



Biogas Production from College Canteen Waste Using IoT and AI/ML: A Sustainable Campus Energy Solution

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Abstract:- At present, India generates more than 60–70 million tonnes of municipal solid waste per year, out of which over 50% is biodegradable organic waste. The rapid increase in municipal solid waste in India has created serious environmental and health concerns. A large portion of this waste is biodegradable and remains underutilized. College canteens generate significant amounts of organic waste, which can be effectively converted into useful energy. Biogas technology offers a sustainable solution by transforming kitchen waste into renewable-fuel through anaerobic digestion. This study focuses on the use of canteen waste for biogas generation and highlights its potential to reduce landfill usage, decrease dependence on LPG, and minimize greenhouse gas emissions. The produced biogas mainly contains methane and carbon dioxide and can be used for cooking and heating purposes. Additionally, the leftover digestate can serve as an organic fertilizer, supporting sustainable practices. The integration of IoT-based sensors and AI/ML techniques enables real-time monitoring and optimization of the biogas production process. Smart biogas systems in educational institutions can improve efficiency, reduce pollution, and promote sustainable campus development.

Keywords: — Biogas, Kitchen Waste, College Canteen, Anaerobic Digestion, Waste-to-Energy, IoT, Machine Learning, Sustainable Campus.

I. Introduction

Kitchen waste is organic material possessing high calorific value and nutritive content for microbes, which enables enhanced methane production efficiency by several orders of magnitude. This characteristic translates to reduced reactor size requirements, lower biogas production costs, and improved overall system efficiency. Despite these benefits, in most cities and urban areas, kitchen waste is disposed of in landfills or discarded improperly, creating significant public health hazards and contributing to the spread of diseases including malaria, cholera, and typhoid [1].

Inadequate waste management practices, particularly uncontrolled dumping, have several adverse environmental consequences. These include pollution of surface and groundwater through leachate formation, promotion of breeding grounds for flies, mosquitoes, rats, and other disease-bearing vectors, emission of unpleasant odors, and release of methane—a potent greenhouse gas contributing to global warming [2].



Biogas is a mixture composed primarily of methane (CH₄) at 55–60% concentration and carbon dioxide (CO₂) at 30–40%, along with trace amounts of other gases [1]. Anaerobic digestion, the microbial process underlying biogas production, involves the breakdown of an organic matter by microbiological activity in the absence of oxygen. Biomethane, the main combustible constituent of biogas, serves as a clean fuel characterized by its odorless nature and blue-burning flame, making it suitable for cooking and heating applications. Notably, 28 cubic meters of biogas is equivalent to one domestic LPG cylinder, and approximately 200 kg of organic waste can generate the equivalent of one LPG cylinder daily.

The integration of modern digital technologies with traditional biogas systems presents new opportunities for process optimization. IoT-enabled sensors facilitate continuous monitoring of critical parameters including temperature, pH, and gas pressure, while AI/ML algorithms can analyze historical data to predict optimal operating conditions and detect anomalies before they lead to system failure. This convergence of biotechnology and digital innovation forms the core contribution of the present review.

II. Biogas: Composition and Production Process

A. Biogas Composition

Biogas is generated under anaerobic conditions through microbial fermentation of organic matter. This technology represents an integral component of the biological geochemical carbon cycle and can be implemented in both rural and urban settings. Table I presents the typical composition of biogas.

TABLE I
COMPOSITION OF BIOGAS

Component	Concentration (by volume)
Methane (CH ₄)	55-60%
Carbon dioxide (CO ₂)	35-40%
Water (H ₂ O)	2-7%
Hydrogen sulphide (H ₂ S)	20-20,000 ppm (2%)
Ammonia (NH ₃)	0-0.05%
Nitrogen (N)	0-2%
Oxygen (O ₂)	0-2%
Hydrogen (H)	0-1%

B. Biogas Production Process

The biogas production process encompasses several sequential stages, from feedstock collection to final gas utilization:

Collection of Raw Materials: The initial step involves collecting organic waste serving as feedstock for biogas production. Suitable materials include kitchen waste, food waste, agricultural residues, manure, and sewage sludge.

Waste Pretreatment: This phase may involve crushing or grinding the waste to increase surface area and improve digestion efficiency. Large or bulky materials are broken down into smaller particles to enhance microbial accessibility.



Anaerobic Digester: The prepared waste is fed into an anaerobic digester—a closed tank or vessel where the fermentation process occurs. The digester maintains an oxygen-free environment essential for anaerobic bacterial activity.

Anaerobic Digestion: Within the digester, organic waste undergoes decomposition through complex biochemical reactions mediated by anaerobic bacteria. These microorganisms break organic matter, transforming it into biogas comprising primarily methane and carbon dioxide.

Retention Time: Waste remains in the digester for a specified duration called retention time, allowing sufficient opportunity for bacterial breakdown of organic matter and biogas production. Retention time varies according to feedstock characteristics and digester design.

Biogas Collection: Generated biogas rises to the top of the digester and is collected in gas storage vessels or containers. Efficient collection and storage systems are required for optimal gas utilization.

Biogas Utilization: Collected biogas can be employed in various applications including cooking, heating, and electricity generation. Alternatively, biogas can be upgraded by removing impurities, particularly carbon dioxide, to produce biomethane—a higher-quality gas suitable for injection into natural gas pipelines or use as vehicle fuel.

Digestate Management: The material remaining after fermentation, known as digestate, is rich in nutrients and can be utilized as organic fertilizer. Digestate is typically separated from the liquid phase and may undergo further treatment or composting before agricultural application.

Monitoring and Maintenance: Continuous monitoring of the biogas production process ensures optimal conditions and enables timely identification of potential issues. Regular maintenance of the digester and associated equipment maximizes production efficiency.

The specific details of the biogas production process vary depending on factors including digester type (e.g., continuously stirred tank reactor, plug flow reactor, or fixed dome digester) and feedstock characteristics.

C. Anaerobic Digestion Mechanism

Anaerobic digestion is a biochemical process wherein microorganisms break down complex organic matter into simpler by-products in the absence of oxygen. The process comprises four sequential stages:

1. Hydrolysis: As the initial step of anaerobic digestion, hydrolysis involves the breakdown of macromolecules into micromolecules. This stage encompasses conversion of organic polymers into monomers through enzymatic action mediated by hydrolytic bacteria. Macromolecules including polysaccharides, proteins, and complex fatty acids are converted into soluble sugars, amino acids, and simpler fatty acids respectively. Carbohydrates typically convert to sugars within hours, whereas proteins and lipids require several days for complete breakdown [12].

2. Acidogenesis: This stage involves formation of volatile fatty acids from substrates produced during hydrolysis. Sugars, amino acids, and fatty acids are converted into



short-chain organic acids, alcohols, hydrogen, and other intermediate compounds through fermentative bacterial activity.

3. Acetogenesis: Acetogenesis represents a fermentation process wherein volatile fatty acids are converted into acetic acid, carbon dioxide, and hydrogen by specific groups of acetogenic bacteria. These microorganisms play a crucial role in preparing substrates for the final methanogenic stage.

4. Methanogenesis: The final stage of anaerobic digestion produces methane as the primary end-product. Methanogenic archaea, specifically methanogens, are responsible for biomethane production under suitable environmental conditions. End-products from acetogenesis are converted into methane, carbon dioxide, and hydrogen. Optimal digestion requires pH maintenance between 5.5–8.5 and temperature control between 30–60°C [4]. During methanogenesis, reduction reactions between carbon dioxide and hydrogen contribute approximately one-third of total biomethane production.

III. Literature Review

Microbial Mechanisms and Process Fundamentals

Ray et al. [1] examined the microbial mechanisms involved in biogas production and emphasized that anaerobic digestion is a multi-stage biochemical process involving hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Their study highlighted that cooperative action among different anaerobic bacterial groups is essential for stable biogas production. Optimal performance was achieved under mesophilic conditions with temperatures ranging from 25°C to 45°C, pH close to neutral (6.5–7.5), and sufficient moisture content. The study also reported that improper control of these parameters leads to reduced methane yield and process instability.

Kitchen Waste as Feedstock

Umapathy et al. [2] conducted experimental investigations using kitchen waste collected from a college canteen. Their laboratory-scale experiments compared biogas production from cow dung alone and mixtures of cow dung with kitchen waste. The results demonstrated that addition of kitchen waste significantly increased biogas yield due to its higher volatile solids content. The produced biogas burned with a stable blue flame, confirming adequate methane concentration and fuel quality.

Pathak et al. [3] presented a comprehensive review on biomethane production from kitchen waste and identified key operational parameters influencing gas yield. The authors reported that kitchen waste has an optimal carbon-to-nitrogen ratio of approximately 25:1 and can produce around 0.3 m³ of biogas per kilogram of waste. The study emphasized the importance of particle size reduction through shredding or grinding, as smaller particle sizes enhance hydrolysis, reduce hydraulic retention time, and improve overall digestion efficiency. The review also highlighted that proper agitation prevents scum formation and improves microbial contact with the substrate.

Digester Design and Performance

Bouallagui et al. [4] and Rajendran et al. [5] investigated mesophilic anaerobic digestion of food and kitchen waste, reporting methane concentrations ranging from 55% to 60% in the produced biogas. Their studies confirmed that household- and institutional-scale biogas plants offer reliable solutions for decentralized energy generation while reducing dependence on fossil fuels. These systems were found to be particularly suitable for hostels, colleges, and community kitchens.



Research published in IJRSET [10] highlighted that kitchen waste contains high calorific value and provides essential nutrients for microbial growth. The studies emphasized the need for maintaining alkalinity and pH stability to prevent acidification of the digester. The digestate obtained after anaerobic digestion was reported to be rich in nitrogen, phosphorus, and potassium, making it suitable for use as organic fertilizer and supporting sustainable agricultural practices.

Institutional Applications

Ingle [6] developed and designed a biogas plant specifically for treatment of kitchen waste, providing design parameters and operational guidelines for institutional-scale implementation. Ziauddin and R. [7] conducted production and analysis studies on biogas from kitchen waste, confirming its suitability as a renewable energy source for cooking applications.

Babu et al. [8] presented a comprehensive design methodology for biogas plants targeting college canteen applications, considering factors including waste generation rates, digester sizing, and gas utilization patterns. Orhororo et al. [9] designed a bio-waste grinding machine specifically for anaerobic digestion systems, addressing the critical pretreatment requirement for particle size reduction.

Dinde et al. [11] recently investigated biogas production from kitchen waste generated in educational institutions, providing updated performance data and economic analysis. Their study confirmed that institutional biogas plants demonstrate favorable payback periods and significant environmental benefits.

Integration of Digital Technologies

Recent advances in IoT and AI/ML technologies have opened new possibilities for biogas system optimization. Continuous monitoring of parameters including temperature, pH, and gas pressure enables real-time process control and early detection of operational issues. Machine learning algorithms can analyze historical sensor data to identify patterns, predict optimal operating conditions, and forecast potential system failures before they occur.

The application of AI/ML techniques to biogas production represents an emerging research area with significant potential for improving system efficiency, stability, and automation. Predictive models trained on operational data can optimize feeding schedules, temperature control, and pH adjustment, while anomaly detection algorithms can identify deviations from normal operating conditions that may indicate impending process instability.

Table II summarizes key contributions from the reviewed literature.

Table Ii Summary Of Literature Review On Biogas Production From Kitchen Waste

Author & Year	Focus Area	Key Contribution
Ray et al. (2016)	Microbial Mechanisms	Identified optimal operating parameters (25-45°C, pH 6.5- 7.5) for stable biogas production
Umaphathy et al. (2015)	Feedstock Analysis	Demonstrated increased biogas yield with kitchen waste-

		cow dung mixtures
Pathak et al. (2022)	Process Optimization	Reported optimal C:N ratio (25:1) and biogas yield (0.3 m ³ /kg) for kitchen waste
Bouallagui et al. (2003)	Digester Design	Confirmed methane concentration (55-60%) in mesophilic digestion
Rajendran et al. (2012)	Household Systems	Reviewed small-scale digester designs for decentralized applications
Babu et al. (2018)	Institutional Design	Provided design methodology for college canteen biogas plants
Dinde et al. (2024)	Educational Institutions	Updated performance data and economic analysis for campus installations

Despite the substantial body of research on biogas production from kitchen waste, several gaps remain:

- Limited IoT Integration: Most existing studies rely on manual monitoring and offline data collection, with limited

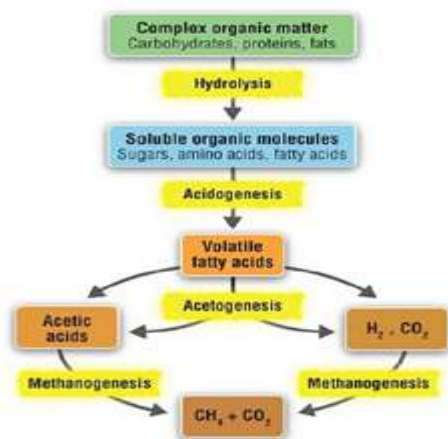


Figure 1: Flow chart of an aerobic digestion |

- Implementation of real-time sensor networks for continuous process monitoring.
- **Absence of AI/ML Applications:** The application of machine learning techniques for predictive optimization of biogas production remains largely unexplored in the context of small-scale institutional digesters.
- **Automated Control Systems:** Few studies have addressed the development of closed-loop control systems that automatically adjust operating parameters based on real-time sensor data.
- **Predictive Maintenance:** Research on AI-based predictive maintenance for biogas systems is scarce, despite its potential to reduce downtime and improve system reliability.



- **Integration with Campus Energy Systems:** Limited attention has been paid to the integration of biogas systems with overall campus energy infrastructure and smart grid concepts.
- The present review addresses these gaps by synthesizing knowledge from both biogas research and digital technology domains, providing a foundation for the development of smart, IoT-enabled biogas systems enhanced by AI/ML analytics.

IV. Objectives

Based on the identified research gaps, this review establishes the following objectives:

- To study and understand the anaerobic digestion process involved in biogas production from kitchen waste, establishing the biochemical and microbiological foundations necessary for process optimization.
- To analyze the suitability of kitchen waste as a feedstock for biogas generation based on its physicochemical characteristics, including carbon-to-nitrogen ratio, volatile solids content, and nutrient profile.
- To evaluate the effect of operational parameters such as temperature, pH, particle size, dilution ratio, and retention time on biogas yield, synthesizing findings from experimental studies to identify optimal operating ranges.
- To assess the feasibility of replacing conventional fuels such as LPG with biogas for cooking applications in institutional settings, considering both technical performance and economic viability.
- To examine the environmental benefits of biogas production, including reduction of organic waste disposal, mitigation of greenhouse gas emissions, and contribution to circular economy principles.
- To explore the integration of IoT-based monitoring systems and AI/ML analytical techniques for real-time process optimization, predictive control, and early warning detection in biogas plants.
- To propose a conceptual framework for smart biogas systems combining anaerobic digestion technology with digital monitoring and control infrastructure suitable for college campus implementation.

V. Methodology For Smart Biogas System Implementation

This section presents a methodology for implementing IoT-enhanced biogas systems with AI/ML-based optimization, synthesizing findings from the reviewed literature with emerging digital technology applications.

A. System Architecture

The proposed smart biogas system architecture comprises three interconnected layers:

- **Physical Layer:** The physical layer includes the anaerobic digester, feedstock preparation equipment, gas storage system, and utilization appliances. Digester design follows established parameters from the literature [6], [8], with sizing based on daily waste generation rates from the target institution.
- **Sensing and Control Layer:** IoT sensors continuously monitor critical parameters:
 - Temperature sensors (thermocouples or RTDs) placed at multiple points within the digester
 - pH sensors for monitoring digester chemistry
 - Pressure sensors for gas accumulation measurement



- Gas composition sensors (methane, CO₂, H₂S concentrations)
- Flow meters for feedstock input and gas output quantification
- These sensors interface with microcontrollers or programmable logic controllers (PLCs) that perform data acquisition and initial signal processing. Actuators including valves, pumps, and heating elements enable automated control based on sensor feedback.
- Analytics and Application Layer: Sensor data transmitted to a central server or cloud platform enables advanced analytics including:
 - Real-time visualization and alerting
 - Historical data storage and trend analysis
 - Machine learning model training and deployment
 - Predictive optimization and control recommendations

B. Data Collection and Monitoring Protocol

Continuous data collection forms the foundation for AI/ML applications. Key parameters and recommended monitoring frequencies include:

TABLE III RECOMMENDED MONITORING PARAMETERS FOR SMART BIOGAS SYSTEMS

Parameter	Monitoring Frequency	Optimal Range
Digester Temperature	Continuous	35-40°C (mesophilic)
pH	Hourly	6.8-7.5
Gas Pressure	Continuous	5-15 mbar
Methane Concentration	Daily	≥55%
Feedstock Volume	Per feeding	Based on design
Gas Production Rate	Continuous	0.2-0.4 m ³ /kg VS
Ambient Temperature	Hourly	-

C. AI/ML Model Development Framework

The development of AI/ML models for biogas optimization follows a systematic process:

1. Data Preprocessing: Raw sensor data requires cleaning, normalization, and handling of missing values. Time-series alignment ensures consistent temporal resolution across parameters.
2. Feature Engineering: Relevant features for model development include:
 - Current and historical values of monitored parameters
 - Rolling averages and trends
 - Time-based features (hour of day, day of week, season)
 - Derived variables (C:N ratio estimates, volatile solids loading)
3. Model Selection and Training: Appropriate machine learning techniques for biogas applications include:
 - Regression Models: Predicting biogas yield based on operating parameters
 - Classification Models: Identifying normal vs. abnormal operating conditions
 - Time Series Forecasting: Predicting future gas production and parameter trends
 - Anomaly Detection: Identifying deviations indicating potential process instability
 - Reinforcement Learning: Optimizing control actions (feeding, heating, mixing) to maximize gas production



Model Evaluation and Deployment: Models are evaluated using appropriate metrics (RMSE for regression, accuracy/F1 for classification) and deployed for real-time inference. Continuous monitoring of model performance enables retraining and refinement as additional data become available.

Implementation Workflow

The step-by-step implementation workflow for a smart biogas system in a college campus includes:

- **Feasibility Assessment:** Quantify daily canteen waste generation, assess available space, determine energy requirements, and evaluate economic viability.
- **System Design:** Size digester based on waste volume (typical retention time 30-40 days), select appropriate digester type (fixed dome, floating drum, or plug flow), design feedstock preparation area, and specify IoT sensor and control hardware.
- **Installation and Commissioning:** Construct digester, install sensors and control systems, establish data communication infrastructure, and commission with initial feedstock and inoculum.
- **Data Collection and Baseline Establishment:** Collect baseline operational data for minimum 2-3 months to establish normal operating patterns and variability.
- **Model Development:** Develop and train AI/ML models using collected data, validate model performance, and refine as needed.
- **Deployment and Optimization:** Deploy models for real-time prediction and control, continuously monitor performance, and implement closed-loop optimization.
- **Evaluation and Scaling:** Assess system performance against objectives, document lessons learned, and plan for scaling or replication.

Expected Outcomes and Performance Indicators

Implementation of smart biogas systems with IoT and AI/ML integration is expected to yield:

- **Increased Biogas Yield:** 15-25% improvement through optimized parameter control
- **Enhanced Stability:** Reduced process upsets and faster recovery from disturbances
- **Reduced Manual Intervention:** Automated monitoring and control minimizing labor requirements
- **Predictive Maintenance:** Early warning of equipment issues before failure
- **Data-Driven Optimization:** Continuous improvement based on accumulated operational data
- **Educational Value:** Real-time data for student projects and research

VI. Conclusion

The present review demonstrates that kitchen waste can be effectively utilized for biogas production, offering a sustainable solution for organic waste management and renewable energy generation in institutional settings. The reviewed literature establishes that biogas systems show stable performance and produce usable gas suitable for cooking applications, indicating their potential to partially replace conventional fuels such as LPG in college canteens.

Key findings from the literature include:

- Optimal biogas production from kitchen waste occurs under mesophilic conditions (35-40°C) with pH maintained between 6.8-7.5 [1], [4].



- Kitchen waste exhibits favorable characteristics for anaerobic digestion including high volatile solids content and appropriate carbon-to-nitrogen ratio of approximately 25:1 [3].
- Methane concentrations in biogas from kitchen waste typically range from 55-60%, confirming suitability as a fuel for cooking applications [2], [4].
- Institutional biogas plants demonstrate economic viability with favorable payback periods when considering fuel savings and reduced waste disposal costs [8], [11].
- Digestate produced during anaerobic digestion serves as nutrient-rich organic fertilizer, supporting circular economy principles and reducing dependence on chemical fertilizers [10].

The integration of IoT-based monitoring enables continuous observation of key operating parameters such as temperature, pH, and gas pressure, thereby improving process control and reducing the need for manual intervention. Real-time sensor networks provide the data infrastructure necessary for advanced analytics and automation.

The application of AI/ML techniques for data analysis offers significant potential for identifying trends, understanding parameter interactions, predicting optimal operating conditions, and detecting anomalies before they lead to process failure. Machine learning models trained on historical operational data can provide decision support for operators and enable gradual automation of routine control tasks.

Overall, the reviewed evidence confirms that biogas production from college canteen waste is technically feasible, environmentally beneficial, and suitable for institutional implementation. The integration of smart technologies including IoT sensors and AI/ML analytics represents a promising direction for enhancing system performance, reliability, and automation. This convergence of traditional biotechnology with modern digital tools supports the development of sustainable campus energy solutions while providing educational opportunities for students and contributing to institutional sustainability goals.

VII. Future Scope

Based on the identified research gaps and emerging technological opportunities, several directions for future work are identified:

- **Development of Specialized Low-Cost Sensors:** Research into affordable, robust sensors specifically designed for biogas monitoring applications would reduce implementation costs and improve accessibility for educational institutions with limited budgets.
- **Advanced AI/ML Model Development:** Exploration of deep learning architectures including Long Short-Term Memory (LSTM) networks and Transformer models for time-series prediction of biogas production and early warning of process instability.
- **Closed-Loop Control Systems:** Development and validation of automated control systems that adjust feeding rates, mixing intervals, and temperature regulation based on real-time sensor data and AI predictions.
- **Integration with Campus Energy Management:** Research on integrating biogas systems with broader campus energy infrastructure including smart grids, energy storage, and demand-response systems.



- Life Cycle Assessment: Comprehensive life cycle analysis comparing environmental impacts of smart biogas systems with conventional waste management and energy supply approaches.
- Scale-Up Studies: Investigation of optimal designs and control strategies for larger installations serving multiple institutions or community-scale applications.
- Student Engagement Platforms: Development of educational interfaces and curricula leveraging real-time biogas data for hands-on learning in engineering, environmental science, and data science programs.
- Policy and Regulatory Frameworks: Research on policy mechanisms and regulatory approaches that would incentivize adoption of smart biogas systems in educational institutions across India.

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