation of the pathway of the RSSI (Received Signal Strength Indicator), the strength of the signal received by the ESP32 during operation of a biogas plant, via the smart biogas technology (SBT) system for a few hours. The RSSI (Received Signal Strength Indicator) measures the strength of the signal received by the ESP32, allowing us to assess the reliability of the smart biogas technology (SBT) system's data transmission.

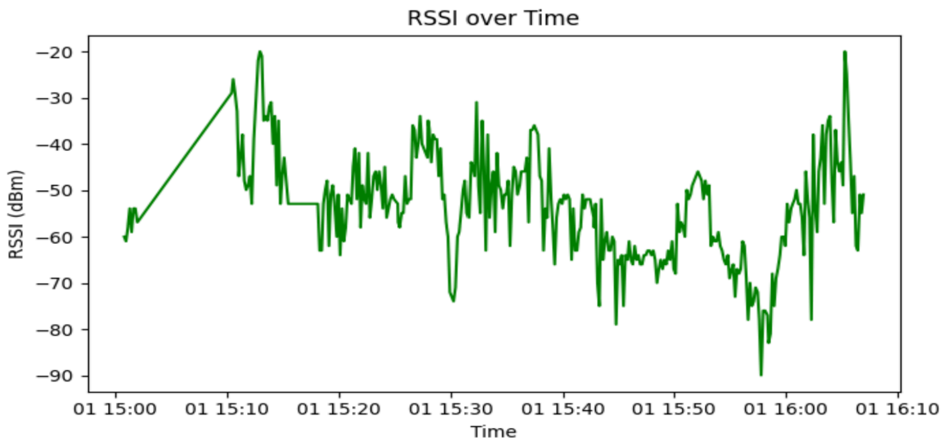


Fig. 11. A graph of RSSI over time.

From the above graphical representation, the RSSI (Received Signal Strength Indicator) is between -100 dBm and -20 dBm. This rationale behind this result will be expressed in the discussion section.

On ending the results section, kindly find the data generated from the smart biogas technology (SBT) system in the appendix of this document. The above graphs were generated using the UI/UX software component, a work in progress.

5. Discussion

The gas concentration levels recorded by the ESP32-based monitoring system reflect an inverse relationship between the analog readings and the actual gas concentration in the plant environment. Higher analog values (above 700) correlate with lower gas concentrations, indicating periods of lower biogas production or system inactivity. Conversely, lower analog values signify higher gas concentration levels, reflecting active stages in the biogas production cycle, where the system was not connected yet.

Over the monitoring period, these key observations were noted:

(1) **Gas Concentration Levels**: Gas concentration readings displayed noticeable fluctuations, with several peaks and troughs throughout the monitoring period. For instance, at times when the concentration was lowest, analog readings surged above 700, indicating an inverse relationship;

(2) **Temperature and Humidity Trends**: Temperature and humidity values remained consistent across most intervals, averaging 33.9274 °C and 44.475 °C respectively. Although there was no direct influence observed between temperature, humidity, and gas concentration in this dataset, these environmental parameters provide insights into the stability of the production environment.

Each data point includes a precise timestamp, allowing for accurate tracking over time. This facilitates the identification of any temporal patterns or correlations within the biogas production process, particularly when gas concentration levels exhibit changes in response to environmental conditions.

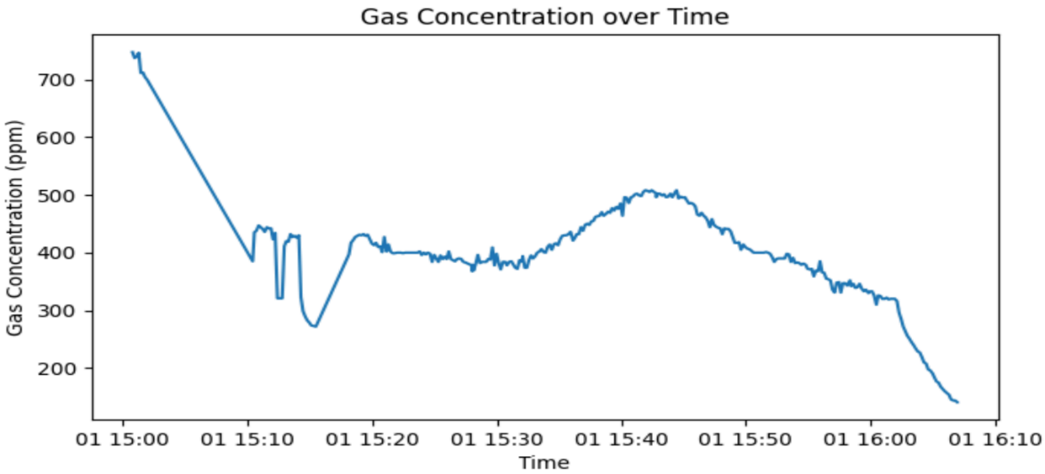
5.1.1. Methane Concentration Trends, Raw Data (in parts per million, PPM)

Methane gas (CH_4) is the primary component of biogas, and its concentration is a direct indicator of the efficiency of the anaerobic digestion process. Methane is produced when organic materials such as animal manure, food waste, and plant materials are broken down by microorganisms in an oxygen-free environment. The concentration of methane in a biogas digester can fluctuate depending on factors such as the temperature, the type of feedstock used, and the microbial activity within the digester.

During this test, gas concentration readings ranged from 225 ppm to about 800 ppm, with higher concentrations indicating efficient methane generation. The raw analog values were converted to real methane concentrations using the MQ4 sensor and the calibration curve provided by the sensor's datasheet. Spikes in the gas concentration could suggest periods of increased microbial activity, potentially influenced by favorable environmental conditions such as optimal temperature or moisture levels.

The continuous rise in gas concentration is a positive indicator that the biogas system is functioning efficiently. Maintaining stable gas production is critical for ensuring the system's long-term viability, and continuous monitoring helps operators make informed decisions about feedstock input and environmental control.

Below represents the raw data of the methane sensor from the testing that was done:



5.1.2. Methane Gas Concentration Trends, Cleaned Data (in parts per million, PPM)

Below is a snapshot of the gas concentration data showing high analog readings (low concentration levels), indicating periods when the system was turned on but not connected to the biogas plant, hence very high analog readings indicating very low or no gas production. This continued until it was connected and then the analog readings started dropping indicating gas production.

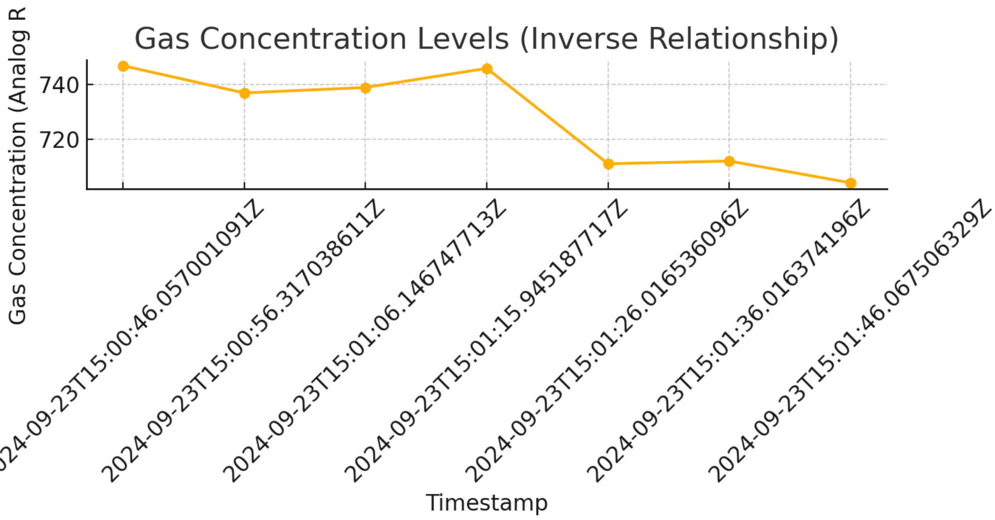


Fig. 12 Snapshot of Gas Concentration Levels Indicating Low Concentration Periods

The observed inverse relationship between the sensor readings and actual gas concentration suggests that gas density affects sensor output in a nonlinear fashion. This relationship highlights a critical aspect of biogas plant monitoring: while analog readings provide a baseline for concentration detection, they require careful interpretation, especially when environmental variables (e.g., temperature, humidity) remain stable.

Inverse Relationship Interpretation: When analog readings peaked (e.g., values above 700), it suggested lower gas density or less active phases in the biogas production cycle. This might indicate downtime or inactive periods within the system. On the other hand, lower readings correlated with higher concentration levels, representing more active biogas production phases where gas output is elevated.

Environmental Impacts on Sensor Accuracy: Temperature and humidity, while stable, might influence sensor accuracy under different operational phases of the plant. A higher temperature, for example, could influence gas density, indirectly affecting analog readings. Further monitoring over an extended period could provide more insights into this relationship.

Device Performance: The ESP32 device maintained consistent readings throughout the monitoring period. The RSSI values recorded suggest stable signal strength and data transmission reliability, which is crucial for continuous monitoring in industrial settings..

Moreover, below is a snapshot of the gas concentration data during active periods, showing lower analog readings that correlate with higher gas concentrations. These periods represent more intensive gas production phases within the biogas plant.

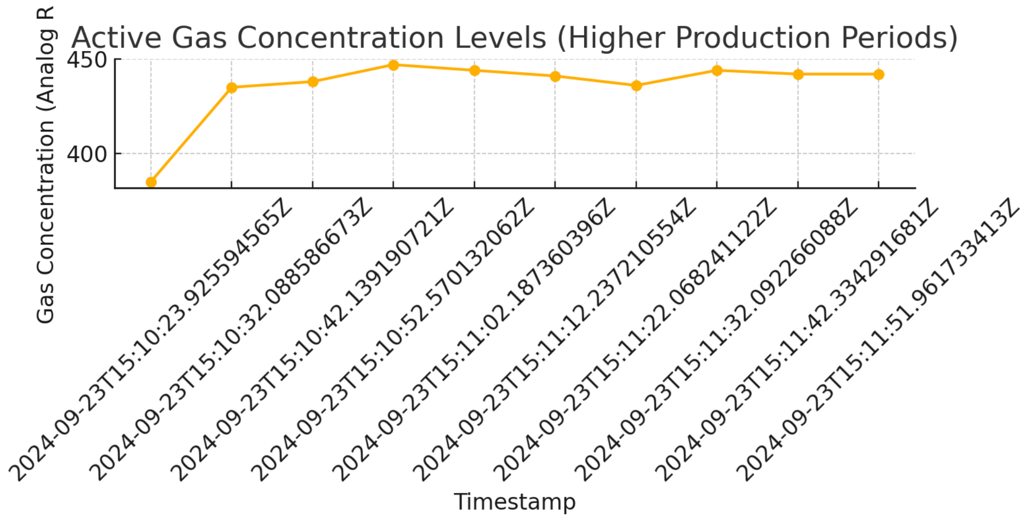


Fig. 13 Snapshot of Active Gas Concentration Levels Indicating Higher Production Phases

The steady rise indicates stable gas production, with spikes suggesting moments of higher methane generation.

Overall, the data gathered from the IoT monitoring device offers valuable insights into the operational dynamics of biogas production. Future iterations of this monitoring approach might consider additional calibration for analog-to-concentration conversion, taking into account environmental factors to further enhance reading accuracy

5.2. Environmental Conditions: Temperature and Humidity

Environmental conditions, particularly temperature and humidity, play a vital role in the anaerobic digestion process. Microbial activity responsible for breaking down organic matter is highly sensitive to temperature fluctuations. In general, anaerobic digestion occurs most efficiently within the mesophilic temperature range, which is between 25°C and 40°C. Data as visualized below suggests that the test system operated pretty well within the optimal range for efficient methane production, for a mesophilic system..

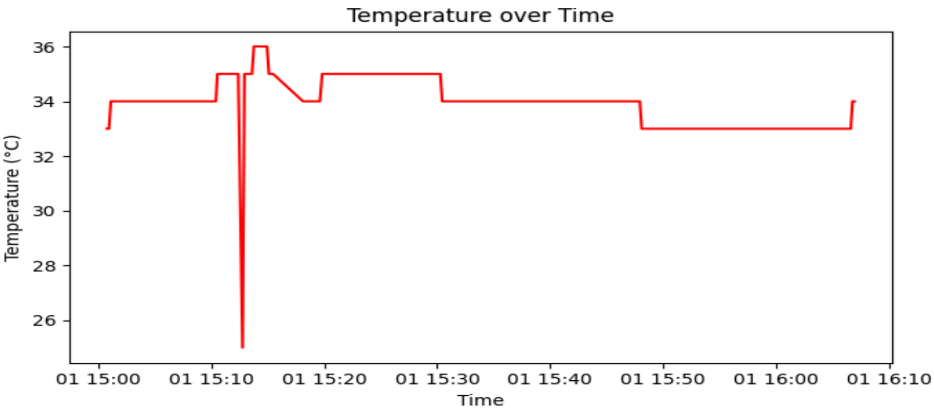


Fig. 14 A graph of temperature over time.

Humidity, while less directly impactful than temperature, still plays a role in maintaining the right moisture content inside the digester. During this test, humidity fluctuated between 64% and 65%. Dry conditions can slow down microbial activity, while excessively moist environments may reduce gas production efficiency. In future iterations, adding moisture regulation systems could help stabilize humidity levels and improve gas yields.

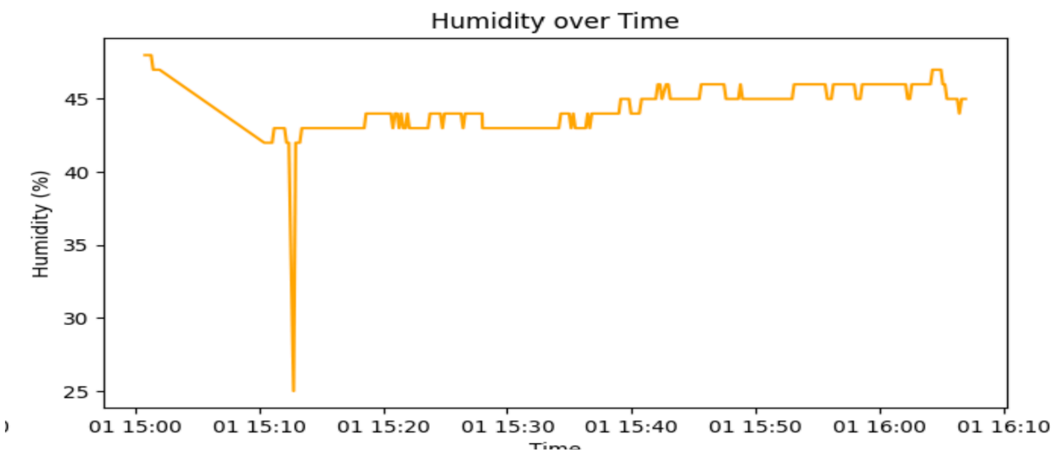


Fig. 15 A graph of humidity over time.

The drop in temperature and humidity at the time 15:12 indicates the end of the inactive periods when the system was just connected to the plant and started reading the consistent humidity and temperature values.

5.3. RSSI (Signal Strength) Performance

Reliable data transmission is critical in monitoring biogas systems, especially in remote or industrial settings. The RSSI (Received Signal Strength Indicator) measures the strength of the signal received by the ESP32, allowing us to assess the reliability of the system's data transmission. In this test, RSSI values ranged from -41 dBm to -16 dBm. Strong signal values above -30 dBm indicate stable data transmission, while weaker signals below -40 dBm suggest possible environmental interference or obstacles affecting the signal.

Maintaining a stable and reliable connection ensures that real-time data can be continuously monitored, enabling operators to make timely adjustments to the system if needed. In future setups, adding LoRa signal boosters could further enhance data transmission over longer distances or in challenging environments.

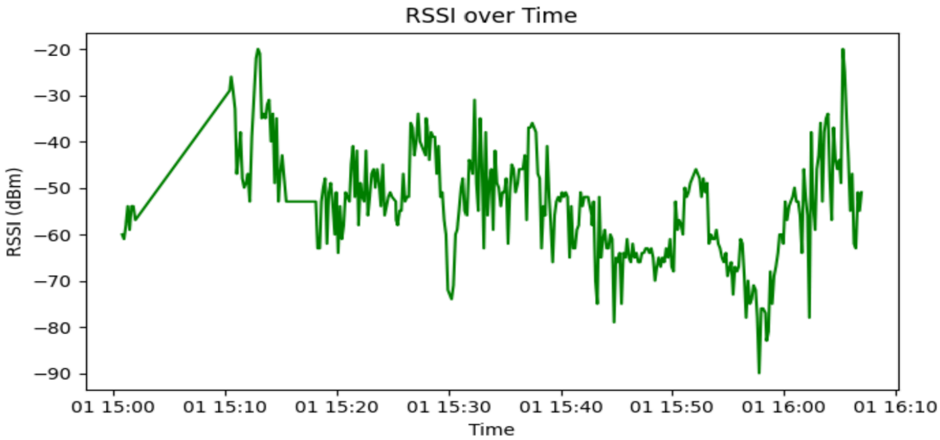


Fig.16 A graph of RSSI over time.

5.4. Timestamp Correlation and Data Patterns

Accurate and consistent data logging is essential for long-term monitoring of biogas systems. In this test, data points were recorded at 10-second intervals, ensuring continuous monitoring without any significant gaps in the timestamps. By maintaining a consistent logging schedule, operators can reliably track changes in gas production, environmental conditions, and system performance over time. Any missing data points could lead to gaps in understanding system behavior, which is why continuous and reliable data transmission is crucial.

5.5. Discussion on Gas Concentration and Temperature Relationship

The analysis of gas concentration relative to temperature indicates a correlation of approximately 0.22. This suggests that temperature has a mild effect on gas concentration levels. Specifically:

(1) **Higher Temperatures**: Periods of elevated temperatures tend to show slightly reduced analog readings, potentially indicating increased gas concentration. This could reflect the biogas plant's response to thermal conditions, where increased temperatures promote more active gas production.

(2) **Lower Temperatures**: During relatively cooler periods, analog readings (indicating gas concentration) are generally higher, suggesting a decrease in gas production. This may be due to lower metabolic rates in microbial activities within the biogas plant as temperature drops.

This relationship is not strongly linear, indicating that temperature might play a supportive role rather than a direct one. Further testing over extended periods or under different seasonal conditions might provide more insights into how temperature fluctuations impact biogas concentration.

Below is a scatter plot showing the observed relationship between temperature and gas concentration:

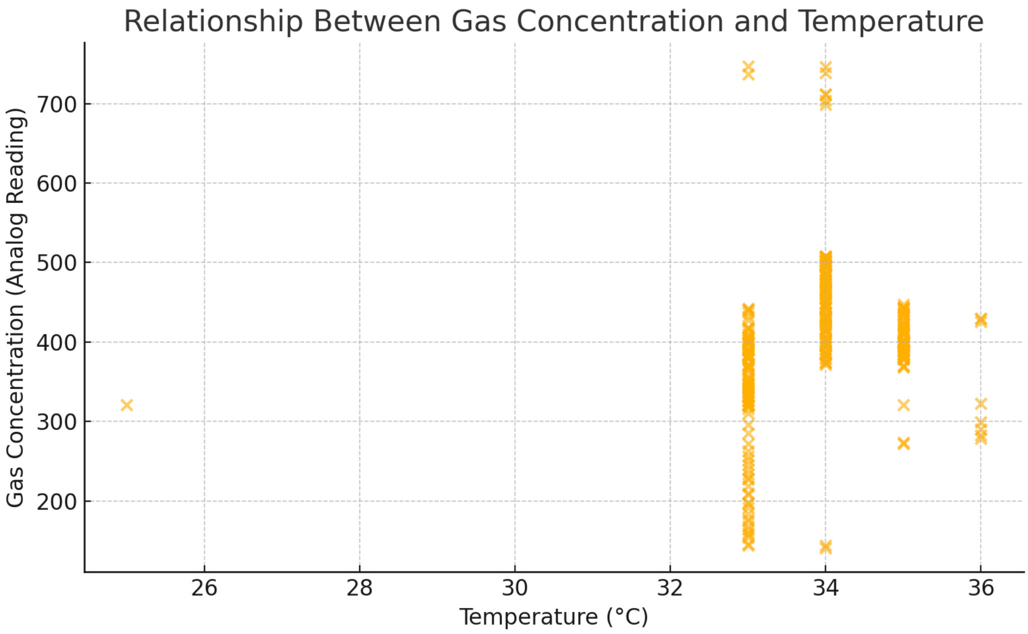


Fig. 17 Scatter Plot of Gas Concentration vs. Temperature

In the course of this study, we were able to establish that there is a relationship between biomethane production and temperature. This validates findings from other researchers conducted. Certainly, other parameters like humidity, pH, pressure, amongst other environmental parameters need to be studied, even over weather and seasonal variations to consolidate the effects that have on the biogas systems, and to that effect, on the smart biogas system as well for optimum efficiency. Moreover, our research method was appropriate, however, time was a constraint (a limited sample size), thus future developments will take this into consideration as well as the isolated (controlled) and system-wide effects of parameters like humidity, pH, pressure, amongst other environmental parameters. Basically in comparison to other researches, this info is quite rare as methodologies, feedstock type, and the cycle times are varied, however, the results obtained are in tandem with normal functioning bigas systems. In its entirety, this was a good level of progression in this phase of the project. The subsequent phase will improve upon the agility and flexibility of the system together with efficiency, effectiveness, and safety.

6. Conclusion

The smart biogas system demonstrated reliable performance throughout the test, with continuous biomethane gas monitoring, together with other parameters such as humidity and internal system temperature for the biodigester. The monitoring system provided valuable real-time insights into the behaviour of the biogas digester, validating its potential for informed decision-making and system optimization. As every system on this plant, this system also requires further improvement for the system's efficiency, thus, the following recommendations are suggested:

- **Environmental Control**: Introduce moisture control systems to better regulate humidity levels inside the digester, which may improve gas output.
- **Extended Functionality:** Incorporate the pH component to improve upon the reliability of the smart biogas system. This should also allow adjustments for further upgrades in the future, as sustainability in designs are also vital in managing resources efficiently and effectively.
- **Signal Enhancement:** Consider using LoRa signal boosters to improve data transmission reliability, particularly in remote or challenging environments.
- **Extended Monitoring:** Conduct longer-term tests to assess the system's performance over different weather conditions, seasons, and varying feedstock conditions, which is vital for further and necessary optimization capabilities. In addition to this, the capacity of the battery needs to be extended, as well as featured a dynamic micro-solar panel component to recharge the battery efficiently.
- **Software component for improved user experience:** Due to technical constraints and time limitations, the software component for improved user experience was not completed in this phase, resulting only in the visualization of data generated from the system. In the next phase, a skilled team with the necessary expertise will focus on completing and rigorously testing this component to enhance user experience.
- **System Scalability:** Explore scaling the system to relatively larger biogas setups to evaluate their performance, and consider integrating additional sensors to monitor gas quality and other variables.

7. References

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8. Appendix

Gas conce	device	humidity	rssi	temperatu	time
225	ESP32	65	-41	28	2024-10-02T17:16:21.4969995Z
373	ESP32	64	-17	28	2024-10-02T17:16:31.30316535Z
465	ESP32	64	-16	28	2024-10-02T17:16:41.341199773Z
540	ESP32	64	-17	28	2024-10-02T17:16:51.375363593Z
586	ESP32	65	-16	28	2024-10-02T17:17:01.629568754Z
547	ESP32	65	-17	27	2024-10-02T17:17:11.241741111Z
511	ESP32	66	-16	27	2024-10-02T17:17:21.886237496Z
577	ESP32	66	-16	27	2024-10-02T17:17:31.297774398Z
615	ESP32	66	-20	27	2024-10-02T17:17:41.366100448Z
651	ESP32	66	-17	27	2024-10-02T17:17:51.486137649Z
676	ESP32	66	-18	27	2024-10-02T17:18:01.631533038Z
693	ESP32	66	-19	27	2024-10-02T17:18:11.478435248Z
707	ESP32	66	-18	27	2024-10-02T17:18:21.499672541Z
718	ESP32	66	-17	27	2024-10-02T17:18:32.159123912Z
721	ESP32	66	-18	27	2024-10-02T17:18:41.354240715Z
731	ESP32	66	-16	27	2024-10-02T17:18:51.563730288Z
739	ESP32	66	-26	27	2024-10-02T17:19:01.224481774Z
746	ESP32	66	-19	27	2024-10-02T17:19:11.683353707Z
752	ESP32	65	-21	27	2024-10-02T17:19:21.290633641Z
749	ESP32	65	-19	27	2024-10-02T17:19:31.518803687Z
752	ESP32	65	-18	27	2024-10-02T17:19:41.980641929Z
758	ESP32	65	-17	27	2024-10-02T17:19:51.402364199Z
763	ESP32	65	-17	27	2024-10-02T17:20:01.485155383Z
769	ESP32	65	-18	27	2024-10-02T17:20:11.291975049Z
752	ESP32	65	-17	27	2024-10-02T17:20:21.316708454Z
777	ESP32	65	-17	27	2024-10-02T17:20:31.354271181Z
784	ESP32	64	-18	27	2024-10-02T17:20:41.372025759Z
784	ESP32	64	-18	27	2024-10-02T17:20:51.83467883Z
790	ESP32	64	-17	27	2024-10-02T17:21:01.242428219Z
786	ESP32	64	-19	27	2024-10-02T17:21:11.482258512Z
789	ESP32	64	-18	27	2024-10-02T17:21:21.30661267Z
787	ESP32	65	-18	27	2024-10-02T17:21:31.370634756Z
795	ESP32	64	-20	27	2024-10-02T17:21:41.394362616Z
799	ESP32	64	-19	27	2024-10-02T17:21:51.623814927Z
800	ESP32	64	-20	27	2024-10-02T17:22:01.649502057Z
801	ESP32	64	-19	27	2024-10-02T17:22:11.276831728Z

A Table of Data Points From Smart Biogas Technology (SBT) System Test Run