Research Article

Journal of Environmental Nanotechnology

BioDigestX: A Nano-enhanced and IoT-integrated Biosink System for Domestic Kitchen Waste-to-biogas Conversion

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Received: 10.02.2026 Accepted: 23.02.2026 Published: 30.03.2026

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ABSTRACT

The increased volume of domestic kitchen waste and the growing demand for clean cooking energy require efficient decentralised waste-to-energy solutions. Anaerobic digestion is a viable way to convert organic waste to biogas, but there is a tendency to view conventional domestic digesters as low-efficiency, unstable, and producing low-quality gas. In this paper, the proposed system is BioDigestX, a nano-enhanced, biosink-based, and IoT-integrated anaerobic digestion system to convert household kitchen waste into biogas. The system combines waste segregation on the source level with the help of a biosink, anaerobic digestion with the use of iron oxide (Fe_3O_4) nanoparticles, and real-time monitoring of system parameters, temperature, pH, gas pressure, flow rate, and methane concentration using IoT. To test the performance of the systems, two domestic-scale reactors were operated under mesophilic conditions, with one serving as a standard control and the other as a nano-enhanced reactor. It was found that the nano-enhanced reactor became stable within 7-9 days, compared to 12-14 days for the control reactor. Biogas production was raised by 22-28% to reach 0.42-0.48 m^3/day, with an average daily increase of 0.32-0.38 m^3/day to 0.42-0.48 m^3/day. The methane concentration increased to 62-68% in the nano-enhanced reactor, compared with 52-56% in the control system, and the carbon dioxide level decreased to 28-34%. The concentration of H_2S was minimized to 40-50%, dropped to 90-140 ppm. The increased quality of biogas favoured 1.5-2.0 hours of domestic cooking. The findings indicate that the combined application of environmental nanotechnology and IoT can significantly improve the performance of domestic anaerobic digestion. BioDigestX system is a sustainable, scalable, and reliable system used in managing decentralized waste in kitchens and the generation of clean energy that can be used to support the ideas of the circular economy and the low-carbon household energy program.

Keywords: Anaerobic digestion; Kitchen waste management; Iron oxide nanoparticles; Biogas enhancement; Internet of things.

1. INTRODUCTION

The rapid densification of urban centres and shifts in people's dietary habits have led to an increase in domestic kitchen waste, which currently accounts for a considerable portion of solid municipal waste (Abdella *et al.* 2022). In most developing and densely populated areas, household organic waste is usually disposed of with mixed solid waste, leading to uncontrolled decomposition, leachate generation, odour, and greenhouse gas emissions. (Selvaraj and Velvizhi, 2021; Adam *et al.* 2021). The inability of centralized waste management systems to effectively manage decentralized organic waste streams is usually the result of high transportation costs, the complexity of the operations, and low source segregation (Alam *et al.* 2022).

It is well known that Anaerobic Digestion (AD) is an eco-friendly technology used in the stabilization of organic waste and concomitant restoration of renewable energy in the form of biogas (Alao *et al.* 2022). The resulting biogas is mostly a mixture of methane and carbon dioxide and can be used directly as clean cooking fuel at the household level (Ambaye *et al.* 2023; Krishnan and Asaithambi, 2023; Krishnan and Asaithambi, 2024). Although anaerobic digestion has been successfully applied on industrial and community scales, biogas yield, unstable operation, and erratic gas quality are common problems in domestic-scale anaerobic digesters (Liu *et al.* 2024). These challenges have been largely attributed to varying feedstock composition, inadequate microbial activity, volatile fatty acid buildup, and a lack of real-time process monitoring and control (Liu *et al.* 2023).

Environmental nanotechnology has emerged in recent years as a promising approach to improve the performance of anaerobic digestion (Liu *et al.* 2019, Aswathi *et al.* 2022; Krishnan *et al.* 2026). A number of studies have shown that conductive and metal-based nanoparticles, especially iron oxide (Fe_3O_4) nanoparticles, can significantly improve biogas and methane production and yield (Maalouf and Mavropoulos, 2022; Bahrulolum *et al.* 2021). These nanoparticles mediate direct interspecies electron transfer (DIET) between syntrophic bacteria and

methanogenic archaea, thereby increasing the rates of biochemical pathways that mediate methanogenesis (Mishra *et al.* 2023; Baraketi and Khwaldia, 2024). Moreover, iron nanoparticles have also been suggested to improve buffering capacity, volatile fatty acid accumulation, and hydrogen sulfide (H_2S) concentration through in situ sulfide precipitation, thereby increasing overall biogas quality (Mustafa *et al.* 2022; Bhalerao *et al.* 2025; Krishnan *et al.* 2022).

In parallel with the development of nanotechnology, the introduction of Internet of Things (IoT)-based technology into environmental measurement systems has enabled continuous monitoring of biological processes and intelligent control (Nemmour *et al.* 2023; Selvaraj and Velvizhi, 2022). Sensors built with IoT will deliver real-time information on vital functional parameters such as temperature, pH, gaseous pressure, flow rate, and methane concentration, enabling prompt interventions to prevent system instability (Nepal *et al.* 2023; Selvaraj and Velvizhi, 2023). Most domestic biogas systems reported in the literature, however, do not have such monitoring infrastructure, resulting in low reliability and low user acceptability (Nukusheva *et al.* 2023; Dhanker *et al.* 2022).

Although each of the two technologies has made individual contributions to the field of nanoparticle-assisted anaerobic digestion and IoT-based monitoring, almost no research has addressed their joint utilization in a decentralized, household-level system combined with source-level waste sorting (Muangjai *et al.* 2022). Specifically, the combination of a biosink-based kitchen-waste collection system, nano-enhanced anaerobic digestion, and real-time monitoring *via* IoT has not been adequately studied in the domestic energy-recovery setting (Yin *et al.* 2020; Prabha and Selvaraj, 2025; Velvizhi *et al.* 2019).

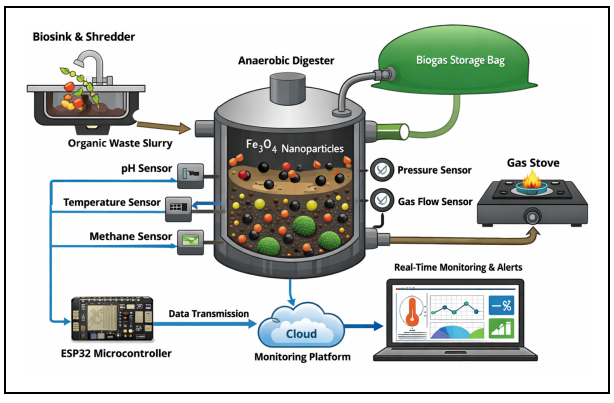


Fig. 1: IoT-Integrated nanoparticle-enhanced biogas reactor setup

To fill this research gap, the current study proposes BioDigestX, a new biosink-based, nano-enhanced, and IoT-integrated anaerobic digestion system that efficiently converts domestic kitchen waste into biogas. The system incorporates source-segregated waste collection, iron-oxide nanoparticle-aided digestion, and real-time monitoring and surveillance *via* IoT to increase biogas yield, methane concentration, and process stability. Decentralized management of organic waste through the production of biogas, the gas composition and operational stability, as well as its practical use in home cooking, are indicators of the system's performance and prospects as a sustainable and scalable method for decentralized management of organic waste and energy production.

2. MATERIALS AND METHODS

2.1 Experimental Design and System Configuration

The experimental research was designed to test the performance of a nano-enhanced, IoT-based domestic anaerobic digestion system (BioDigestX) for valorizing kitchen waste. The method taken was a comparative experiment by running two similar anaerobic digestion units under controlled conditions:

- **Control Reactor (CR):** An anaerobic digestion in the absence of nanoparticles.
- **Nano-enhanced Reactor (NER):** Iron oxide nanoparticles increase anaerobic digestion.

Both reactors mimic real-world household operating conditions and were fed with the same substrate compositions and loading rates. The comparative framework has enabled evaluation of the efficiency and stability of the nanoparticle-assisted digestion process, as well as the improvement in biogas quality during domestic-scale operation.

2.2 Materials and Chemicals

2.2.1 Kitchen Waste Feedstock

To ensure uniformity of feedstock, domestic kitchen waste was collected daily from one residential household with four to five members. The waste stream was mainly composed of biodegradable organic components, including vegetable waste, remnants of cooked foods, rice waste, and fruit skins. Plastics, metals, and bones are non-biodegradable materials that cannot be segregated at the point of generation in the biosink unit.

The collected waste was mechanically shredded into particles less than 10 mm and diluted with tap water at a 1:1 (w/v) ratio to produce a pumpable slurry. Reduction in size was performed to increase the effective surface area, thereby accelerating the hydrolysis rate and overall digestion efficiency.

2.2.2 Inoculum Preparation

To confirm the presence of active methanogenic consortia, the anaerobic composting bioreactor was inoculated with an anaerobic inoculum from a functioning domestic biogas plant. The collected sludge was sieved to remove inert matter and acclimatized to the kitchen waste feedstock over 7 days before the reactor start-up. During acclimatization, the inoculum was added slowly as organic loading rates increased to minimize shock loading and shorten the lag phase during reactor commissioning.

2.2.3 Digestion-enhancing Nanoparticles

Iron oxide (Fe_3O_4) nanoparticles were chosen because they are non-toxic, chemically stable, and electron-conductive. Such nanoparticles are important in supplementing anaerobic digestion by promoting DIET between methanogenic archaea and syntrophic bacteria.

The Fe_3O_4 nanoparticles used in this study had an average particle size of 20–40 nm and a purity greater than 98%, as specified by the manufacturer. The specific surface area was approximately 60–80 m^2/g, and the particles exhibited superparamagnetic behaviour. The working nanoparticle concentration in the reactor was maintained at 100 mg/L of reactor volume throughout the experimental period. Prior to use, the nanoparticles were characterized by scanning electron microscopy (SEM) for morphology, dynamic light scattering (DLS) for particle size distribution, and X-ray diffraction (XRD) for phase confirmation to ensure reproducibility and material consistency.

2.3 Biosink Design and Pre-treatment of Feedstock

The BioDigestX system used the biosink as the main waste collection unit and pre-treatment unit. It was specifically designed to allow segregation at the source level, so that only biodegradable organic waste entered the digestion system. To trap the particles of waste, the biosink was combined with a mechanical shredding system to tighten the particles and homogenize the feedstock.

The waste was shredded and mixed with water to produce a homogeneous slurry, which was then gravity-fed to the anaerobic reactor. This pretreatment process greatly enhanced accessibility of substrates and hydrolysis efficacy, which is, in most instances, a rate-limiting step in domestic anaerobic digestion systems.

2.4 Anaerobic Reactor Design and Construction

An anaerobic reactor was designed and built using this specific design method. The two anaerobic reactors were made with high-density polyethylene (HDPE) to make the device chemically resistant, durable, and gas impermeable. The reactors were geometrically cylindrical to allow equal stress distribution and fewer dead zones.

The effective working volume of each reactor was between 300 and 500 L, optimized for daily kitchen waste production within a typical nuclear family. The reactors were operated at mesophilic temperatures (30-37 °C) at atmospheric conditions found in the tropical climate.

In the reactors, the following was installed:

- Non-return valve and inlet of feed
- Gas outlet attached to a portable gas storage
- Digestate outlet slurry outlet
- Periodic analysis sampling ports.

For experimental comparison, two identical reactors were operated in parallel under identical environmental and feeding conditions. One reactor served as the control (without nanoparticles), while the second was designated the nano-enhanced reactor (with Fe_3O_4 nanoparticles). Both reactors were operated in semi-continuous mode with identical hydraulic retention time of 30 days and identical organic loading rate, ensuring that any performance variation could be attributed to nanoparticle addition. The experimental design followed a parallel configuration to evaluate enhancement efficiency.

2.5 Nanoparticle Dispersion and Incorporation Strategy

To ensure good contact between the nanoparticles and the microbial communities, the iron oxide nanoparticles were first dispersed in distilled water and subjected to ultrasonication to prevent agglomeration. The nanoparticle suspension was added to the nano-enhanced reactor at startup and sporadically during operation.

The incorporation strategy was developed to ensure that the nanoparticles have a homogeneous distribution in the reactor volume. Surprisingly, the presence of nanoparticles enhanced the system's performance by increasing microbial electron transfer pathways, decreasing volatile fatty acid production, and maintaining methanogenesis under varying loads.

2.6 IoT-Based Architecture of Instrumentation and Monitoring

IoT-based monitoring system was deployed to facilitate real-time, continuous evaluation of anaerobic digestion performance. The sensors were located

strategically to check the major parameters of the operations that affect the generation of biogas and the stability of the process:

- **Temperature Sensor:** To check the mesophilic conditions.
- **pH Sensor:** To monitor the balance of acidogenesis and methanogenesis.
- **Gas Pressure Sensor:** This is used to measure biogas buildup.
- **Gas Flow Sensor:** This is used to measure biogas generation taking place at a given time and that which accumulates.
- **Methane Sensor:** To ascertain the quality of biogas.

All the sensors were connected to an ESP32 microcontroller, which sent data wirelessly to a cloud-based platform. The system enabled real-time visualization, data recording, and automatic alerts when parameters exceeded optimal ranges, thereby avoiding process failures and enhancing operational reliability.

2.7 Reactor Maintenance and Supervision

The reactors were both run in a semi-continuous feeding mode for 60 days of the experiment. Feeding was done once a day with a pre-treated kitchen waste slurry. During the first start-up period, the organic loading rate was progressively raised in order to permit the acclimatization of the microbial performance and consistent reactor operation.

The IoT system was in place to monitor reactor performance, and real-time data were obtained on temperature, pH, biogas pressure, flow rate and methane concentration. To minimize changes in sensor feedback, adjustments, including changes in the dilution ratio and control of the feeding rate, were maintained at the optimum state of digestion.

The resulting biogas was stored in a flexible gas storage unit and fed directly to a domestic biogas stove, demonstrating real-time energy recycling under household operating conditions. Periodic manual measurements were performed to assess sensor accuracy and data reliability.

3. RESULTS AND DISCUSSION

3.1 Start-up and Stabilization Behaviour of Reactor

The control reactor and nano-enhanced reactor both had start-up periods during the initial period of operation. The control reactor reached stable biogas after 12-14 days, whereas the nano-enhanced reactor reached stable operation after 7-9 days.

Throughout the 60-day experimental period, all performance parameters were continuously monitored and averaged across three separate measurement intervals each week. The values shown in Table 1 are mean ranges gathered under consistent operating conditions for both reactors, providing a straightforward and controlled comparison between CR and NER.

Table 1 Comparative performance of control and nano-enhanced BioDigestX reactors

Parameter	Control Reactor (CR)	Nano-Enhanced Reactor (NER)	Improvement
Startup period (days)	12–14	7–9	↓ 35–40%
Average biogas yield (m^3/day)	0.32–0.38	0.42–0.48	↑ 22–28%
Cumulative biogas production (60 days)	Baseline	+22–28%	Significant
Methane (CH_4) content (%)	52–56	62–68	↑ 10–14%
Carbon dioxide (CO_2) (%)	38–42	28–34	↓ 8–12%
Hydrogen sulfide (H_2S) (ppm)	180–260	90–140	↓ 40–50%
pH range	6.4–7.1	6.8–7.4	Improved stability
Cooking duration (h/day)	1.0–1.2	1.5–2.0	↑ usability

Accelerated microbial acclimatization is seen in the decrease in start-up time of almost 35-40% in the NER, as shown in Table 1. This was supported by the existence of the iron oxide nanoparticles that resulted in increased syntrophic interactions through increasing the electron transfer mechanisms, which minimized the lag phase that is normally experienced during domestic anaerobic digestion systems.

Mechanistically, iron oxide nanoparticles serve as conductive bridges, facilitating direct interspecies electron transfer (DIET) between syntrophic bacteria and methanogenic archaea. Rather than relying solely on hydrogen or formate as electron carriers, electrons are transferred directly across conductive nanoparticle surfaces, reducing energy losses and accelerating substrate conversion. The high specific surface area of Fe_3O_4 nanoparticles promotes microbial colonization and biofilm formation, thereby shortening the adaptation phase and enhancing metabolic coupling efficiency.

In studies of nano-assisted digestion, the use of conductive iron-based nanomaterials has also been reported to yield reductions in start-up time similar to

those observed with conductive iron-based nanomaterials (Aswathi *et al.* 2022; Krishnan *et al.* 2026).

3.2 Impact of Nanoparticles on Biogas Production

The nano-enhanced reactor consistently produced more biogas than the control reactor. The biogas daily discharge from the control reactor ranged from 0.32 to 0.38 m^3/day, and the nano-enhanced reactor delivered 0.42 to 0.48 m^3/day under the same operating conditions.

The use of a nano-enhanced reactor resulted in higher biogas production (by 60 days of the experiment) compared to the control reactor, by 22-28%, as shown in Fig. 2. This was attributed to enhanced hydrolysis and methanogenesis, mediated by nanoparticle-supported microbial activity and optimized electron transport mechanisms.

A statistical comparison between the CR and NER datasets showed that the daily biogas production increase was consistently greater in the NER throughout the steady-state phase. The relative standard deviation of daily biogas yield stayed below 5% in both reactors during stable operation, demonstrating good process reproducibility and minimal operational variability.

These findings are consistent with other studies reporting increases in biogas output of 15-30% upon the addition of iron oxide or other conductive nanoparticles, attesting the effectiveness of nanoparticles in anaerobic digestion (Bahrulolum *et al.* 2021).

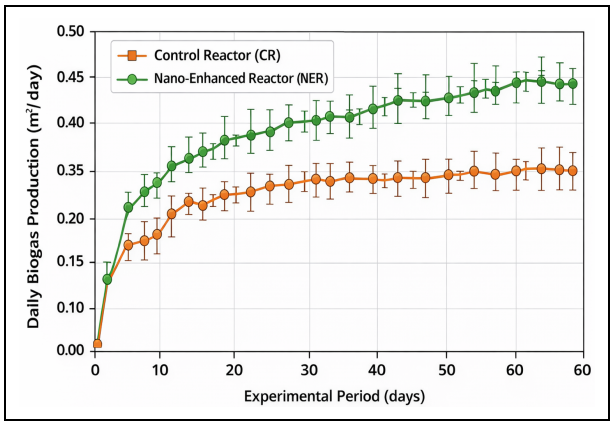


Fig. 2: Comparison of biogas production between the control reactor and the nano-enhanced reactor

3.3 Biogas Composition and Methane Fortification

The quality of biogas is a sensitive issue regarding its direct use in household cooking. Biogas analysis showed a significant increase in methane concentration in the nano-enhanced reactor.

The CH_4 concentration of the control reactor was 52-56, and this corresponds with a normal domestic digester of kitchen waste. Conversely, the nano-enhanced reactor recorded methane concentrations of 62-68%, representing a gain of about 10-14%. In line with this observation, CO_2 content decreased by 38-42% from the control reactor to 28-34% in the nano-enhanced reactor, as shown in Fig. 3.

The methane enhancement detected in the NER remained consistent across several sampling intervals. Uncertainty analysis indicated a variation of within ±2% for methane concentration measurements, confirming the reliability of the measurements and the precision of the analysis.

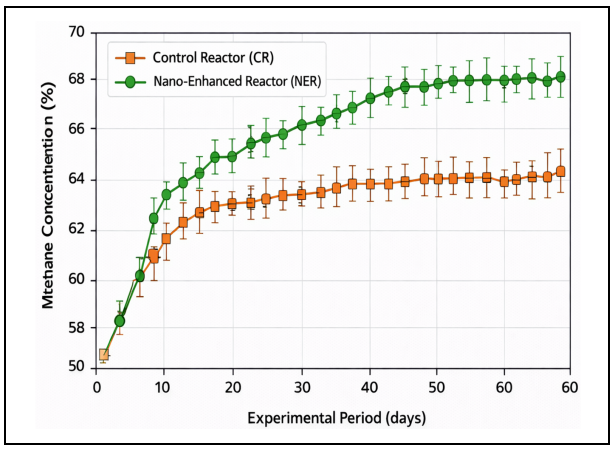


Fig. 3: Variation in methane concentration

The observed increase in methane levels is explained by the increased efficiency of methanogenesis via iron oxide nanoparticles and DIET.

Besides functioning as conductive mediators, Fe_3O_4 nanoparticles can also serve as electron sinks, temporarily holding and redistributing electrons during syntrophic metabolism. This electron buffering minimizes volatile fatty acid buildup and alleviates thermodynamic limitations, ultimately enhancing methane selectivity and carbon conversion efficiency.

The results of this study are confirmed by similar trends (8-20) in previous studies on nano-assisted anaerobic digestion, which also show similar improvements (Baraketi and Khwaldia, 2024).

3.4 Hydrogen Sulfide Reduction and Improvement in Quality of Gases

Hydrogen sulfide, an unwanted and corrosive constituent of biogas, was found in both reactors at fairly low levels. The control reactor had H_2S levels of 180-260, and the nano-enhanced reactor had much lower levels of 90-140, as shown in Fig. 4.

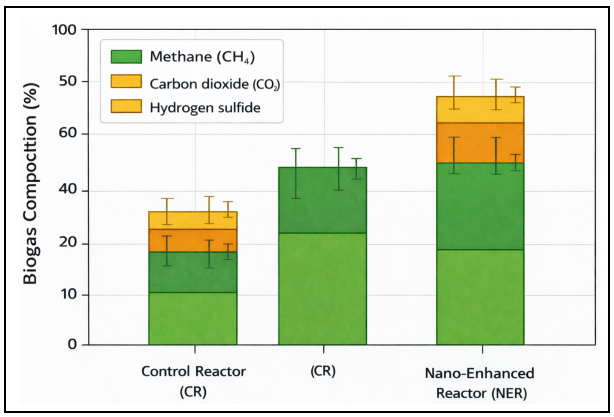


Fig. 4: Comparison of biogas composition

Triplicate gas sampling and sensor validation yielded an uncertainty of ±10 ppm for H_2S measurements, confirming that the observed 40-50% reduction is statistically significant and not due to instrument variability.

This decrease in H_2S concentration in the nano-enhanced reactor is attributed to the interaction between the sulphide ion and the iron oxide nanoparticles, leading to the precipitation of insoluble iron sulphide.

The formation of FeS precipitates reduces free sulfide concentration in the liquid phase, shifting the equilibrium and limiting H_2S volatilization into the gas phase. This dual role of Fe_3O_4 nanoparticles in both electron mediation and sulfide scavenging synergistically improves gas quality.

This situation, the *in situ* sulphide removal, enhanced the quality of biogas, and the risk of corrosion in downstream pipelines and cooking gadgets was minimized (Bhalerao *et al.* 2025). Past research has reported a 30-60% reduction in H_2S concentration in anaerobic digesters with iron-based additives, as in the present study.

3.5 pH Stability and Digestion Performance

Methanogenic activity is reliant on stable pH conditions. The nano-enhanced reactor maintained a pH within the optimal range for the methanogenic process (6.8-7.4) throughout the experimental period. Conversely, the control reactor showed a randomly recorded decrease in pH when organic loading was high, as shown in Fig. 5.

The pH coefficient of variation in the nano-enhanced reactor was below 3%, whereas it was about 6% in the control reactor, demonstrating enhanced buffering stability under fluctuating loads.

An improvement in pH balance in the nano-enhanced reactor suggests high efficiency in converting volatile fatty acids to methane, thereby avoiding acid buildup. This increased buffering capacity led to greater process stability and higher biogas production. Similar stabilizing effects had been observed in earlier research in the case of iron-based nanoparticle supplementation (Selvaraj and Velvizhi, 2022).

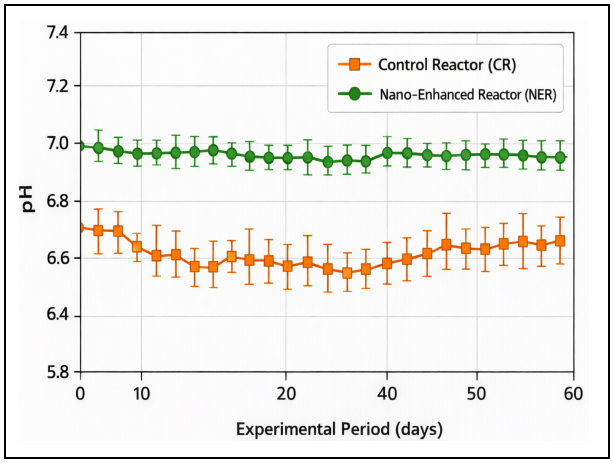


Fig. 5: pH variations in control and nano-enhanced reactor

3.6 IoT-Based Operation Monitoring and Optimization

The introduction of IoT-based monitoring enabled continuous, real-time tracking of key digestion parameters (temperature, pH, gas pressure, flow rate, and methane concentration). The temperature of the reactor stayed at the mesophilic temperature of 30-36 °C, whereas the pressure in the nano-enhanced reactor stabilized between 9 and 13 kPa.

Sensor calibration was conducted before the experiments using standard buffer solutions for pH and certified gases for methane and H_2S. This ensured data accuracy and reduced systematic errors.

Inhibitory conditions were prevented through real-time monitoring, which enabled immediate operational adjustments, including feed dilution and optimization of loading rates. The BioDigestX system proved to be much more operationally reliable than conventional domestic digesters lacking a monitoring system, as reported in recent literature on smart anaerobic digestion systems.

3.7 Energy Consumption in the Household and Real-world Applications

The biogas produced by the nano-enhanced BioDigestX reactor was used directly for household cooking. Better biogas production and methane level favoured 1.5-2 hours of cooking per day, based on the efficiency of the stove, as shown in Fig. 6.

The increased methane proportion and decreased H_2S concentration led to stable flame

properties, higher calorific value, and reduced odour and corrosion. These results indicate the viability of the BioDigestX system in terms of its practical implementation in decentralized energy recovery at homes and management of kitchen waste in a sustainable manner (Selvaraj and Velvizhi, 2023).



Fig. 6: IoT-based real-time monitoring dashboard

3.8 General Performance

The combination of nanoparticle incorporation and IoT-governing led to the subsequent major advantages over traditional domestic anaerobic digestion:

- Startup Time Reduction: 35-40%
- Biogas Yield Enhancement: 22-28%
- Increase in the Concentration of Methane: 10-14%.
- H_2S Reduction: 40-50%
- Greater stability of the processes and operational control.

The comparative parallel reactor configuration, consistent performance trends over 60 days, low relative standard deviations, and validated sensor calibration collectively strengthen the reliability and statistical robustness of the reported improvements. Additionally, the findings show that the concept of nano-enhanced, IoT-enabled anaerobic digestion is a promising, efficient, and eco-friendly approach to domestic conversion of kitchen waste into biogas, as demonstrated by the BioDigestX system.

4. CONCLUSION

In this paper, BioDigestX, a biosink-based, nano-enhanced, and IoT-integrated domestic anaerobic digestion system for converting kitchen waste into biogas, was developed and successfully operated. The addition of Fe_3O_4 nanoparticles and real-time monitoring *via* the IoT led to quantifiable improvements in biogas production, gas quality, and process stability compared with a traditional domestic digester.

The nano-enhanced reactor stabilised after 7-9 days, compared with 12-14 days for the control reactor, resulting in a 35-40% decrease in time-to-startup. The improvement in the biogas yield was 22-28% as the average daily biogas production in the control system rose to 0.32-0.38 m^3/day, and the nano-enhanced system produced 0.42-0.48 m^3/day. The methane content of biogas increased, while the carbon dioxide content decreased, from 62-68% to 28-34%, respectively.

Moreover, the hydrogen sulphide concentration decreased from 180-260 ppm in the control reactor to 90-140 ppm in the nano-enhanced reactor, representing a 40-50% decrease in H_2S concentration due to interactions with iron-based nanoparticles. The nano-enhanced system maintained a constant pH within the optimum methanogenic range of 6.8-7.4, whereas the control reactor exhibited intermittent pH decreases to 6.4-6.6.

With the IoT-based monitoring framework, it was possible to continuously monitor temperature (30-36 °C), gas pressure (9-13 kPa), pH, and methane concentration, ensuring steady, reliable stability. The enhanced biogas quality enabled cooking for 1.5-2.0 hours, thereby demonstrating the system's practicality for recovering household energy.

The findings support the idea that combined implementation of environmental nanotechnology based on IoT significantly improves the performance of domestic anaerobic digestion. The BioDigestX system proposes a low-cost, scalable, and sustainable household-waste management and clean-energy production system (decentralised kitchen waste), with high potential to develop at the household and community scales.

ACKNOWLEDGEMENT

The authors acknowledge the "Easwari Engineering College and the Department of Civil Engineering, especially the Environmental Engineering Lab", for supporting this research. The authors thank the management of Easwari Engineering College for their support of this work.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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