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Research Article

Development of an IoT-Enabled Hybrid Bioreactor from Kitchen Waste and Bagasse for Decentralised Green Hydrogen Production

Suyash Meena, Preenon Bagchi*

Department of Bioinformatics, School of Life and Basic Sciences, Jaipur National University, Jaipur, Rajasthan, INDIA.

ABSTRACT

Background: Fossil fuel dependency and the growing burden of organic waste disposal present urgent challenges, particularly in developing nations where decentralised energy solutions are most needed. **Objectives:** This study describes the concept and preliminary proof-of-concept development of a low-cost, IoT-enabled hybrid bioreactor intended to convert kitchen waste and sugarcane bagasse into green hydrogen through anaerobic dark fermentation and thermochemical gasification. **Materials and Methods:** The work began with the construction of a glass model reactor, which allowed direct visual observation of fermentation activity. Kitchen waste and bagasse were mixed into a slurry and subjected to anaerobic conditions; maintaining stable temperature and pH proved difficult without automated controls, but visible gas bubble formation was observed between 16 and 36 hours after loading. **Results:** A flame test on the collected gas produced a pale blue flame, providing initial qualitative confirmation of hydrogen generation. **Conclusion:** Based on these prototype observations and relevant literature, a stainless-steel reactor design (Grade 316L, 10-litre working capacity) was proposed, incorporating a sensor suite -including DS18B20 temperature probes, industrial pH electrodes, piezo-resistive pressure transducers, and MQ-8 hydrogen sensors -coordinated by an ESP32 microcontroller with cloud-based data transmission via Thing Speak. Projected operational estimates for co-processing approximately 2 kg kitchen waste and 1.5 kg bagasse over a 48-hr cycle suggest a hydrogen production rate of around 0.7 L/hour, yielding roughly 19.2 L per kilogram of total waste input under stable mesophilic conditions (pH 6.8-7.2; 35-45ºC). The modular system architecture is designed for scalable deployment from households to community level. This article presents the prototype findings, proposed system design, and estimated performance data alongside a review of the relevant literature.

Keywords: Biohydrogen, Dark Fermentation, Decentralised Energy, ESP32, Flame Test. Glass Prototype, Hybrid Bioreactor, Iot Monitoring, Kitchen Waste, Sugarcane Bagasse.

Correspondence:
Dr. Preenon Bagchi
Associate Professor, Department of Bioinformatics, School of Life and Basic Sciences, Jaipur National University, Jaipur-302017, Rajasthan, INDIA.
Email: prithish.bagchi@gmail.com

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INTRODUCTION

The global energy sector is under pressure to transition away from fossil fuels, and hydrogen has attracted considerable interest as an alternative owing to its high energy density and clean combustion -when used in fuel cells, water is the only by-product (IEA, 2019). Conventional hydrogen production via steam methane reforming, while commercially mature, carries substantial carbon dioxide emissions and relies heavily on non-renewable natural gas reserves (Gupta and Basile, 2020). This has prompted growing interest in biological and thermochemical routes to hydrogen generation from waste biomass.

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In India, two particularly abundant and underutilised feedstocks are kitchen waste and sugarcane bagasse. Kitchen waste from households and canteens is rich in carbohydrates, proteins, and lipids that can be converted anaerobically by microbial communities. Bagasse -the fibrous residue left after sugarcane juice extraction -has high lignocellulosic content and calorific value. The Central Pollution Control Board (CPCB, 2021) estimates that India generates around 62 million tonnes of municipal solid waste annually, with 50-60% being organic matter, while the Indian sugar industry produces approximately 100 million tonnes of bagasse per year (ISMA, 2020) much of which remains poorly utilised.

Rural energy access is another pressing concern. The IEA (2022) reports that nearly 24 million rural households in India still lack reliable electricity, and over 40% depend on biomass or kerosene for cooking. Decentralised, locally adaptable clean energy solutions are therefore urgently needed -and hydrogen produced from local waste streams can directly address this need, while also reducing solid waste burdens. This aligns with the circular economy framework and with SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production).

Integrating Internet of Things (IoT) technology into biomass-to-energy systems adds a practically important dimension. Continuous sensor-based monitoring of temperature, pH, pressure, and gas composition allows automated process control and remote oversight -capabilities that are especially valuable in community-level installations where dedicated technical staff may not be available (Patil *et al*., 2022; Jain and Agarwal, 2021). Cloud-connected dashboards make such systems accessible even to non-expert operators.

This paper describes the development process starting from a glass reactor prototype used for initial observations, through to the proposed design of an IoT-enabled hybrid bioreactor coupling dark fermentation of kitchen waste with thermochemical gasification of bagasse. The primary aim is to demonstrate the feasibility of this integrated concept as a low-cost, community-scale green hydrogen production approach suitable for rural and semi-urban Indian settings.

REVIEW OF LITERATURE

Hydrogen Production from Organic Waste via Dark Fermentation

Dark fermentation has become a well-established biological route for hydrogen generation from organic feedstocks including food scraps and kitchen waste. Microbial communities -particularly Clostridium butyricum and Enterobacter aerogenes -can convert carbohydrates to hydrogen under strictly anaerobic conditions (Kapdan and Kargi, 2006). Key factors influencing yield include inoculum-to-substrate ratio, operating temperature (typically 30-37°C), and pH (5.5-6.5) (Li *et al*., 2007; Zhang *et al*., 2011). Feedstock pretreatment and solid retention time also affect efficiency (Prakash *et al*., 2012; Lee *et al*., 2018), and carbohydrate-rich substrates such as fruit and vegetable waste tend to outperform protein- or lipid-heavy slurries in terms of hydrogen output (Liu *et al*., 2013; Das and Veziroğlu, 2008).

Hydrogen Generation from Bagasse via Thermochemical Processes

Bagasse, with its high lignocellulosic content and calorific value, is well-suited for thermochemical hydrogen production. Gasification under oxygen-limited conditions at 600-900°C yields syngas containing 40-60% hydrogen, particularly when nickel-based catalysts are used (Lu *et al*., 2019; Khodakov *et al*., 2025). Hydrothermal carbonisation and supercritical water gasification have also shown promise for wet bagasse pulp, reducing the need for energy-intensive drying (Henriques *et al*., 2020; Zhou *et al*., 2021).

Hybrid Bio-Thermochemical Systems

Combining dark fermentation with downstream gasification of residual organic material has attracted growing research interest. Such hybrid approaches pair the selectivity of biological fermentation with the broad substrate conversion capability of thermochemical processing, improving overall hydrogen yields and minimising waste residue (Liu *et al*., 2015; Dagar *et al*., 2019). Bioelectrochemical systems can further augment hydrogen production by applying external potential to drive otherwise unfavourable reactions (Gupta *et al*., 2020; Hernández *et al*., 2024).

IoT Integration in Biomass-to-Energy Systems

IoT-enabled monitoring of biomass conversion systems has grown steadily, driven by the need for precise automated process control. Sensor networks tracking temperature, pH, hydrogen concentration, CO_2, CH_4, and pressure support real-time adaptive control (Patil *et al*., 2022; Jain and Agarwal, 2021). Cloud connectivity via platforms such as Thing Speak or Firebase enables predictive maintenance and continuous performance visualisation (Chaudhary *et al*., 2023; Roy *et al*., 2022). Safety features including leak detection and threshold-triggered shutdowns have been shown to be critical for small-scale decentralised installations (Singh and Kumar, 2021; Rana *et al*., 2023).

Decentralised and Community-Level Applications

Decentralised hydrogen systems are increasingly recommended for rural and peri-urban settings lacking centralised energy infrastructure. Pilot projects in India have shown social feasibility when user-friendly design and community engagement are prioritised (Pandey *et al*., 2020; Mehta *et al*., 2022). Life cycle assessment studies confirm significant environmental benefits, with greenhouse gas reductions of up to 70% compared to landfill disposal or grid-connected thermal generation (Shinde *et al*., 2021; Kumar *et al*., 2023).

MATERIALS AND METHODS

The methodology followed a staged approach -beginning with hands-on prototype construction and observation, and progressing to the design of a fully instrumented IoT-enabled system. Each stage informed the next, with practical observations from the initial prototype directly shaping the proposed design.

Waste Collection and Preprocessing

Feedstock was collected from two sources: kitchen waste from households and institutional canteens, and sugarcane bagasse from nearby sugar mills and local vendors. Kitchen waste was manually sorted to remove non-biodegradable items such as plastic and metal before processing. Both feedstocks were shredded and pulped to produce a reasonably homogeneous slurry with approximately 15-20% total solids. Particle size was kept below 5 mm to promote consistent fermentation, and moisture content was measured using a moisture analyser (Li *et al*., 2007; Dagar *et al*., 2019). Proximate and ultimate analyses -including volatile solids content, carbon-to-nitrogen ratio, and calorific value -were carried out in triplicate for each feedstock batch.

Reactor Design

The first step was building a glass model reactor, which was chosen specifically to allow direct visual observation of what was happening inside the system during fermentation. The transparent walls made it easy to watch for bubble formation and track the general behaviour of the slurry over time. Observations from this prototype -including when and where bubbles appeared and how the slurry behaved under anaerobic conditions -formed the basis for proposing the scaled-up stainless steel reactor design.

The proposed reactor uses corrosion-resistant Grade 316L stainless steel with a 10-20 litre working volume, incorporating a mixing impeller for slurry homogenisation, a thermostatic heating jacket for temperature regulation, and integrated sampling ports with a gas collection unit. A complementary gasifier module for bagasse processing at 5-10 kg/hour is also proposed, featuring a fixed-bed reaction zone, Ni-based catalyst bed, controlled air inlet for oxygen limitation, and a char removal system with thermal insulation (Lu *et al*., 2019). The modular design allows either unit to operate independently or in tandem depending on feedstock availability.

IoT Sensor Integration

Based on the limitations observed during manual monitoring of the glass prototype -particularly the difficulty of maintaining stable temperature and pH in the slurry -a comprehensive sensor array is proposed for the stainless-steel reactor. This includes DS18B20 digital sensors and PT100 probes for temperature (±0.5°C accuracy), industrial pH probes for continuous fermentation monitoring, piezo-resistive pressure sensors (±1 kPa) at the reactor outlet, and MQ-8 hydrogen gas sensors for headspace concentration measurement. Capacitive moisture and ultrasonic level sensors are planned for slurry volume monitoring. All sensor outputs would relay to an ESP32 microcontroller for data acquisition via MQTT and HTTP protocols at 5 min intervals, with wireless transmission to cloud services for storage and analysis.

Cloud Connectivity and Dashboard

Sensor data are planned to be streamed to a Thing Speak cloud platform, with each parameter mapped to an individual channel and displayed as time-series graphs. A web-based dashboard and companion mobile interface are being developed using ReactJS and Flutter, providing real-time visualisation, historical trend analysis, yield forecasting, and automated alert notifications. Data security is intended to be maintained through user authentication, SSL/TLS encryption, and role-based access control.

Automation and Safety Mechanisms

Relay-driven actuators are proposed to manage heating elements, the mixing motor, and safety valves based on real-time sensor readings. Hydrogen leak detectors would be positioned near the reactor enclosure with a safety threshold of 2% H_2 in air. If critical parameters are breached -pressure exceeding 1.5 bar, temperature above 45°C, or pH outside the 5-7 range -the system is designed to trigger immediate SMS, email, and application notifications. Violations persisting beyond two consecutive minutes would initiate an automatic emergency shutdown, isolating the reactor and disabling the heating circuit.

Testing and Optimisation

Laboratory trials with the glass prototype assessed system behaviour across varying feedstock ratios: pure kitchen slurry, pure bagasse slurry, and blended mixtures (70:30 and 50:50). The parameter space explored included temperatures of 30, 35, and 37°C; pH values of 5.5, 6.0, and 6.5; and different feed particle sizes and bagasse blending ratios. Performance metrics of interest include hydrogen yield per gram of volatile solids, volumetric production rate, and yield reproducibility across replicates. Response surface methodology and ANOVA are planned for statistical optimisation once the full sensor-equipped system is operational.

Scale-Up and Pilot Deployment

Following laboratory validation, pilot deployment is planned at two sites: a rural community kitchen and an institutional mess hall, each for a three-month continuous operational period with ongoing data logging and operator feedback collection. Design iterations informed by practical operational insights are expected to improve usability, yield consistency, and mechanical robustness.

Techno-Economic and Environmental Assessment

A cost analysis estimating equipment, consumable, and operation-and-maintenance expenditures is planned to provide per-unit and per-kilogram hydrogen cost estimates. Life cycle assessment will be conducted in accordance with ISO 14040/44 standards, comparing greenhouse gas savings against baseline disposal scenarios including landfilling and incineration. Break-even analysis will identify payback periods across different operational scales.

RESULTS AND DISCUSSION

Hydrogen Generation Performance

The earliest experimental work was carried out using a glass model reactor, which allowed straightforward visual observation of fermentation progress. Kitchen waste and sugarcane bagasse were mixed into a slurry and loaded under anaerobic conditions. Maintaining stable temperature and pH throughout the fermentation proved to be one of the more practical challenges at this stage -the heterogeneous nature of the slurry meant conditions would shift over time, and manual intervention was frequently needed.

Despite these difficulties, visible gas bubble formation was observed consistently between 16 and 36 hr after loading. To check whether the gas being produced was hydrogen, a simple flame test was conducted on the collected gas. The gas burned with the characteristic pale blue flame associated with hydrogen combustion, providing an initial qualitative confirmation that the fermentation process was generating hydrogen.

On the basis of these prototype observations and published fermentation kinetics, operational parameters and yield estimates for the proposed stainless steel reactor were projected. Co-processing approximately 2 kg of kitchen waste and 1.5 kg of bagasse over a 48-hr cycle under stable mesophilic conditions (pH 6.8-7.2; 35-45ºC) is estimated to yield an average hydrogen production rate of around 0.7 L/hour, or roughly 19.2 L per kilogram of total waste input. These projections are consistent with reported values for comparable dark fermentation systems operating on food and agro-industrial waste (Kapdan and Kargi, 2006; Wang *et al*., 2020). Comparative data are summarised in Table 1.

Sensor Performance and IoT Monitoring

The IoT monitoring framework -comprising the ESP32 microcontroller, Thing Speak cloud integration, and multi-sensor array -has been designed and configured on the basis of the prototype observations. Full sensor deployment and live data acquisition are planned for the next development phase once the stainless steel reactor is fabricated. Estimated energy consumption Figures for all powered device components under continuous operation are presented in Table 2.

Process Optimisation Insights

Working with the glass prototype made clear how sensitive the fermentation process is to temperature and pH fluctuations. Even modest drops in temperature slowed or disrupted bubble formation, and pH shifts appeared to reduce gas output noticeably. These direct observations reinforced the necessity of the automated control logic planned for the stainless steel reactor. In the proposed system, threshold-triggered heating and buffering protocols are expected to maintain mesophilic conditions without the need for constant manual adjustment -one of the main advantages of an IoT-enabled bioprocess over a manually monitored one (Patil *et al*., 2022; Kalamaras *et al*., 2025).

Comparison with Conventional Biogas Systems

Compared to traditional biogas digesters designed around methane output, the proposed IoT-enabled hydrogen system offers several meaningful advantages: a higher energy density output fuel, real-time process transparency through cloud dashboards, and automated responses to process deviations that improve consistency and reduce operational downtime (Singh and Kumar, 2021). The use of open-source hardware -including the ESP32 microcontroller and MQ-series sensors -combined with free-tier cloud services keeps capital costs substantially lower than proprietary control systems. A detailed comparison of the two system types is provided in Table 3.

Limitations and Pathways for Improvement

Several limitations of the current work are worth acknowledging openly. The yield Figures reported are projected estimates derived from glass prototype observations and literature benchmarks -they have not yet been directly validated using a

Table 1: Normalised Hydrogen Yield and Literature Comparison.

Metric	Value (Current Study)	Literature Values	Source
Total H_2 Produced	~67.2 L over 48 hr (estimated)	-	-
Avg. Production Rate	~0.7 L/hr (projected)	-	-
H_2 per kg total waste (3.5 kg)	~19.2 L/kg (estimated)	15-35 L/kg (food/agro waste)	Wang *et al*., 2020; Lin and Lay, 2004
H_2 per kg volatile solids (80%)	~24 L/kg VS (projected)	20-35 L/kg VS	Kapdan and Kargi, 2006; Wongthanate *et al*., 2014
H_2 per litre of reactor volume	~3.36 L/L reactor (estimated)	3.0-5.0 L/L reactor	Mu *et al*., 2007; Pan *et al*., 2008
Optimal Temperature Range	35-45ºC (target)	35-40ºC (mesophilic digestion)	Chou *et al*., 2008
pH Range for Optimal Activity	6.8-7.2 (target)	6.5-7.5	Lin and Lay, 2004
IoT Monitoring System	Proposed (ESP32 + Thing Speak)	Rare in small-scale digesters	Nanda *et al*., 2021

Table 2: Estimated Energy Consumption of Device Components.

Component	Specification	Power Rating	Daily Usage	Energy (Wh/day)	Remarks
Heater	100W immersion (thermostat-controlled)	100 W	6 hr	600	Maintain 35-40°C digester temp
Mixer (Agitator)	DC motor, 12V @ 0.8A	9.6 W	4 hr	38.4	Uniform slurry mixing
pH Sensor	Analog, continuous monitoring	30 mW	24 hr	0.72	Continuous pH monitoring
Temperature Sensor	DS18B20 Digital Sensor	3 mW	24 hr	0.072	Internal temperature tracking
Gas Pressure Sensor	BMP180 or MPX5010	5 mW	24 hr	0.12	Pressure tracking
Hydrogen Sensor	MQ-8 Gas Sensor	800 mW	4 hr	3.2	Intermittent sensing during production
Humidity Sensor	DHT22 Sensor	2.5 mW	24 hr	0.06	Monitors reactor air humidity
Slurry Volume Sensor	Ultrasonic HC-SR04	15 mW	1 hr	0.015	Periodic measurement
ESP32 Microcontroller	Dual-core WiFi MCU	240 mW	24 hr	5.76	Data acquisition and cloud comms

Table 3: Comparison of IoT-Enabled Hydrogen System with Traditional Biogas Digesters.

Parameter	Traditional Biogas Digester	IoT-Enabled Hydrogen System (Proposed)
Feedstock	Cow dung, kitchen/agricultural waste	Kitchen waste and sugarcane bagasse
Primary Output	Methane-rich biogas (50-70% CH_4)	Hydrogen gas (H_2)
By-products	Slurry (organic fertilizer)	Water vapour, char (if gasification used)
Initial Setup Cost	₹15,000-₹40,000 (household scale)	₹50,000-₹80,000 (with IoT setup)
Operational Cost	Low (manual monitoring)	Moderate (sensor maintenance, cloud)
Energy Yield	~5-6 MJ/m³ (biogas)	~12-14 MJ/m³ (hydrogen)
Conversion Efficiency	~30-35% in cookstoves/engines	~50-60% in fuel cells/modified burners
Automation and Monitoring	Minimal (manual operation)	Proposed real-time automated alerts
Scalability	Community and household levels	Modular: household to institutional scale
Environmental Impact	Moderate GHG reduction	High GHG reduction; cleaner combustion
Technical Skill Required	Low	Moderate (training needed for IoT features)

fully instrumented sensor-equipped system. The temperature and pH instability encountered during manual slurry fermentation highlights how dependent the process is on stable conditions, and reinforces why the automated sensor framework is a central part of the proposed design rather than an optional add-on. The MQ-8 hydrogen sensor is also known to drift during extended multi-day operation, requiring periodic recalibration (Aweenagua *et al.*, 2024). A comprehensive energy-yield balance accounting for heating and mixing demands has not yet been fully quantified and remains part of the planned techno-economic assessment.

DISCUSSION

The glass prototype provided practical proof-of-concept evidence for hydrogen generation from kitchen waste and bagasse under anaerobic conditions -the flame test confirming hydrogen in the collected gas was a meaningful milestone. These prototype observations, along with the challenges experienced in manual process control, shaped the specific design decisions behind the proposed stainless steel reactor and its IoT monitoring framework. The estimated performance Figures align with published benchmarks for early-stage dark fermentation prototypes and are expected to improve substantially with feedstock preprocessing, inoculum optimisation, and the automated process control enabled by the sensor network. A summary comparison is presented in Table 4.

Challenges for Rural Deployment

Before widespread rural deployment is feasible, several practical challenges need to be addressed. The initial setup cost, while favourable over a full lifecycle, is higher than conventional biogas

Table 4: Discussion Summary -Current Performance vs. Benchmark Targets.

Aspect	Current Performance / Status	Benchmark / Target
Hydrogen yield	~0.7 L/hr (~16-20 L/kg dry feed) -estimated from prototype	50-90 L/kg dry feed (optimised systems)
Operating conditions	pH 6.8-7.2; 35-45ºC (target for proposed reactor)	pH 5.5-6.5; 35-40ºC optimal (Kapdan and Kargi, 2006)
IoT monitoring	Designed and proposed; full deployment planned	≥95% sensor accuracy in published systems
Automated control	Proposed threshold-triggered logic	Full adaptive logic with predictive thresholds
Cost structure	Low-cost prototyping (<₹50,000)	Comparable minimal capital implementation

digesters and may require subsidies or micro-financing to enable community adoption. Operating IoT-enabled systems requires a baseline level of digital literacy, suggesting that structured training programmes for end users would be necessary. Cloud-based monitoring also depends on reliable internet connectivity, which can be intermittent in remote areas. Seasonal variation in bagasse availability could disrupt steady hydrogen production, making adequate storage and preprocessing capacity important to plan for. Finally, India's regulatory framework for decentralised hydrogen production is still evolving, and clear policy guidance and financial incentives will be needed to support scalable deployment.

CONCLUSION

This study presents the concept development and preliminary proof-of-concept for a low-cost, IoT-enabled hybrid bioreactor for green hydrogen production from kitchen waste and sugarcane bagasse. The work began with a glass model reactor built specifically to allow direct visual observation of the fermentation process. Bubble formation was observed consistently between 16 and 36 hr after loading the kitchen waste and bagasse slurry, and a flame test on the collected gas confirmed the presence of hydrogen. The practical difficulty of maintaining stable temperature and pH during manual slurry fermentation was a key observation from this stage, and directly motivated the automated sensor-and-control framework proposed for the scaled-up system.

Based on these prototype observations and established fermentation literature, projected performance estimates suggest the proposed stainless steel reactor -incorporating ESP32-based IoT monitoring and automated process control -could achieve approximately 19.2 L of hydrogen per kilogram of total waste input under stable mesophilic conditions over a 48-hr cycle. The modular, open-source hardware architecture is designed to be scalable from rural household to institutional deployment.

The next phases of this work will focus on fabricating the full stainless steel reactor, commissioning the sensor network, and experimentally validating the projected yield Figures. Long-term sensor reliability, feedstock preprocessing optimisation, and a comprehensive techno-economic and life cycle assessment are identified as key priorities. With continued technical development and appropriate policy support, this type of decentralised, waste-derived hydrogen production system has real potential to contribute to energy access and waste management goals in rural and semi-urban India, in alignment with the National Green Hydrogen Mission and broader net-zero commitments.

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ABBREVIATIONS

IoT: Internet of Things; **ESP32:** Espressif Systems Microcontroller (Dual-Core Wi-Fi/Bluetooth); **H_2:** Hydrogen Gas; **pH:** Potential of Hydrogen; **VS:** Volatile Solids; CH_4**:** Methane; **CO_2:** Carbon Dioxide; **ISR:** Inoculum-to-Substrate Ratio; **SRT:** Solid Retention Time; **MQTT:** Message Queuing Telemetry Transport; **LCA:** Life Cycle Assessment; **MSW:** Municipal Solid Waste; **SDG:** Sustainable Development Goal; **IEA:** International Energy Agency; **CPCB:** Central Pollution Control Board; **ISMA:** Indian Sugar Mills Association; **SMR:** Steam Methane Reforming; **RSM:** Response Surface Methodology; **ANOVA:** Analysis of Variance.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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