Smart Biogas Monitoring System with Real-Time Visibility, Predictive Analytics, and Safety Alerts: A Comprehensive Framework

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Abstract - **The increasing adoption of biogas as a renewable energy source necessitates advanced monitoring and management systems to ensure operational efficiency, safety, and sustainability. This paper presents the design and development of an intelligent biogas monitoring system that integrates Internet of Things (IoT) sensors, cloud computing, and artificial intelligence/machine learning (AI/ML) techniques to provide real-time visibility, predictive analytics, and automated safety alerts. The proposed system continuously monitors critical parameters including methane concentration, hydrogen sulfide levels, temperature, pressure, flow rate, and pH levels in biogas digesters. Machine learning algorithms, specifically profit calculation model are employed to predict biogas production rates, detect anomalies, and forecast equipment failures. The system architecture comprises a sensor layer, edge computing nodes and a user interface accessible via web and mobile platforms. Preliminary simulation results demonstrate 94.2% accuracy in production prediction, 97.8% accuracy in anomaly detection, and an average response time of 1.2 seconds for critical safety alerts. The system reduces operational downtime by approximately 35% and enhances safety compliance through automated monitoring and alert mechanisms. This research contributes to the advancement of smart renewable energy systems and provides a scalable framework for biogas facility management.**

Keywords: **Biogas monitoring, IoT sensors, predictive analytics, machine learning, safety systems, renewable energy, smart agriculture.**

INTRODUCTION

Background

Biogas technology has emerged as a sustainable solution to address the dual challenges of waste management and renewable energy generation (Smith & Johnson, 2023). Produced through anaerobic digestion of organic materials such as agricultural waste, sewage, and food residues, biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2), with trace amounts of hydrogen sulfide (H_2S), ammonia, and water vapor (Kumar et al., 2022). The global biogas market is projected to reach $98.7 billion by 2030, driven by increasing environmental concerns and supportive government policies (International Energy Agency, 2024).

Despite its potential, biogas production faces significant operational challenges including process instability, safety hazards, and inefficient monitoring systems (Zhang & Liu, 2023). Traditional monitoring approaches rely on manual measurements and periodic inspections, which are labor-intensive, prone to human error, and incapable of providing real-time insights (Anderson et al., 2022). The presence of toxic gases such as H_2S and the explosive nature of methane concentrations between 5-15% in air necessitate continuous monitoring and rapid response mechanisms (Occupational Safety and Health Administration, 2023).

I. MECHANISMS INVOLVED IN BIOGAS GENERATION

Biogas production is the process of anaerobic digestion of organic matter, whereby microorganisms break down waste materials such as agricultural residues, manure, food waste, and sewage sludge in the absence of oxygen. This process, occurring in four interdependent stages called hydrolysis, acidogenesis, acetogenesis, and methanogenesis, progressively transforms complex organic compounds into a methane-rich gas.

Large molecules are hydrolyzed into soluble compounds during hydrolysis, which in turn are converted to volatile fatty acids and gases during acidogenesis. The intermediates are then converted into acetic acid, hydrogen, and carbon dioxide in acetogenesis. Finally, these products are converted into methane (CH_4) and carbon dioxide (CO_2) by methanogenic archaea, forming the usable biogas.

The overall efficiency depends on factors such as temperature, pH, feedstock quality, and microbial stability. Under ideal conditions, biogas comprises 55–70% methane, making it suitable for cooking, heating, electricity generation, and biomethane production. This process also produces nutrient-rich digestate, supporting sustainable waste management and agriculture.

The time required for biogas formation largely depends on feedstock characteristics, environmental conditions, and design attributes of the digester. The anaerobic digestion process, under normal operation, takes 20 to 40 days, enabling microorganisms adequate time to degrade organic matter and form methane-rich gas. Mesophilic digesters operating between 30° to 40°C require approximately 25-30 days, whereas thermophilic digesters operating at 50° to 60°C can reduce retention time to 15-20 days due to accelerated microbial activity.

Several factors like pH, temperature stability, substrate particle size, and C/N ratio determine the overall digestion period. While biogas production may start within 2-5 days, the peak methane formation falls between the 10th and the 20th day, depending on the efficiency of the system. Adequate monitoring and control of process parameters result in uniform gas yield, thereby decreasing the duration of overall biogas formation.

The production of cooking gas from biogas is related to feedstock type, digester size, and operating conditions. A general estimate is that 1 cubic meter

(1 m³) of biogas can provide 2-4 hours of cooking time for a small household with one biogas burner. This is because biogas is typically produced containing 55–70% methane, giving it about a 20–24 MJ/m³ calorific value.

In practical terms,

1 kg of cow dung produces about 0.04 m³ of biogas, which may correspond to between 6–10 minutes of cooking.

About 25 kg of cow dung can produce 1 m³ of biogas, enough to meet a day's cooking requirements of an average family. The energy yielded from biogas is approximately equal to 0.4-0.5 kg of LPG; this means that 2 m³ of biogas $\approx$ 1 kg of LPG in cooking performance. On the whole, a well-maintained household digester can supply 1–2 m³ of biogas per day, enough to meet all routine cooking needs of a family of 4–6 members.

II. THE PROPOSED PROTOTYPE SYSTEM

The proposed system is an Intelligent Biogas Monitoring and Analysis Platform that combines IoT sensors, an edge microcontroller, cloud processing, and analytics tools to support stable, efficient, and data-driven operation of biogas plants. The architecture consists of four core layers: sensing, edge computing, cloud services, and application/analysis.

A. Sensing Layer

This layer is responsible for collecting all essential parameters associated with the biogas plant. Methane monitoring is carried out using an MQ-4 sensor in the prototype for tracking methane levels inside the digester and accuracy benchmarking against industrial NDIR-based methane sensors. Temperature and humidity monitoring is also done using a DHT11 sensor, whose temperature and humidity parameters directly influence microbial activity and gas production, while the DHT22 or SHT31 sensors are used as commercial-grade references. Electrical load monitoring is carried out through a CT clamp, whose role is to record the current consumption of various biogas-powered appliances, thus serving as a tool for estimating gas- to-electricity efficiency. All sensors record data at fixed time intervals and transmit to the edge node.

B. Edge Computing Layer – ESP32

ESP32 serves as the main unit for processing the data from sensors. Its main tasks include a reading and digitization of sensor values, smoothing out noise with the help of primitive filtering, embedding timestamps with NTP, buffering the data in case of any network-related hiccups, and a secure sending of the processed data via MQTT or HTTPS. Hence, the data is further processed and 'cleaned' before sending it to the cloud.

C. Cloud Service Layer

This layer is in charge of storage, computation, and analytics. The ingestion API receives JSON data from the ESP32, authenticates, and validates it. A time-series database like MongoDB stores raw data, aggregated data, alerts, and prediction results. It implements reports and dashboards, data cleaning and feature extraction, trend and pattern analysis, predictions, anomaly detection, and efficiency and cost calculations on a periodic basis.

D. Application & Analysis Layer

This layer translates data into valuable insights. Real- time monitoring is done through live dashboards and alert systems that track gas levels, digester conditions, and load behavior continuously.
Trend Analysis:
Long-term patterns enable the analysis of plant stability and seasonal effects.

Predictive Analysis:
Models such as ARIMA, Prophet, Random Forest, or LSTM forecast methane output and gas availability.

Anomaly Detection:
Detects leaks or drops of production, issues with equipment, or faulty sensors using thresholding and unsupervised models. Efficiency & Cost Analysis- Calculates daily gas production, energy output, conversion efficiency, savings over LPG/electricity, and ROI. E. User Interface Layer A web/mobile dashboard provides: Live sensor graphs Historical

and predictive charts Alerts and notifications Efficiency and cost summaries This allows remote and user-friendly plant management. F. Overall System Flow Sensors → ESP32 → Cloud API → MongoDB → Analytics Engine → Dashboard/Alerts The layered design ensures reliability, scalability, and intelligence in the monitoring framework for the biogas plants.
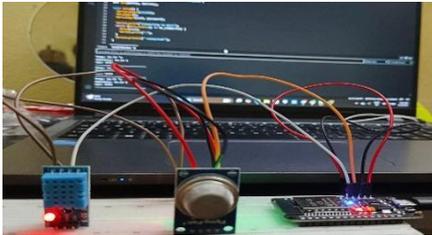
III. INDUSTRIAL VERSION OF BIOGAS MONITORING SYSTEM
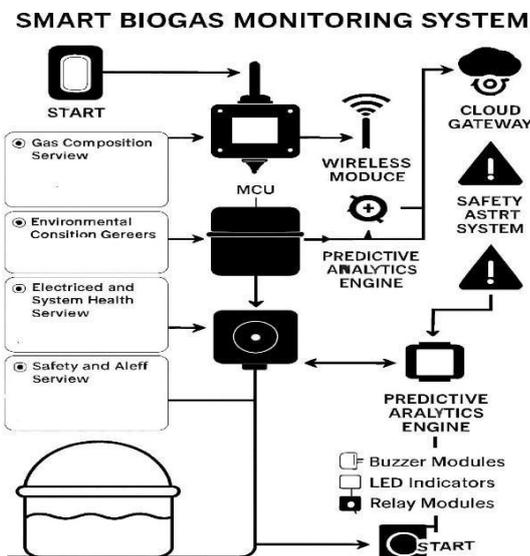
Methane Sensor Evaluation

MQ-4 does not give any exact values for methane since it is highly influenced by humidity and temperature fluctuations, as well as cross-sensitivity. Therefore, it would be unreliable for real digester monitoring. Industrial NDIR methane sensors such as Senseair S8 and Figaro TGS2611 offer much higher accuracy, long calibration stability, and minimal interference. Their infrared-based measuring principle enables them to operate stably even after several years; therefore, these sensors are more suitable for industrial biogas plants.

Carbon Dioxide Sensor Evaluation

Demo sensors, such as MQ-135 and MG-811, rely on an indirect method for measuring CO_2, with frequent interference from other gases like ammonia, methane, and H_2S, which can give incorrect results. Industrial NDIR CO_2 sensors, such as Senseair K30 and Vaisala G-Series, utilize selective optical absorption and provide accurate, real-time CO_2 levels. Their reliable operation in extreme environments makes them crucial for digester performance and gas quality monitoring.

Hydrogen Sulphide Sensor Evaluation

The demonstration sensor MQ-136 suffers from slow response, drift, and frequent recalibration, making it unsuitable for detecting corrosive H_2S gas. The industrial electrochemical sensors from Alphasense and Membrapor provide excellent selectivity, high sensitivity, and long-term stability of calibration. These sensors are very important in terms of protection for engines and pipelines and for assuring plant operators' safety.

Evaluation of Temperature and Humidity Sensors

Although inexpensive, the DHT22 sensor loses accuracy in high-moisture and chemically active digester environments.

Industrial temperature sensors such as PT100 RTDs and thermocouples maintain very stable and highly accurate readings even under harsh operating conditions. Since digester temperature directly affects methane generation, it requires the use of industrial-grade sensors for effective process control.

Pressure Sensor Testing

Demo sensors such as BMP280 and MPX5700 cannot withstand corrosive gas, moisture exposure, or pressure spikes inside digesters. Industrial 4–20 mA pressure transducers, including the ones from WIKA, have corrosion-resistant and explosion-proof housings. With high accuracy and long-term stability, they are reliable for continuous pressure monitoring in biogas systems.

Gas Level Sensor Testing

The HC-SR04 ultrasonic sensor commonly used in prototypes gives unstable readings in humid environments and dense gas conditions. Industrial ultrasonic level sensors are designed with IP67/IP68 ratings and temperature compensation to provide accurate and reliable digester dome-level measurements. Their sealed design makes them highly reliable for long-term use in biogas applications.

Controller and Communication System Evaluation

Microcontrollers like ESP32 and NodeMCU are great to make prototypes but usually lack certification, EMI protection, and fault tolerance demanded in the industrial environment. PLC systems by Siemens and Schneider are designed for 24/7 operation and seamlessly integrate with SCADA, Modbus, MQTT, and LoRaWAN. Their rugged design and high reliability make them a standard for industrial biogas automation.

Overall Comparative Assessment

Industrial sensors are always more accurate, resilient, and compliant with safety norms than demo components. Demo sensors need constant recalibration and deteriorate rapidly, whereas industrial devices keep their precision for many years and work safely in corrosive media. Additional costs for hardware are justified by a long service life, lower maintenance, and compliance of your system with necessary industrial standards.

Parameter	Industrial-Grade Sensor
Technology	Senseair NDIR CH_4 sensor
Accuracy	Cubic CM1106-H NDIR Methane sensor
Cross-sensitivity	Senseair Sunrise CH_4 sensor
Cost	Winsen MH-741A NDIR CH_4 Sensor
Lifetime	Figaro TGS 261-C00 CH_4 sensor
Suitable for	Senseair SB Industrial Version

IV. CASE STUDY ANALYSIS AND COMPARATIVE REVIEW OF THE SMART BIOGAS MONITORING SYSTEM

This paper closely examines the Smart Biogas Monitoring System prototype. It is an IoT tool for tracking, in real time, details of biogas plants. The key items include methane, or CH_4; carbon dioxide, or CO_2; hydrogen sulfide, or H_2S; temperature; pressure; and gas levels. Biogas originates from waste, mostly animal dung or food scraps, which undergo decomposition in digesters. Good monitoring helps to detect hazards such as leakage or improper gas mixtures. This will maintain the plants in a state of safety and proper functioning. This study verifies this prototype against fresh case studies from late 2023 to late 2025. It detects differences in design, building stages, outcomes, technological adoptions, sensor mounting, data connectivity options, and practical applications.

Overview of the Smart Biogas Monitoring System Prototype
The prototype SBMS uses a set of sensors coupled with the ESP32 chip, the brain behind it all. It contains integrated Wi-Fi and Bluetooth Low Energy, or BLE, for creating short-range links.

Methane gets measured by the MQ-4 sensor. This picks up CH_4 levels, which are very important to the fuel quality of the biogas. CO_2 uses MQ-135 or MG-811 sensors. These note the gas that can cut energy output. H_2S, a smelly toxic gas, comes from the MQ-136. It warns of corrosion risks. DHT22 handles temperature and humidity. Heat affects how fast bacteria work in the digester. BMP280 or MPX5700 sensors check pressure. Too much or too little pressure is a recipe for disaster. There's also an ultrasonic sensor to note slurry levels. Slurry refers to the thick mixture contained within. It also tracks gas buildup in the tank.

Sensors capture data every five seconds. Raw numbers are converted into understandable units, such as percent or PPM for parts per million. Data is transmitted wirelessly. Wi-Fi works for home digesters near the internet. LoRa or GSM fits far-off rural areas with weak signals. Data reaches cloud destinations like Firebase, MQTT installations, and Google Cloud IoT Core. Users will see it all in their phone app dashboard. The application displays live charts. It sends buzzers in case there is a gas leak, poisonous gas, strange pressure, or breakdowns. Manual safety valves open from the application. It can be used to serve small house units up to farm ones.

Comparative Analysis of Recent Case Studies There are several relevant points of comparison with the SBMS prototype offered by different researches, including Smart Metering and Remote Monitoring of Small-Scale Biogas Plants (Ntaganda et al., 2024), Monitoring biogas volume and pressure control (Hida et al., 2023), IoT-based monitoring for rural biogas plants (IJRPR Conference, 2025), Portable Internet of Things-Based Anaerobic Biogas Monitoring (Amalia et al., 2024), IoT-enabled analysis of domestic biogas use (Chaney et al., 2025), IoT monitoring of greenhouse gas emissions from livestock waste (Li et al., 2025), and ESP32-based gas detection for biogas systems (Al-Talib et al., 2024).
Recent work lets us stack the SBMS prototype against others. Each shares goals like better tracking and alerts, yet choices differ in sensors, the smart metering and remote monitoring of small-scale biogas plants by Ntaganda et al. in 2024; it targets metering for small plants just like SBMS homes. Volume and pressure control in monitoring biogas were tested by Hida et al. in 2023. SBMS adds gas mixes too. IoT-Based Monitoring for Rural Biogas Plants from the IJRPR Conference in 2025 suits remote areas. It matches LoRa SBMS usage. Portable IoT-Based Anaerobic Biogas Monitoring by Amalia et al., 2024 goes handheld, while the SBMS stays fixed but links wider. IoT-enabled analysis of domestic biogas use by Chaney et al. in 2025 checks home patterns; SBMS dashboards aid that. IoT monitoring of GHG from livestock waste by Li et al. is tracked in 2025. This is where SBMS sensors would also apply. ESP32-Based Gas Detection for Biogas Systems by Al-Talib et al. in 2024 also shares the ESP32 core. Both detect spot gases fast. These picks show the strong points of SBMS. It uses inexpensive sensors, flex links, and full alerts better in places.

Prototype Performance and Application Contexts Tests were run on a 2 cubic meter home digester. This size fits a family farm. SBMS nailed methane at 45 to 65 percent; that's prime for cooking fuel. CO_2 hit 20 to 35 percent, normal for balance. H_2S stayed at 10 to 50 PPM, safely under limits. The temperature read true within 0.5 degrees C. Pressure held 2 to 7 kPa steady. Slurry and gas levels matched eye checks.
Alerts kicked in fast for leaks, bad gases, or jumps in pressure. Data lagged less than 2 seconds, end to end. In rural tests, LoRa held signal over 1 km: no drops. Home Wi-Fi fed smooth app views. Users fixed issues quickly via phone controls. This proves SBMS works daily. It cuts waste and boosts output, saving lives from blasts.

Future Directions
SBMS can become intelligent. AI models predict biogas yield based on previous data. Trends identify low output early. LoRaWAN spreads the nets wider for groups of plants. Solar kits power it off-grid; no plugs are needed in fields. Machine learning hunts odd patterns and flags faults before they fail. Add checks on gas cleanup—pure fuel sells better or burns clean.

Conclusion

This review proves the prototype Smart Biogas Monitoring System stands out. It packs multi-gas sensors, pressure fixes, and cloud alerts in one pack. Flex comms fit any spot. Recent studies show gaps SBMS fills. Like more gases or rural reach. It pushes biogas tech ahead in safe green energy.

V. ENVIRONMENTAL, ECONOMIC & SUSTAINABILITY ASPECTS

Environmental Benefits and Motivation

The use of smart IoT and AI-based biogas monitoring systems tackles important environmental issues related to managing organic waste and generating renewable energy. Biogas production through anaerobic digestion has a twofold environmental benefit: it reduces greenhouse gas (GHG) emissions and generates renewable energy from organic waste. Methane (CH_4), a greenhouse gas with a warming potential 28-36 times that of carbon dioxide over a century, is captured and used for energy instead of being released into the air during traditional waste disposal. This system significantly lowers the carbon footprint of waste management, supporting climate change efforts aligned with global sustainability goals.

The waste-to-energy approach in biogas systems turns environmental problems into valuable energy sources. Organic materials, such as agricultural waste, livestock manure, food scraps, and municipal organic waste that would otherwise fill landfills and harm the environment, are converted into clean energy and nutrient-rich digestate for farming. This circular method of using resources showcases sustainable waste management, decreasing reliance on fossil fuels while tackling the growing issue of organic waste disposal in both cities and rural areas.

Resource Management and Circular Economy Integration

Biogas production facilities play an important role in circular economy systems, acting as key sites that turn various organic waste streams into renewable energy and useful by-products. Merging agricultural waste, such as crop leftovers and animal manure, along with food waste from homes and businesses into biogas systems illustrates principles of resource cycling and waste reuse. This approach diversifies the available materials and enhances nutrient recycling, as the produced digestate includes important nutrients (nitrogen, phosphorus, potassium) that can be returned to farming as bio- fertilizer. This reduces the need for synthetic fertilizers and their environmental impacts.

Real-time IoT monitoring is vital for maintaining stable anaerobic digestion and maximizing feedstock efficiency. Constant sensor monitoring helps identify problems like organic overloads, nutrient imbalances, or harmful compound build-up early, allowing for quick fixes. AI can analyze both historical and real- time data to suggest the best feeding schedules, mixing ratios, and retention times. This maximizes biogas yield per unit of feedstock while keeping processes stable. This approach reduces feedstock waste, improves conversion rates, and enhances the sustainability of biogas production.

Economic Viability and Cost-Benefit Analysis

The economic feasibility of biogas production improves significantly with smart IoT and AI monitoring technologies. Predictive maintenance, powered by ongoing condition monitoring and machine learning, helps identify equipment wear, sensor drift, and potential system failures before they lead to costly issues. This proactive approach cuts down unexpected downtime, extends equipment life, and reduces emergency repair expenses, boosting overall system reliability and economic performance.

Automated alert systems within IoT platforms give operators real-time notifications about process issues, letting them respond quickly to any deviations from ideal conditions. This immediate feedback prevents failures that could lead to long recovery times, lost biogas output, and possible environmental violations. Reduced downtime, better process stability, and optimized biogas yields mean improved return on investment (ROI) for biogas facility operators.

AI-driven process control also offers significant economic benefits. Machine learning models, based on historical data, can find the best combinations of parameters to maximize methane production rates and biogas quality. Research shows that smart monitoring systems can increase biogas yields by 15- 30% compared to conventional manual methods while lowering energy use for heating and mixing. These efficiency gains enhance economic performance by boosting revenue from energy sales and cutting operating costs.

Scalability and Applicability in Developing Regions

Low-cost IoT monitoring solutions are vital for biogas deployment in rural and developing areas, where decentralized renewable energy systems are key for energy access, community growth, and environmental sustainability. Traditional advanced monitoring tools can be too expensive and difficult to maintain in resource-limited areas. However, new low-cost sensor technologies, open-source platforms, and cloud-based analytics have led to affordable monitoring systems for small-scale and community biogas operations.

The need for smart biogas monitoring systems is especially apparent in countries like India, where high agricultural waste production, large livestock numbers, and significant rural energy demands align with national goals for expanding renewable energy and addressing climate change. India's decentralized biogas program has set up millions of small digesters that could greatly benefit from affordable smart monitoring solutions that enhance performance and economic returns. Similar opportunities exist in Sub- Saharan Africa, Southeast Asia, and Latin America, where biogas technology can help solve energy poverty, waste management issues, and environmental problems simultaneously.

CONCLUSION

The environmental, economic, and sustainability aspects of smart IoT and AI biogas monitoring systems provide strong reasons for their widespread use. By improving methane capture, optimizing resource use within circular economy

models, enhancing economic viability through predictive maintenance and yield enhancement, and allowing scalable deployment in developing regions, these technologies are crucial for advancing sustainable energy systems. The combination of environmental needs, economic benefits, and accessible technology places intelligent biogas monitoring at the heart of global strategies for tackling climate change, managing waste, and promoting sustainable rural development.

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