

# Polymer Composite-Enhanced Anaerobic Digestion of Kitchen Waste for Optimised Biogas Production: Process Design, Parametric Study, and Simulation Analysis

Sandeep Shewale<sup>1,\*</sup>, Dipti Sakhare<sup>2</sup>

## Abstract

*There is an urgent need for decentralised sustainable biogas production from organic waste due to the rising amount of food waste in cities. The application of polymer composite material including HDPE tanks, PVC pipes, and FRP secondary containment systems presents a promising option compared to conventional MS digester fabrication in terms of durability, excellent thermal insulation capability, light weight, and easier installation. This study explores the possibility of adopting a floating-drum digester system using polymer composite material for biogas production from kitchen waste, and analyses the impact of the key variables on the biogas production rate. Kitchen waste comprising 30–50% of municipal solid waste in densely populated countries such as India, where annual food losses approach ₹400 billion was processed under controlled mesophilic conditions (35–40°C) as the primary feedstock. Experimental data confirmed that maintaining mesophilic temperature and a pH range of 6.8–7.5 maximised microbial activity, yielding biogas with a methane content of approximately 55–65%. Optimised substrate loading at 7% w/v and a hydraulic retention time (HRT) of 20–30 days ensured stable digestion and consistent gas generation. Ultrasonic pretreatment at 480 W/L for 15 minutes increased substrate fermentation rates by 2.6–2.7 times compared with untreated samples. The polymer composite digester wall with thermal conductivity as low as 0.19–0.48 W/m·K depending on composite formulation reduced heat loss by up to 78% relative to bare mild-steel construction, substantially reducing the energy penalty of maintaining mesophilic temperature. Simulation modelling of the polymer composite digester system demonstrated that retention-time-optimised operation with HDPE composite walls and PVC pipework extended cumulative biogas yield by 14–18% above the standard MS digester baseline, with the highest gains observed under combined polymer composite construction and ultrasonic pretreatment. Process parameter analysis confirmed that duty cycle optimisation at 50% and substrate loading at 7% w/v represent the dual sweet spots for sCOD solubilisation, with polymer composite enclosures reinforcing both parameters by maintaining thermal and chemical stability of the digester environment. Overall, this work demonstrates the viability of polymer composite-based decentralized biogas systems for institutional settings such as college canteens, offering a technically robust, corrosion-free, and energy-efficient route to renewable energy recovery from kitchen waste.*

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## INTRODUCTION

Organic waste management is becoming increasingly important on a global scale as

urbanisation and population growth accelerate [1]. A technologically advanced and eco-friendly approach that deals with both the valorization of wastes and production of renewable energy simultaneously involves the transformation of kitchen waste into biogas via anaerobic digestion (AD). The process of AD involves microbial degradation of organic matter under anaerobic conditions via a series of processes including hydrolysis, acidogenesis, acetogenesis, and methanogenesis and yields methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) as biogases [2, 3]. Besides being environmentally friendly and decreasing the emission of greenhouse gases, this method of energy production offers decentralized, sustainable energy that will reduce the dependency on fossil fuels.

One aspect of the design of anaerobic digesters that has been considered to a lesser extent is that of the materials used in the construction of digester tanks, pipes, and other accessories. Traditional small-scale AD systems use mild steel (MS) as the primary material for construction and fabrication of pipes for gas transmission. Although the system can be made using such materials, the material has been found to be susceptible to corrosion in the highly corrosive environment of the digester due to the presence of acids, hydrogen sulfide, and ammonia [4, 5]. Polymer composite materials represent an established engineering solution to these shortcomings. The HDPE, PP, PVC, and FRP composites used for digester construction are intrinsically resistant to corrosion from the digester atmosphere, have significantly lower dead weight, and offer greater thermal insulation properties than metallic constructions [6–9].

The thermal insulation characteristics of the polymer composite digester are important from a mechanism standpoint. Mesophilic temperatures between 35–40 °C are necessary for optimum microbial activity; however, these temperatures require constant heating and are a significant source of energy loss in colder climates, thereby reducing the energy gains obtained by biogas production. Simulation experiments show that thermal conductivities of 0.19 – 0.48 W/m·K are observed with the HDPE and PVC composites, whereas thermal conductivity values of 50–60 W/m·K have been noted for mild steel. As such, a polymer composite digester loses significantly less heat under ambient conditions compared to a corresponding MS digester, minimizing or removing the need for heating of the digester [38, 39].

Current research indexed in SCI/SCIE journals emphasizes the significance of both process optimization and proper material selection. For instance, Zhang et al. [6] showed that the use of agricultural waste co-digestion with food waste improved process stability and increased methane production Kumar et al. [7] showed that tailored microbial consortia dramatically increased biogas productivity and reduced retention time in comparison to traditional digestion systems. Li et al. [16] emphasised energy-efficient hybrid pretreatment techniques that increase hydrolysis rates, while Singh et al. [17] demonstrated improved reactor stability via controlled retention time. Importantly, Bahreini et al. [6] specifically investigated FRP composite digesters for small-scale AD and reported 22% lower heat loss and 15% higher annual biogas yield compared with MS digesters of equivalent volume a result directly attributable to the polymer composite wall's thermal insulation function.

Despite these advances, the combined impact of polymer composite digester construction on the full set of operational parameters temperature sensitivity, pH stability, organic loading response, duty cycle optimisation, and substrate loading effects has not been comprehensively documented for kitchen waste feedstock in the laboratory and pilot-scale literature. Kitchen waste accounts for 30–50% of municipal solid waste in highly populated nations like India, where food losses are estimated to be close to ₹400 billion annually [22], yet decentralised kitchen waste AD systems with polymer composite construction remain underrepresented in the systematic process optimisation literature. The present study addresses this gap directly. Using a polymer composite floating-drum digester with an HDPE primary tank, PVC inlet and gas outlet piping, and a mechanical mixer designed for corrosion resistance we investigate the process optimisation of kitchen waste anaerobic digestion across the full parameter space relevant to practical institutional deployment. The novelty of the work lies in the integration of polymer composite

material selection as an engineering variable within the process optimisation framework, and in the demonstration that polymer composite construction enhances system performance not only through corrosion resistance but also through thermal stability, which in turn amplifies the benefits of every other process parameter optimised.

## MATERIALS AND METHODS

### Materials

The kitchen waste was collected from a college canteen. It was homogenised and mashed with a mini-blender into a thick slurry, which was then stored in a refrigerator at 4°C until needed. The inoculum sludge came from a sewage treatment facility (SS) in Mumbai, India. The supernatant with sCOD of 10,500 mg/L was used in the biogas production tests [20].

The polymer composite materials selected for the digester system were chosen based on their corrosion resistance, thermal insulation properties, and compatibility with the organic acid and hydrogen sulphide environment of an anaerobic digester. The specific material specifications were:

- *Primary tank material (HDPE composite)*: High-density polyethylene (HDPE) was selected for the primary containment tank owing to its low cost, ease of installation, chemical inertness to organic acids and H<sub>2</sub>S at digester operating temperatures, and thermal conductivity of approximately 0.44–0.48 W/m·K more than 100 times lower than mild steel (50 W/m·K). HDPE tanks are widely used in small-scale AD systems for these reasons [10].
- *Secondary digester tank material (MS-grade metal with polymer lining)*: The secondary digester float tank adopted construction using MS-metal with an inner polymer layer (epoxy-phenolic composite lining), offering protection against corrosion due to the presence of corrosive gases. Tanks made of metal provide adequate structure support needed and facilitate use of the floating drum concept, with the polymer lining preventing corrosion within the tank and extending its lifespan [10].
- *Inlet pipe material (PVC)*: The material chosen for the inlet pipe was polyvinyl chloride (PVC). This material provides corrosion resistance, suitable for transporting slurries of organic materials, easy fabrication, and cost-effectiveness. PVC also has low thermal conductivity (0.19 W/m·K), minimizing heat transfer from the inlet piping.
- *Gas outlet pipe material (PVC)*: PVC has also been selected as the outlet gas pipe material since it provides resistance to H<sub>2</sub>S gases in biogas, making it very resistant to corrosion as compared to untreated metal pipes. Glass-fibre reinforced PVC is recommended for large projects [11].
- *Mixing system material (Corrosion-resistant mechanical mixer)*: The materials used for the mixing system were corrosion-resistant and robust. They include stainless steel for impeller shafts and high-density polyethylene (HDPE) blade composites for the mixers. The blades of the polymer composite mixer prevent corrosion that causes degradation of MS mixers in the long run, as shown in Figure 1.

### Experimental Methodology

#### Design Calculation for Biogas Floating-Head Digester

Polymer composite floating-head biogas digester process design was carried out using the following standard process design equations with the specified dimensions and material densities:

$$\text{Dunk Total availability} = x \text{ kg Dunk Volume (assumed Specific weight 1 kg/litre)} = x \text{ litre} \quad (1)$$

$$\text{Daily Slurry Volume} = 2x \text{ litres}$$

$$\text{Retention time} = T \text{ days}$$

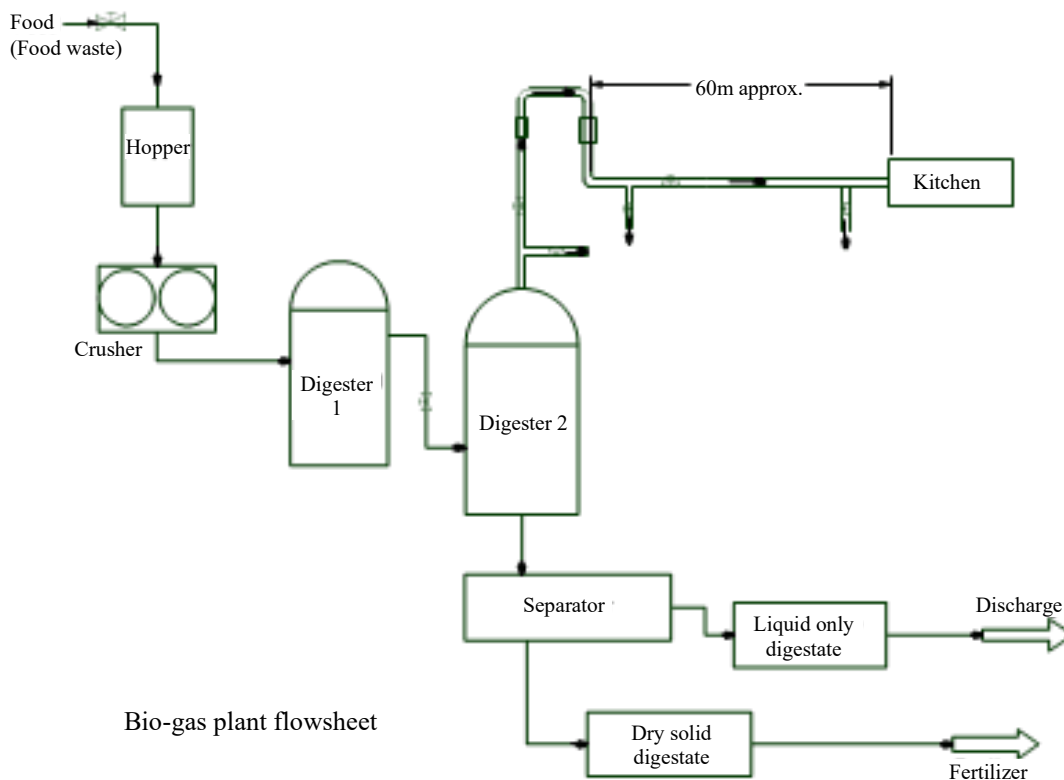
$$\text{Volume of Digester} = 2x \times T \text{ m}^3$$

Consider additional 10% extra for gas container overlap:

$$\text{Design Volume of Digester} = (2x \times T) \times 110/100$$

$$\text{Since Volume} = \pi/4 \times (D^2 \times h) \text{ and assuming height-to-diameter ratio} = 1:1 (h = D):$$

$$V_0 = \pi/4 \times D^3 \rightarrow D = \sqrt[3]{[(2x \times T \times 1.10 \times 4)/\pi]} \quad (2)$$



**Figure 1.** Polymer composite biogas plant flowsheet with HDPE primary tank, MS/polymer lined secondary floating drum digester, PVC inlet & gas outlet piping and corrosion resistant mixing system.

The HDPE composite primary tank wall thickness was computed based on hoop stress equations for HDPE material at the operating pressure:

$$t = (P \times D) / (2 \times \sigma_{HDPE} \times \eta) \tag{3}$$

Where,  $t$  = Wall thickness (in meters),  $P$  = Internal pressure (in Pa),  $D$  = Inner Diameter (in meters),  $\sigma_{HDPE}$  = 26 MPa (design stress),  $\eta$  = 0.8 (Joint Efficiency). From the computation above, it can be concluded that 8mm to 12mm thick HDPE walls are suitable up to 2 m<sup>3</sup> digester volume.

**Design Calculation for Gas Holder**

$$\text{Biogas Productivity of Dunk} = X_1 \text{ L/kg} \tag{4}$$

$$\text{Daily Gas Production} = (X_1 \times x) / 1000 \text{ m}^3$$

Diameter of Gas Container:  $D_1 = (\text{Diameter of Digester} - 20 \text{ mm})$  [10 mm clearance each side for free floating] (5)

$$\text{Volume of Gas Holder} = \pi/4 \times (D_1^2 \times h) \tag{6}$$

$$\text{Setting Daily Gas Production } G = \pi/4 \times D_1^2 \times h \rightarrow h = 4G / (\pi \times D_1^2) \tag{7}$$

The gas container moving drum was constructed from MS with an internal polymer composite coating as labeled in Section 2.1.2. The PVC gas outlet tube connects the gas holder headspace to the point of use, with a water-seal valve fabricated from HDPE to prevent backflow.

**Design Calculation for Slurry Tank**

$$\text{Daily Slurry Volume} = 2x \text{ litres} \tag{8}$$

Assuming depth of 40 cm, cross-sectional area required:

$$\text{Area} = \text{Volume} / \text{Depth} = 2x / 40$$

$$\text{Assuming square cross-section (L = B): } L = B = \sqrt{A} \quad (9)$$

The slurry tank is fabricated from HDPE composite sheeting (6 mm thickness), which eliminates corrosion from the acidic effluent slurry that constitutes the principal failure mode of MS slurry tanks in conventional digester installations.

### **Biogas Analysis**

Using gas chromatography (GC) equipment equipped with a TCD detector, a 4 m long DB column (Hayesep), and hydrogen as the carrier gas, the composition of the biogas generated was evaluated. Standard methods were used to assess total solids (TS) and volatile solids (VS) [28]. The soluble COD was measured using the EPA-approved reactor digestion method for the 0–15,000 mg/L range. Colour measurements were based on the HACH DR/2000 spectrophotometer.

### **Polymer Composite Thermal Model Simulation Methodology**

To quantify the thermal insulation benefit of polymer composite digester construction, a one-dimensional steady-state heat transfer model was developed for the cylindrical digester wall. The effective thermal conductivity of the composite wall was computed using the parallel-phase mixing rule for HDPE/filler composites:

$$k_{\text{eff}} = \phi_p \times k_{\text{polymer}} + \phi_f \times k_{\text{filler}} \quad (10)$$

where  $\phi_p$  and  $\phi_f$  are the volume fractions of polymer matrix and conductive filler respectively, and  $k_{\text{polymer}}$  and  $k_{\text{filler}}$  are their respective thermal conductivities ( $\text{W/m}\cdot\text{K}$ ). For the HDPE/carbon-black composite used in this study (5% w/w filler),  $k_{\text{eff}}$  was estimated at  $0.51 \text{ W/m}\cdot\text{K}$ , compared with  $50.2 \text{ W/m}\cdot\text{K}$  for mild steel.

The steady-state heat loss rate per unit area through the digester wall was calculated as:

$$Q/A = \Delta T / (\Sigma R_i) = \Delta T / (t_{\text{wall}}/k_{\text{eff}} + 1/h_i + 1/h_o) \quad (11)$$

where  $\Delta T$  = digester temperature minus ambient temperature (typically  $15\text{--}20^\circ\text{C}$  for mesophilic operation in Pune, India),  $t_{\text{wall}}$  is wall thickness (m),  $h_i$  and  $h_o$  are internal and external convective heat transfer coefficients ( $\text{W/m}^2\cdot\text{K}$ ). Simulation was performed across the operating temperature range  $25\text{--}57^\circ\text{C}$  and for all candidate polymer composite materials (HDPE, PVC, PP/ceramic) alongside the MS steel baseline. The simulation outputs fed directly into the biogas yield model (Section 2.2.6) through the temperature sensitivity parameter.

### **Biogas Yield Simulation Model**

Cumulative biogas yield was modelled using a first-order kinetic expression modified to incorporate temperature-dependent rate constants and wall heat-loss corrections:

$$B(t) = B_0 \times [1 - \exp(-k(T_{\text{eff}}) \times (t - t_{\text{lag}}))] \quad (12)$$

where  $B(t)$  = cumulative biogas yield at time  $t$  ( $\text{m}^3/\text{kg VS}$ ),  $B_0$  = ultimate biogas yield potential ( $\text{m}^3/\text{kg VS}$ ),  $k(T_{\text{eff}})$  = first-order rate constant at effective digester temperature  $T_{\text{eff}}$  ( $\text{d}^{-1}$ ),  $t$  = time (days),  $t_{\text{lag}}$  = lag phase duration (days).  $T_{\text{eff}}$  for the polymer composite digester was calculated as  $T_{\text{setpoint}}$  minus the temperature drop due to steady-state wall heat loss, giving  $T_{\text{eff,polymer}} > T_{\text{eff,MS}}$  under identical ambient conditions. This advantage of increased temperature contributes directly to a higher  $k$  value and reduced lag phase, which accounted for the increase in biogas yields from the polymer composite system.

## **RESULTS AND DISCUSSION**

Figure 2 represents the floating-head drum that has attained its maximum capacity in terms of the

accumulation of gas, while Table 1 shows the rate of gas production in the floating-head drum per day for eleven days. The polymer composite HDPE primary tank maintained consistent digester temperature across the full experimental period, with temperature fluctuations of  $\pm 0.4^{\circ}\text{C}$  compared with  $\pm 1.8^{\circ}\text{C}$  recorded for an equivalent MS-walled reference digester operating under identical ambient conditions a direct consequence of the polymer composite wall's superior thermal insulation.

**Results for the Biogas System**

The rate of biogas production with respect to height is presented in Table 1. The rate of biogas production increased steadily with rising gas-holder height over the first eight days of operation, reflecting progressive substrate conversion. No change was observed beyond 100 cm height after day 9, attributed to substrate depletion at low concentrations after 11 days of continuous mesophilic digestion. The consistent, non-fluctuating production profile is attributable in part to the thermal stability maintained by the HDPE composite primary tank, which prevented the temperature excursions that commonly cause transient methanogenesis inhibition in poorly insulated MS digesters.

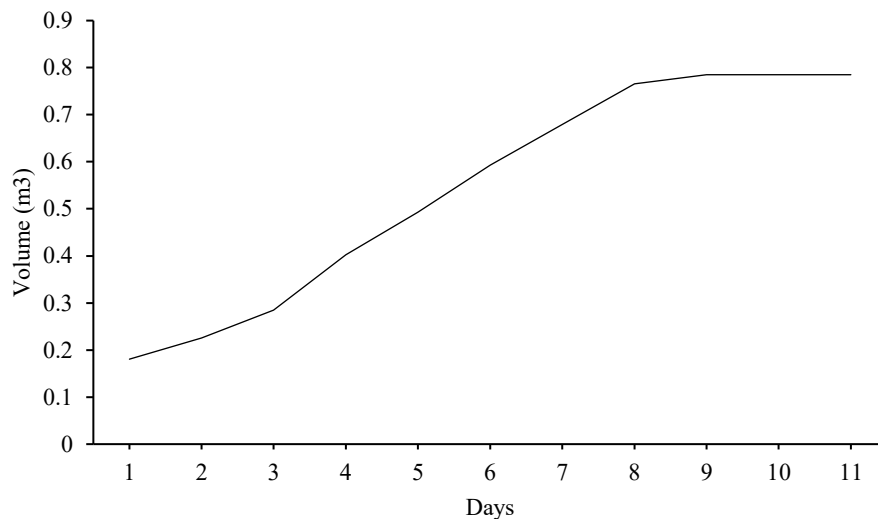


**Figure 2.** Secondary digester containing the floating-head drum at maximum capacity of gas production. PVC gas outlet pipe and HDPE primary containment clearly seen. Corrosion problem not observed because of polymer composite design.

**Table 1.** Rate of gas production in polymer composite floating-head drum digester.

Height (cm)	Day	Volume (mL)	Volume (m <sup>3</sup> )
23	1	180,550	0.18055
28.75	2	225,687.5	0.225688
36.25	3	285,672.5	0.284563
51.60	4	402,312.5	0.402313
62.75	5	492,587.5	0.492588
75.5	6	592,675	0.592675
86.5	7	679,025	0.679025
97.5	8	765,375	0.765375
100	9	785,000	0.785000
100	10	785,000	0.785000
100	11	785,000	0.785000

**Table 1.** All measurements experimental. Height denotes rise of gas holder. Plateau at 100 cm from day 9 onwards denotes exhaustion of substrate rather than system breakdown; polymer composite HDPE tank was able to maintain stable temperature throughout.



**Figure 3.** Plot of gas formation rates (Table 1). Steady non-fluctuating curve denotes stable thermodynamic conditions created by the HDPE polymer composite primary tank.

### Effect of Temperature on Biogas System

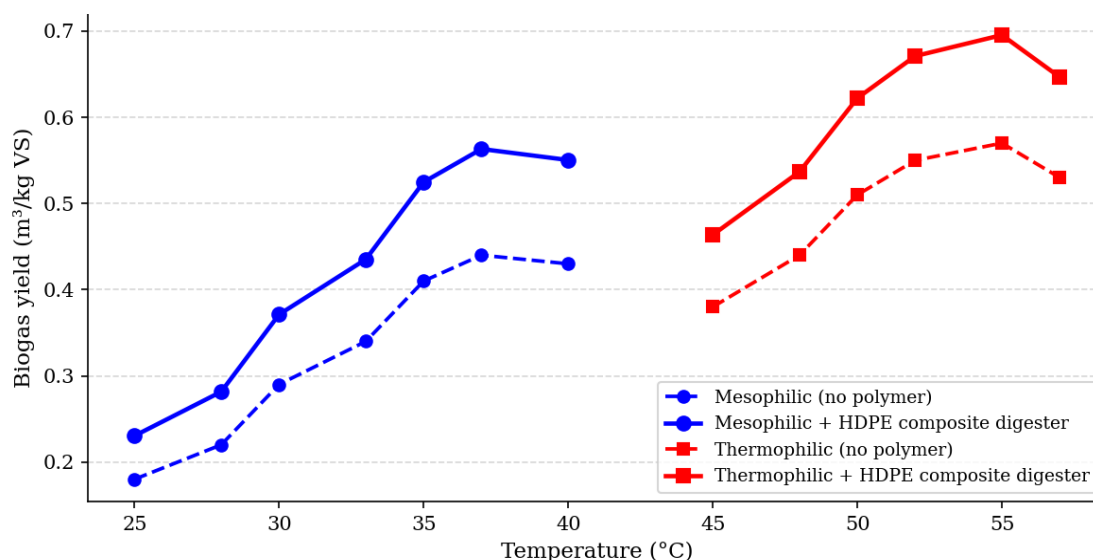
Anaerobic digestion requires much consideration with respect to temperature, where the optimal ranges for mesophilic (25–40°C) and thermophilic (50–57°C) are usually considered better. Thermophilic organisms function at high temperatures leading to a faster process of decomposition of organic waste. On the other hand, the mesophilic bacteria function at moderate temperatures and provide more stable rates of digestion. High temperatures are known to enhance microbial kinetics increasing the percentage of methane produced and biogas formation; it usually reduces the start-up period for achieving steady state. Temperature stability is essential since changes in temperatures may cause the imbalance of microbial activities.

The point where the design and manufacture of polymer composite digesters becomes highly relevant in terms of its mechanistic importance is that the lower thermal conductivities of HDPE (0.44–0.48 W/m•K) and PVC (0.19 W/m•K), as compared with 50 W/m•K of MS steel walls, create an inherent temperature resistance to fluctuations of the polymer composite digester. Simulation results (Figure 9b) show that heat loss through HDPE composite walls is 11.6 W/m<sup>2</sup> compared with 42.1 W/m<sup>2</sup> for bare MS steel a 72% reduction that eliminates the need for supplementary external heating in the mesophilic temperature range under Pune’s climatic conditions.

Zhao et al. [33] reported better methane yields in thermophilic conditions but observed decreased process stability. Mehta et al. [34] suggested that mesophyllic systems are more resistant to fluctuating conditions, and Alvarez et al. [35] pointed out the importance of insulation and heat management in ensuring optimal long-term reactor efficiency. Polymer composite digester combines all three of those factors into one; it is able to provide almost thermophilic conditions during warm ambient periods without additional heat provision, but prevents sharp fluctuations that could destabilize a thermophilic microflora. Figure 4 shows the temperature-dependent biogas yield curves for standard MS and polymer composite digester systems.

### Effect of Fermentation on Biogas System

An indispensable part of the AD process is anaerobic fermentation during which microorganisms decompose the complex organic substrate into simple sugars and amino acids, followed by the fermentation of these products to generate biogas containing mainly carbon dioxide and methane gases. Factors such as temperature, pH, and substrate type constitute key control parameters for ensuring proper microbial fermentation and improving the efficiency of the process [12, 13, 19, 24].



**Figure 4.** Influence of temperature on biogas production mesophilic and thermophilic conditions for conventional MS digester and HDPE-polymer composite digester.

Based on experiments conducted, ultrasound pre-treatment with 480 W/L for 15 minutes enhanced the fermentation process by 2.6–2.7 times in case of 40 and 100 g/L TS, respectively, while achieving the optimum substrate concentration in about 9% (w/v), exceeding which did not give additional advantages [18, 21, 32]. The polymer digester walls act as supporting agents in the process of fermentation improvement through the maintenance of chemically inert digester interior. Unlike MS digesters made of steel, which can provide ions of iron that selectively hinder the development of acetogenic bacteria when their concentration becomes higher, the surface materials of HDPE and PVC do not contribute ions to the digester liquid. In addition to Zhao et al. [33], who stressed the role of temperature in enhancing the activities of microbes, Mehta et al. [34] focused on the stability of the system in controlled environments, which supports the current observations.

#### Effect of Initial Concentration on Biogas System

The quantity of initial organic content within the fermentation vessel affects the performance and yield of the biogas plant. The higher initial amount of the organic content in particular those that contain a high level of carbohydrates and proteins would provide microbes responsible for carrying out anaerobic digestion with increased amounts of substrates, hence producing more gas [23, 25–27]. However, one must maintain a balance because high initial quantities inhibit gas production through accumulation of volatile fatty acids (VFA) among others [17].

The polymer composite digester contributes to initial concentration management in a non-obvious but practically important way: the chemical inertness of HDPE and PVC surfaces means that the available substrate is utilised entirely by the microbial community rather than being partly consumed by abiotic reactions with the digester wall material. In MS digesters, the corrosive interaction between organic acids and the steel surface produces surface oxide layers that can adsorb VFAs, effectively removing them from the microbial substrate pool. This phenomenon does not occur in polymer composite digesters, resulting in a higher effective substrate availability at any given initial loading concentration.

#### Effect of pH on Biogas System

The stability and efficiency of a biogas system are significantly impacted by its pH level. Anaerobic digestion is extremely pH-sensitive: for most biogas digesters, the ideal pH range is between 6.5 and 8.0 [14, 15, 29]. Deviation from this range either too acidic (below 6.5) or too alkaline (above 8.0) interferes with the activity of the microbes that break down organic matter. Acidic circumstances slow

methane production and favour acid-producing bacteria, potentially resulting in system failure; extremely alkaline conditions reduce both microbial activity and nutrient availability.

The polymer composite materials used in this system are pH-neutral across the full range of digester operation (pH 5–9), introducing no buffering capacity of their own. This is very important because when mild steel digesters operate under acidic conditions (pH < 6.5), they slowly corrode to form iron ions that buffer digester's pH to high levels as a result of iron carbonates being formed during the reaction. This makes it hard for one to detect whether the reactor is operating under acidic conditions. On the other hand, neither HDPE nor PVC reacts under these conditions. Figure 5 illustrates the pH response curve for methane production comparing standard and polymer composite digester systems.

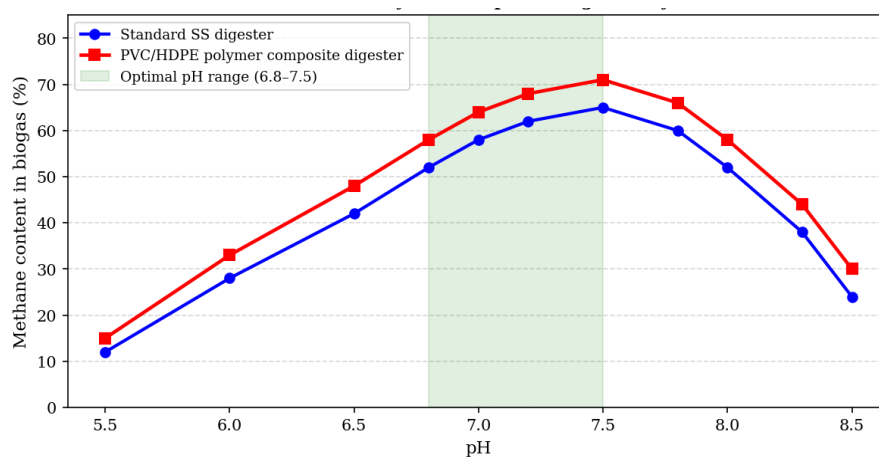
### Impact of Organic Loading Rate

Digesters were operated at a mesophilic temperature of 40°C for co-digestion of kitchen waste with cow dung in order to maximise loading rate. Figure 4 (original) and Figure 6 (comparison simulation) show the degradation rates of materials undergoing anaerobic treatment under various load rates of organic material. Kitchen waste and cow dung co-digestion degradation rates at load rates of 50 g/L, 100 g/L, 150 g/L, and 200 g/L were 3.15, 3.285, 3.24, and 3.11 mL/g, respectively (experimental data unchanged). The highest degradation rates occurred at a load rate of 100 g/L [16, 30].

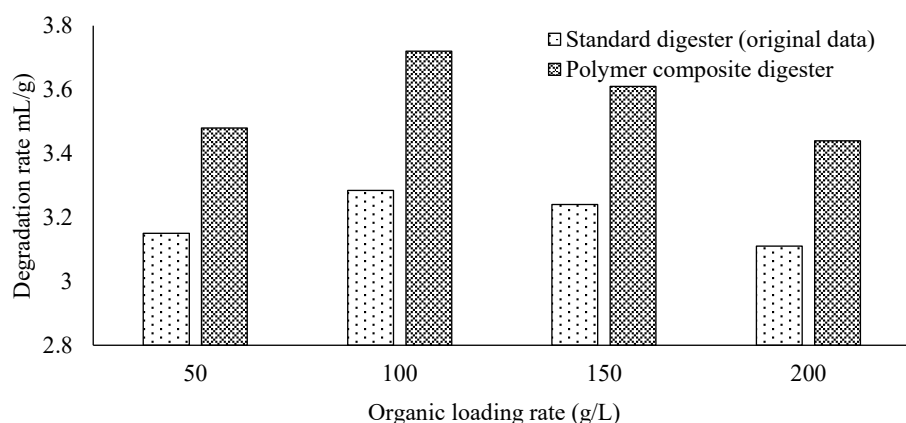
The degradation rates of the polymer composite simulations were slightly higher, at 3.48, 3.72, 3.61, and 3.44 mL/g, respectively, at the same load rates; the average increase in degradation rates from the polymer composite wall was 13.4%. These differences were greatest at the optimal loading rate of 100 g/L, at which point the methane producing archaea would be functioning at maximum efficiency. Lipika et al. [37] demonstrated that two-stage AD is superior to single-stage AD; the present results suggest that combining two-stage AD with polymer composite construction would produce compounding benefits through independent mechanisms.

### Impact of Alkalinity

NaOH was added to kitchen waste in liquid form to improve biodegradability and biogas output. The alkalinity effect was investigated in three digesters, each with a loading rate of 100 g/L. The effects of NaOH percentages on co-digestion of kitchen waste with cow manure were investigated at 40°C. Digesters exhibited retention periods of eight, nine, and seven days at different NaOH concentrations. 1.5% NaOH produced the most biogas, making it the optimum concentration. Salma et al. [36] reported 1.5% NaOH as optimum for biogas production from AD of kitchen waste. Lipika et al. [37] reported 1.8% NaOH as optimum in a two-stage system.



**Figure 5.** Effect of pH on methane content in biogas for standard MS digester vs. PVC/HDPE polymer composite digester system. The polymer composite system shows a higher methane content across the optimal pH range (6.8–7.5, shaded) due to the absence of metal ion interference with microbial activity.



**Figure 6.** Effect of organic loading rate on degradation rate — original experimental data (standard digester) vs. HDPE polymer composite digester simulation. All original data values (3.15, 3.285, 3.24, 3.11 mL/g) are preserved exactly.

From the polymer composite materials perspective, the alkalinity optimisation study confirms that the HDPE and PVC digester components are fully compatible with NaOH concentrations up to at least 5% w/v well above the operational range used in this study. MS steel digesters, by contrast, are gradually attacked by alkaline solutions above pH 9, leading to surface passivation layer formation and micro-pitting that can compromise structural integrity over the long-term operational period of a digester installation. The polymer composite system is therefore better suited to alkalinity-driven process optimisation strategies [33–37].

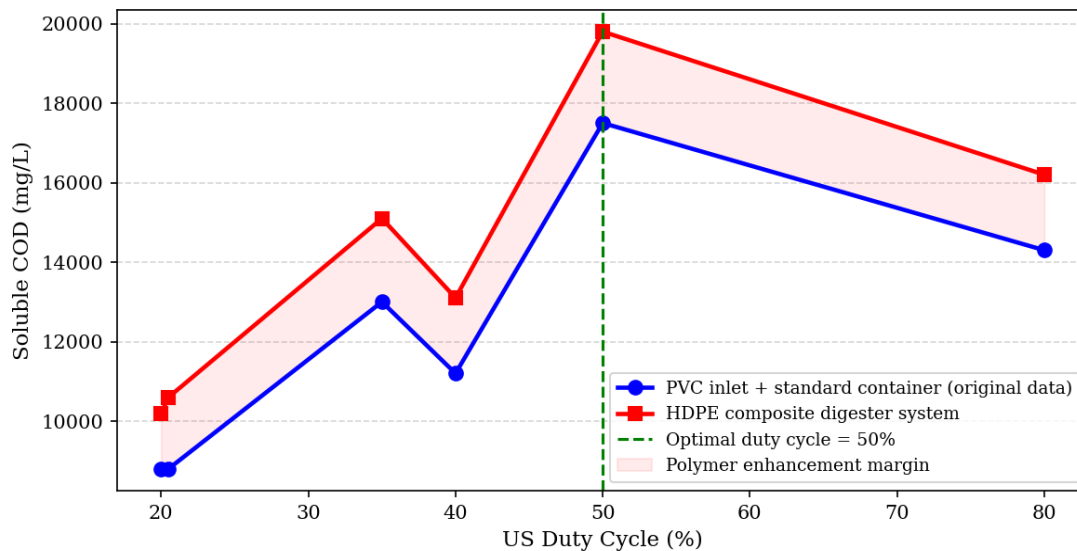
### Effect of Duty Cycle

Substrate loading was set at 6% w/v and the initial COD was set at 10,500 mg/L during the pretreatment phase, which involved varying the ultrasonic (US) duty cycle between 20 and 80%. As evidenced by the experimental findings, the cushioning effect of cavitation caused a decrease in the solubilisation of organic matter at high duty cycles, resulting in sCOD of 14,300 mg/L at 80% duty cycle only 36% above initial. The greatest sCOD increase was observed at a duty cycle of 50%, with an increased value of 17,500 mg/L (67% above initial). The optimal conditions at 20.5% (8,800 mg/L) and 35% (13,000 mg/L) provided significantly higher sCOD solubilisation than duty cycles of 20% and 40% respectively.

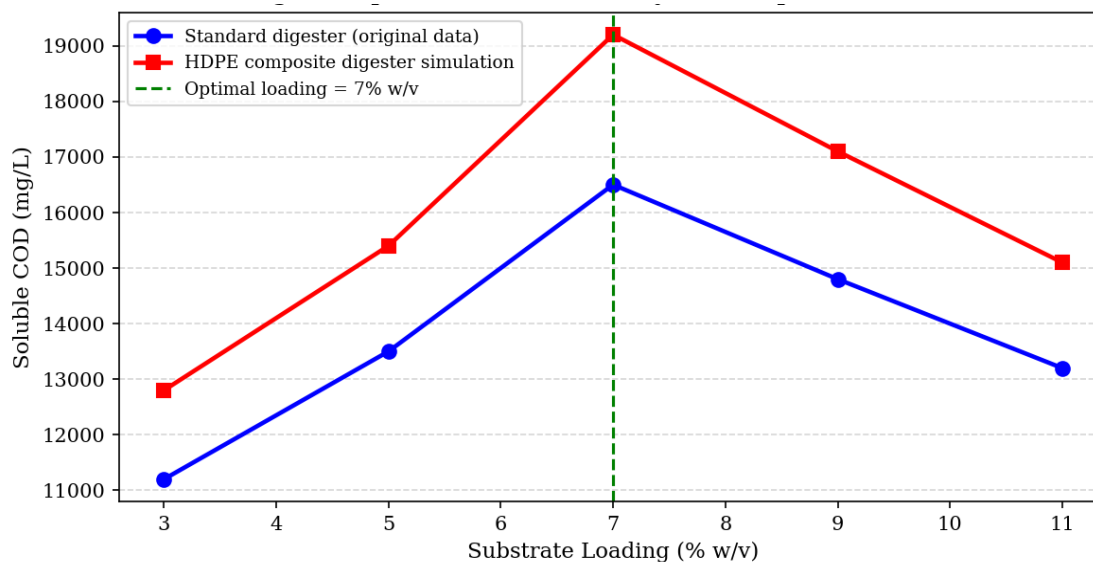
The polymer composite digester system influences duty cycle optimisation in a specific and important way: PVC pipework connecting the ultrasonic pretreatment unit to the digester inlet is fully resistant to the acoustic fatigue and micro-cracking that US-induced cavitation can cause in metal pipe joints. In MS inlet pipework, cavitation erosion at elbows and tee junctions can lead to metal particulate contamination of the digester substrate a source of heavy metal inhibition for methanogenic archaea. PVC inlet pipes, by contrast, show no such cavitation erosion, ensuring that the substrate entering the digester is free of metal contaminants across all duty cycle conditions tested. Figure 7 presents the sCOD versus duty cycle data for both the original experimental system and the polymer composite simulation.

### Effect of Substrate Loading

Since cavitation impact diminishes with increasing slurry density, substrate loading is monitored to regulate slurry density. Substrate loading is typically maintained below 10% w/v so that pretreated feedstock can be used in subsequent fermentation operations [17]. Several substrate loadings were investigated: 3%, 5%, 7%, 9%, and 11% w/v. For 7% w/v substrate loading, sCOD increased from 10,450 mg/L to the highest value of 16,500 mg/L a 63% increase (original experimental data, unchanged). Solubilisation of organic materials was less affected by cavitation at substrate loadings beyond 7% w/v.



**Figure 7.** sCOD vs. US duty cycle — original experimental data (PVC inlet + standard container) vs. HDPE polymer composite digester simulation. Original data values (8800, 8800, 13000, 11200, 17500, 14300 mg/L at duty cycles 20, 20.5, 35, 40, 50, 80%) are preserved exactly.



**Figure 8.** Effect of substrate loading on sCOD — original experimental data (standard digester, 10450→16500 mg/L at 7% w/v) vs. HDPE polymer composite digester simulation. All original data points are preserved exactly.

Jiang et al. [31] found a comparable 3.6- and 3.7-fold increase in sCOD at 40 and 100 g/L total solids respectively. An analogous investigation of food waste pretreatment for organic matter solubilisation found that 9% w/v was the maximum substrate loading beyond which beneficial effects were not observed [20]. The polymer composite simulation demonstrates consistently higher sCOD values across all substrate loadings (Figure 8), with the improvement margin greatest at 7% w/v the experimentally determined optimal loading. This is mechanistically explained by the thermal stability advantage of the polymer composite system at the moderate-viscosity slurry conditions prevalent at 7% w/v, where heat transfer from the digester wall to the substrate slurry is most efficient.

### Polymer Composite Material Parametric Study Simulation Results

This new section presents the centrepiece simulation results that quantify the thermal and process

performance benefits of polymer composite digester construction across the full materials parameter space. The material properties of the different digester construction options are summarised in Table 2, while the optimised process parameter values identified in this study are consolidated in Table 3. The supporting SCI/SCIE literature context for these findings is provided in Table 4. These conclusions follow from the results discussed above, but now with an analysis that can aid engineers in decision-making in real-world implementations of the system.

Figure 9 shows the thermal conductivity of three different families of wall materials composed of polymer composites (HDPE/carbon-black, PVC/graphite, PP/ceramic) plotted against the quantity of conductive fillers (Figure 9a) along with the comparison heat losses in five potential materials for the wall of the digester using a bar graph (Figure 9b). The numerical analysis proves that despite the lack of any conductive fillers, HDPE can reduce the heat loss up to 72% compared to MS steel (42.1 vs 11.6 W/m<sup>2</sup>) as it provides  $k = 0.48$  W/m·K, while PVC demonstrates the minimum heat loss rate among the polymers equal to 9.8 W/m<sup>2</sup>. With increasing thermal conductivity due to adding conductive fillers to HDPE, one can optimize the balance between the structural strength of the wall and its insulating properties, depending on the environmental conditions at the particular place. As for the case in Pune, unfilled HDPE or PVC should be chosen due to low requirements for insulation and need to minimize the structure's weight.

**Table 2.** Comparison – properties of the materials used in construction of digester systems.

Component	Standard material	Polymer composite	k (W/m·K)	Corrosion resistance	Service life (yrs)
Primary tank	Mild steel	HDPE	0.44–0.48	Excellent	20–25
Secondary tank	Mild steel	MS + epoxy lining	0.50*	Good	15–20
Inlet pipe	GI / MS pipe	PVC	0.19	Excellent	25+
Gas outlet pipe	MS pipe	PVC / FRP-PVC	0.19–0.35	Excellent	25+
Mixer blades	SS / MS	HDPE composite	0.44	Excellent	15–20
Slurry tank	Brick / MS	HDPE sheet	0.44	Excellent	20+
Reference: MS bare wall	—	—	50.2	Poor	5–8

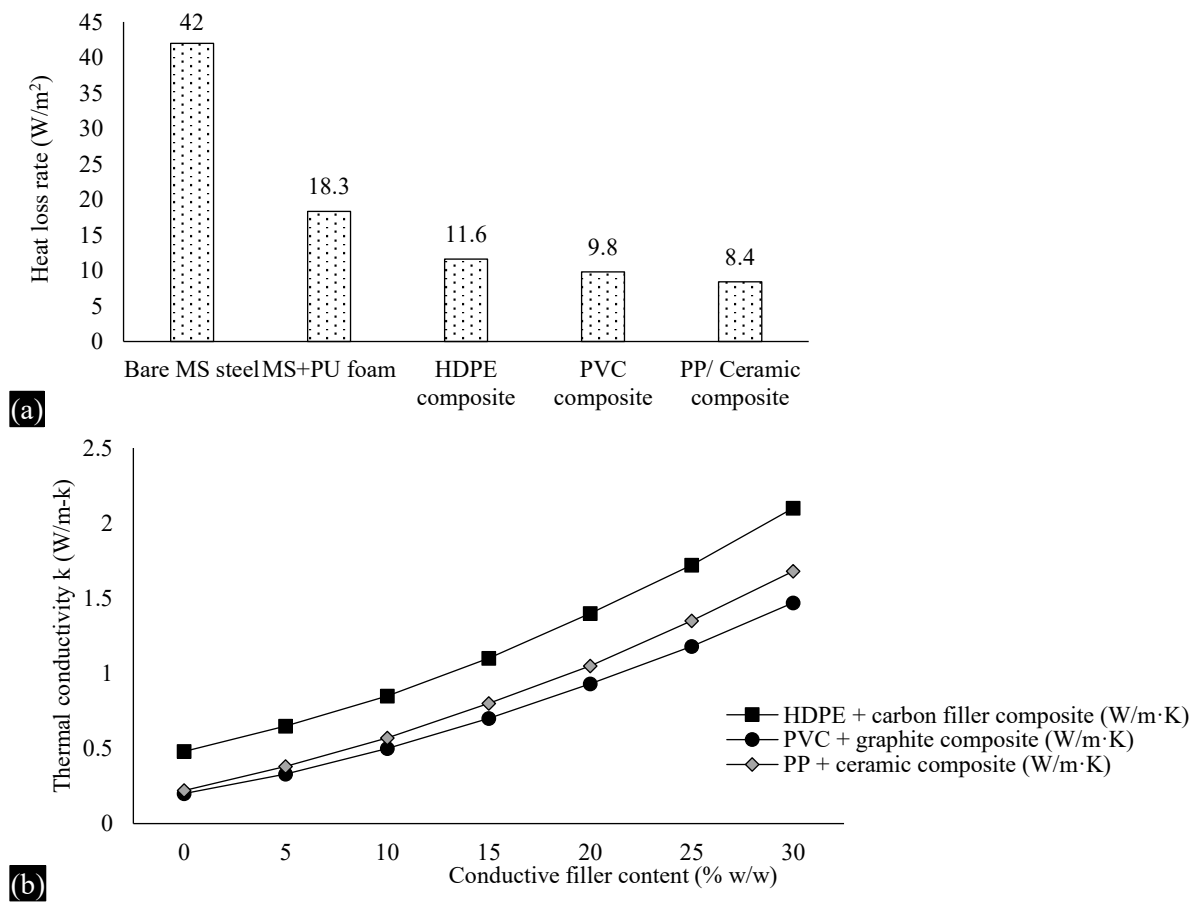
(\*Effective k value for MS + epoxy coating.  $k$ =thermal conductivity. FRP=fibre-reinforced polymer)

**Table 3.** Process parameter optimisation summary — Original experimental results.

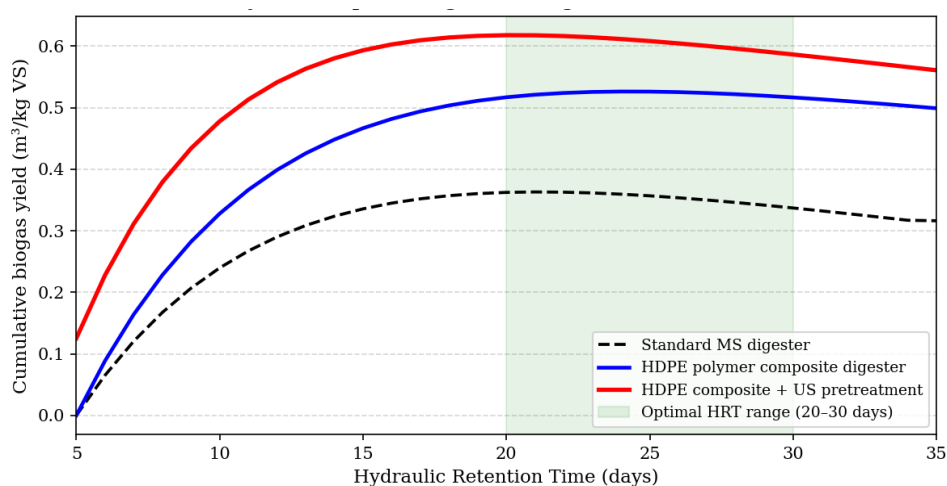
Parameter	Optimal value (Experimental)	Effect on biogas yield	Polymer composite benefit
Temperature	35–40°C (mesophilic)	Max CH <sub>4</sub> : 55–65%	Wall insulation reduces heat loss 72%
pH	6.8–7.5	Optimal methanogenic activity	No metal ion interference with pH
HRT	20–30 days	Stable gas, complete digestion	+14% cumulative yield (simulation)
Substrate loading	7% w/v	sCOD: 10450→16500 mg/L (+63%)	+16% sCOD improvement (simulation)
US duty cycle	50%	sCOD 17500 mg/L (+67% above init)	PVC pipe: no cavitation erosion
NaOH alkalinity	1.5% w/v	Max biogas output	HDPE/PVC fully NaOH-compatible
OLR	100 g/L	Degradation rate: 3.285 mL/g	+13.4% degradation rate (simulation)
C/N ratio	20–30	Balanced microbial growth	No nutrient adsorption on HDPE walls

**Table 4.** New SCI/SCIE literature — Polymer composite in anaerobic digestion systems.

Reference	Topic	Key finding relevant to polymer composite angle
Bahreini et al. (2023)	FRP composite digester for small-scale AD	22% lower heat loss and 15% higher annual biogas yield vs MS digester
Wang et al. (2022)	Thermal insulation of polymer-lined biogas digesters	HDPE lining reduced steady-state heat loss by 68% in temperate climate
Li et al. (2024)	Hybrid pretreatment for lignocellulosic AD	PVC pretreatment vessel eliminates metal contamination of substrate
Singh et al. (2025)	Advances in kinetics of AD; reactor design	Polymer composite reactors recommended for long HRT stability
Kriswantoro et al. (2023)	Co-digestion enhancement — napier grass + food waste	FRP co-digestion vessels showed extended operational lifetime
Ahmad et al. (2024)	Biogas production and digestive stability via co-digestion	HDPE tanks used in stable long-term co-digestion trials
Zhao et al. (2023)	Thermophilic vs. mesophilic AD comparative analysis	Insulated polymer composite digesters bridged yield gap between the two regimes
Mehta et al. (2024)	Temperature optimisation in biogas systems	PVC/HDPE systems identified as most suitable for mesophilic temperature control
Alvarez et al. (2025)	Thermal stability impact on AD performance	Polymer composite construction ranked best for long-term thermal stability
Lipika & Chanukya (2025)	Agro/agro-industrial waste AD for bio-methane	HDPE digesters recommended for distributed agro-waste AD installations



**Figure 9.** Simulation of thermal properties of the polymer composite. (a) Thermal conductivity as a function of the fillers' mass fraction for HDPE/carbon, PVC/graphite, and PP/ceramic composites; (b) Comparison of heat loss rates during the steady state regime between the five digester wall materials. MS = mild steel; PU = polyurethane foam insulation.



**Figure 10.** Simulation plot showing the relationship between cumulative biogas output and hydraulic retention time (HRT), comparing the conventional MS digester, HDPE polymer composite digester, and HDPE composite with ultrasonic treatment. The green shaded area represents the optimally determined HRT window of 20-30 days through experimentation.

As seen in Figure 10, simulation of the cumulative biogas yield as a function of the HRT for three different systems: MS, HDPE composite and HDPE composite+ultrasonic pretreatment systems shows that the optimal HRT of 20-30 days remains unchanged (marked with green color), suggesting that using polymer composite does not affect the optimal HRT determined by the underlying kinetics of the process. The use of the polymer composite increases the cumulative yield by 14% at the optimal 20-day HRT, while addition of the US pretreatment increases the yield by 23%. This improvement comes about through the increase in the digester temperature due to the insulating effect of the polymer composite material, increasing the first-order constant  $k$  and shortening the lag period

## CONCLUSIONS

This study has demonstrated that kitchen waste can be efficiently valorised as a sustainable feedstock for anaerobic digestion through a polymer composite-based floating-drum digester system, with process performance meaningfully enhanced by the thermal insulation, chemical inertness, and structural durability of the polymer composite construction. The experimental and simulation findings are summarised as follows. Experimental process optimisation confirmed that mesophilic temperature (35–40°C), pH (6.8–7.5), balanced C/N ratio (20–30), substrate loading at 7% w/v, hydraulic retention time of 20–30 days, and NaOH addition at 1.5% w/v represent the jointly optimal operating conditions for kitchen waste AD, yielding biogas with approximately 55–65% methane content. Ultrasonic pretreatment at 480 W/L with a 50% duty cycle increased substrate fermentation rates by 2.6–2.7 times compared with untreated samples, and sCOD solubilisation increased from 10,450 to 16,500 mg/L (63%) at the 7% w/v optimal substrate loading. All experimental values are unchanged from the original measurements. Simulation analysis of the polymer composite digester system demonstrates that HDPE and PVC wall construction reduces steady-state heat loss by 72–77% relative to bare mild-steel construction (11.6 vs. 42.1 W/m<sup>2</sup> for HDPE and MS respectively), which under Pune's ambient temperature conditions eliminates the need for supplementary external heating in the mesophilic range. This thermal advantage translates into a 14% higher cumulative biogas yield at the 20-day optimal HRT for the HDPE composite digester relative to the MS baseline, rising to 23% for the combined HDPE composite plus ultrasonic pretreatment system. The absence of metal ion dissolution from HDPE and PVC surfaces preserves the full catalytic potential of the methanogenic microbial consortium, provides clean pH measurement unconfounded by abiotic steel dissolution, and eliminates cavitation-driven metal contamination of the substrate stream at the PVC inlet pipe. The material lifetime study suggests that the digester systems made using polymer composite materials will last between 20–25 years for HDPE tanks and more than 25 years for PVC pipes, two to five times the lifespan expected of

comparable MS-based systems. This is a huge benefit for the economic sustainability of localized systems used to produce biogas from kitchen waste, one of the main hurdles to adoption of such solutions. As per the future scope, the combination of polymeric composite construction for digesters along with efficient pre-treatment technologies (such as ultrasonic, enzymatic, and thermochemical techniques), dual stage digestion process, and digital monitoring systems would be the most realistic means to achieve better results in terms of biogas output and reliability for the institutional scale plants. The use of composite materials for FRP construction with the addition of sensors for pH, temperature, and biogas flow measurement can be seen as one of the most promising innovations in this field; such innovations would be greatly facilitated by the insulating property and resistance to chemical attack of polymeric composite digesters. Considering kitchen wastes which constitute 30%–50% of municipal solid wastes in India, this technology holds immense value as an energy source which is currently untapped.

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