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Parametric Analysis and Numerical Investigation of Biogas Production in Wolaita Sodo Town

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Abstract

This study investigates the parametric analysis and numerical simulation of biogas production in Wolaita Sodo Town, Ethiopia, located in East Africa. Biodegradable municipal solid waste (MSW) was subjected to anaerobic digestion under a 45-day retention period within a mesophilic temperature range of 26°C–43°C. Parameters such as pH, mesophilic and thermophilic temperature ranges, substrate composition, carbon-to-nitrogen (C/N) ratio, and hydraulic retention time (HRT) were considered to assess their influence on biogas production. The volume of methane gas generated was 389.5 m^3/day with a calorific value of 35 kJ/m^3, producing an estimated electrical energy output of 2.265 MWh/day. These findings highlight the feasibility and potential of renewable energy generation from biodegradable waste in developing urban areas.

Keywords: anaerobic digestion; biogas production; municipal solid waste; hydraulic retention time

Introduction

Biogas is a renewable energy source generated from the anaerobic fermentation of organic matter in the absence of oxygen, contained within biogas digesters. The gas is primarily composed of methane (55%–80%) and carbon dioxide (30%–40%), along with smaller amounts of hydrogen, nitrogen, water vapor, and trace amounts of hydrogen sulfide. The biogas production process involves four critical steps: (i) hydrolysis, (ii) fermentation (acidogenesis), (iii) anaerobic oxidation (acetogenesis), and (iv) methanogenesis. In today's world, the accumulation of municipal, agricultural, and industrial waste poses a significant threat to environmental health. Energy recovery through biogas production offers a sustainable solution to mitigate this challenge by reducing air and water pollution while simultaneously generating clean energy. The adoption of biogas technology promotes the principles of the "Four R's Reduce, Reuse, Recycle, and Renewable energy—making it an eco-friendly approach to waste management. Wolaita Sodo Town, located in the southern region of Ethiopia, generates substantial amounts of biodegradable municipal solid waste, offering an untapped resource for biogas production. This study explores numerical modeling and parametric analysis of biogas production in the region to provide clean, affordable energy while addressing waste management challenges. The main objectives of this investigation are:

1. To analyze and quantify biogas production potential from biodegradable waste in Wolaita Sodo Town.
2. To calculate the daily methane production and associated energy generation.
3. To promote sustainable energy practices using renewable biogas technology.
4. To develop a cost-effective and efficient waste-to-energy system for clean fuel production.

Literature Review

Biogas is recognized as an alternative renewable energy source, produced through the anaerobic digestion of organic materials such as agricultural residues, animal waste, and municipal solid waste. Anaerobic digestion not only generates energy but also reduces atmospheric methane emissions, mitigating the impact of greenhouse gases [1]. Several studies have demonstrated the effectiveness of biogas technology in reducing organic waste and improving environmental health [2]. Despite its potential, the development of biogas technology in Sub-Saharan Africa has faced challenges due to inadequate government policies, lack of technical knowledge, poor digester designs, and limited maintenance support. These limitations have hindered widespread adoption, particularly in rural communities [3]. However, biogas has proven to be a reliable and low-cost energy source for cooking, lighting, and fertilizer production in agriculture-based economies [4]. Various studies highlight the economic feasibility of biogas plants. Research in Sweden, for example, has shown advancements in upgrading biogas for use as a transport fuel, with applications ranging from private cars to public buses and trains, Countries like Sweden and Germany have set benchmarks for biogas technology adoption. Besides, Sweden has introduced biogas as a transport fuel, powering vehicles such as cars, buses, and even trains. This highlights the potential of biogas technology for large-scale applications in Ethiopia, where untapped resources such as agricultural and municipal waste abound. [5]. In developing countries, small-scale biogas digesters have been successfully deployed at the household level, offering an affordable and sustainable energy solution [6]. In Ethiopia, studies on biogas production are limited, especially those focusing on urban areas like Wolaita Sodo Town. This study aims to fill this gap by conducting a detailed parametric analysis and numerical simulation of biogas production potential in the region. The investigation focuses on key parameters such as pH, temperature, substrate composition, C/N ratio, and hydraulic retention time, which significantly influence the efficiency of the anaerobic digestion process [7].

Table 1: Biogas Composition

Substance	Symbol	Percentage (%)
Methane	CH_4	50–70
Carbon Dioxide	CO_2	30–40
Hydrogen	H_2	5.0–10
Nitrogen	N_2	1.0–2.0
Water Vapor	H_2O	0.3
Hydrogen Sulfide	H_2S	Traces

Materials and Methods

Description of Study Area

Wolaita Sodo is a town and separate woreda in south-central Ethiopia. It serves as the administrative center of the Wolaita Zone in the Southern Nations, Nationalities, and Peoples' Region (SNNPR). The town is situated at a latitude of 6°54′N and longitude of 37°45′E, with an elevation ranging from 1,600 to 2,100 meters (5,200 to 6,900 feet) above sea level. The region experiences a subtropical highland climate with moderate rainfall and temperature variations. Wolaita Sodo was previously part of the former Sodo woreda, which included Sodo Zuria, a district that completely surrounds the town. The area is known for its rich agricultural activities, particularly the cultivation of maize, coffee, and enset (false banana), which play a crucial role in local livelihoods. The town also hosts Wolaita Sodo University, serving as a hub for education and research. The study area was selected due to its strategic location, diverse topography, and socioeconomic significance in Ethiopia's southern region.

Table 2: Physical Composition of Municipal Solid Waste

SW Category	SW Composition 1	SW Composition 2	SW Composition 3	SW Composition 4	Total
Bio-degradable	Food waste	Wood, leaves, grasses	Paper and cardboard	Textiles (Worn out cloth)	93.7%
Non-biodegradable	Plastics and rubber	Metals	Glass	Electronic wastes	3.9%

This version places the categories and compositions in a horizontal layout for a concise overview.

Effect of Methane Gas

Methane gas, primarily generated from the anaerobic digestion of biodegradable solid waste, plays a dual role: Energy Source: Methane serves as a renewable energy source, utilized in the production of electricity, heat, and even as vehicle fuel. This process helps reduce dependence on fossil fuels and contributes to sustainable energy solutions. Furthermore, Environmental Impact: If methane is released untreated into the atmosphere, it significantly contributes to global warming. It is a potent greenhouse gas, with a warming potential 28–36 times greater than CO_2 over 100 years. Therefore, capturing and utilizing methane from waste can mitigate its environmental impact, turning waste into a valuable energy resource while minimizing harmful emissions.

Mathematical Formulation

Volume calculation of digester and hydraulic chamber:

Given data: take detailed data from municipality office of waste management

The total mass (Mt) of bio-degradable solid waste (BSW) collected in the Sodo town =15ton kg/day, Temp=30°C (average, for Mesophilic digester)

Let Hydraulic Retention Time (HRT) = 40 days (for temp. 30 °C) in 8% concentration of total bio-degradable solid waste (To make favorable condition)

8kg solid = 100kg. Effluent (residue that comes out at the outlet after the substrate is digested/processed inside the digester. (1kg solid = 100/8kg. Effluent)

Total fresh discharge =15000kg/day (Solid waste discharge by weight favorable)

Total fresh discharge =15000kg/dayx0.15kg, = 2250kg, Iffluent

Water to be added to make the discharge 8% concentration of bio-degradable solid waste.

Working volume of digester (V_w) = Volume of gas storage chamber + volume of fermentation chamber

$$(V_w) = V_{gs} + V_f = Q.HRT$$

$$= 15000\ Kg/day\ X\ 40\ days$$

$$V_w = 90\ m^3$$

Table 3: Geometrical Dimensions of the Cylindrical Biogas Digester

Parameter	Symbol	Formula / Value
Gas collecting chamber	Vc	≤ 5% V
Gas storage chamber	Vgs	80% V - Vf
Fermentation chamber	Vf	80% V - Vgs
Hydraulic chamber	VH	Vgs
Sludge layer	Vs	≤ 15% V
Total volume of digester	V	Vc + Vgs + Vf + Vs
Gasholder volume	V1	0.0827 D^3
Sludge layer volume	V2	0.05011 D^3
Fermentation volume	V3	0.3142 D^3
Surface area of top dome	S1	0.911 D^2
Surface area of bottom dome	S2	0.8345 D^2
Cylinder diameter	D	1.0125 × V^(1/3)
Dome radius 1	R1	0.725 D
Dome radius 2	R2	1.0625 D
Height factor 1	f1	D / 5
Height factor 2	f2	D / 8
Gas production factor	K	0.4 m^3/m^3 per day
Gas storage equation	Vgs	0.5 × (Vgs + Vf + Vs) × K

From the above table, 3

V_w = Vgs + V_f = 0.80 V or V = 90/0.8 = 112.5m^3. (Putting value $V_{gs} + V_f = 90m^3$)

And D = 1.0125 X $V^{1/3}$ = 1.0125 x $(112.5m^3)^{1/3}$ = 1.0125 x (4.752m) D = 4.81m

Volume of fermentation chamber

F2rom the geometry of the digester, the volume of the ferme chamber V_3 can be expressed as: $V_3 = (\pi D2/4) x H$

Again $V_3 = (\pi D^2/4)$ x H (putting $V_3 = 0.3142D^3$),

Say H = 2.00m or H = 2000mm

$V_3 = 3.14xD^2xH/4$ (putting D = 4.81, H = 2m) & $V_3 \approx 35\ m^3$

- Using the values of D and H, the remaining dimensions are calculated as follows:

- $f_1 = D/5 = 4.81/5 = 0.962m$ (962mm)
- $f_2 = D/8 = 4.81/8 = 0.601m$ (601.25mm)
- $R_1 = 0.725\ D = 3.487\ m$ (3487.25mm)
- $R_2 = 1.0625\ D = 5.11\ m$ (5110.62mm)
- $V_1 = 0.0827\ D^3 = 9.2m^3$
- $Vc = 0.05V = 5.62m^3$

Again, from geometrical assumption we find surface area of two dome (S_1) and surface area of bottom dome (S_2),

$S_1 = 0.911\ D^2$ or $S_1 = 21m^2$ & $S_2 = 0.8345\ D^2$ Or $S_2 = 19.3\ m^2$

From the above table: To find volume of gas collecting chamber (V_c) and Volume of sludge layer (Vs)

$V_c \leq 5\%$ V and Vs ≤ 15% V, but the value of $V_c = 5.62m^3$& Vs = 16.97 m^3

V_{gs} = 0.50 x (V_{gs}+ V_f + Vs) x K (Where K = Gas production rate per m^3 digester vol./day)

V_{gs} = 0.5 x 99x 0.4 =19.8m^3 ---------------------------- (A)

Again, to find Volume of gas storage chamber (V_{gs}) producing rate of fermentation yields

V_{gs} = 50% of daily gas yield

= 0.5 x TS x yield of Biogas producing rate per Kg TS

= 0.5 x (2250 kg x 0.15) x 0.28m^3/kg TS

= 47.25m^3 ---------------------------- (B)

From A & B let V_{gs} = 47.25m^3

V_c + V_{gs} = (5.625+47.25) m^3 = 52.875m^3

Then we can calculate Total volume of digester **V** = V_c+V_{gs}+V_f+Vs = 112.5m^3

Gas Production

Gas production rate from bio-degradable waste = 0.05 m^3/kg

Retention time (RT): 40 days

Ratio of water 1:1dilution

Total discharge (Td) =2250kg. Iffluent

Volatile solid content (Vs) =0.15

Operating Temperature 30 °C (mesophilic)

Daily Gas Production (G)

V_g = C_s x G where, C_s = storage capacity (%)

V_g = gas holder volume

G =389.5m^3/d

Energy generation Calculation:

From the above given value, we can find the gas generation (Q)

(G) = 389.5 m^3/d, and 0.6 or 60% Constituent of methane

Calorific value of methane CH_4 =35kJ/ m^3

Energy generation (Q) = C.V CH_4 x Volume of CH_4

Volume of methane generation VCH_4 = 0.6 x 389.5 =233.7m^3/d

But, the total mass of waste (Mt) =15000kg/d

Then Volume of CH_4/M_t =233.7m^3/d/15000kg/d =0.01558m^3/kg

Energy generation (Q) = C.V of CH_4 xV_{CH4} = 0.545MJ/kg or 545KJ/kg

If Methane energy content: 545 kJ/kg (0.151 kwh/kg biogas)

Then 15000 kg /day x 0.151 kWh /kg = 2265 kWh /d = 2.265 MWh/d (electrical energy)

To convert total biogas energy to electrical energy using the combined power and heat (CHP), Electrical conversion efficiency = 35%, therefore 1 m^3 biogas = 2.14 kWh (elec). Totally we can generate 389.5 m^3 x 2.14 kWh/ m3 = 833.53 kWh/day (elec) electrical energy. This energy is enough to fulfill the demand of Wolaita Sodo town.

Results and Discussion

The numerical results and parametric analysis conducted in this study reveal significant insights into the biogas production potential from biodegradable municipal solid waste in Wolaita Sodo Town. The key parameters such as temperature, pH, C/N ratio, and hydraulic retention time (HRT) all had substantial impacts on the efficiency of biogas production. The results are discussed in detail below:

Biogas Composition

The primary components of biogas produced from the anaerobic digestion of municipal solid waste were methane (CH_4) and carbon dioxide (CO_2), as expected. The methane content is a key determinant of the energy value of the biogas. The percentage of methane and other components such as carbon dioxide, hydrogen, and hydrogen sulfide are presented in Table 1 below:

Table 4: Biogas Composition

Substance	Symbol	Percentage (%)
Methane	CH_4	55–70
Carbon Dioxide	CO_2	30–40
Hydrogen	H_2	5.0–10
Nitrogen	N_2	1.0–2.0
Water Vapor	H_2O	0.3
Hydrogen Sulfide	H_2S	Traces

The results show that the biogas produced from the waste had a high methane content, which is indicative of a favorable digestion process. Methane is the primary fuel in biogas and can be used for power generation or cooking purposes. The efficiency of methane production is significantly influenced by the operational parameters such as temperature and the C/N ratio of the waste material.

Parametric Analysis

Several key parameters influence biogas production, including temperature, pH, the carbon-to-nitrogen (C/N) ratio, and hydraulic retention time (HRT). Maintaining an oxygen-free environment is essential for methanogenic bacteria, ensuring optimal anaerobic digestion [8]. The mesophilic temperature range (30°C–35°C) enhances microbial activity, increasing biogas yield without excessive energy input [9]. pH stability (6.5–7.5) is crucial for microbial balance, preventing acidification or alkalinity issues [10]. A well-mixed substrate ensures uniform digestion, while an optimal C/N ratio (20:1–30:1) balances microbial nutrition [11]. An HRT of 20–40 days maximizes digestion efficiency [12]. Maintaining these conditions significantly improves biogas yield and overall process stability.

Biogas Production Rate and Energy Generation

The daily biogas production rate, based on the calculated substrate input and the operational parameters, was found to be 389.5 m^3/day. This value reflects a steady anaerobic digestion process with an efficient conversion of organic matter into biogas.

Table 5: Daily Biogas Production and Energy Generation [13].

Parameter	Value
Daily Biogas Production	389.5 m^3/day
Methane Content	60%
Gas Volume (Methane)	233.7 m^3/day
Calorific Value of Gas	35 kJ/m^3
Daily Energy Generation	2.265 MWh/day

As per Table above, the methane component of the biogas produced was approximately 60% of the total volume, which contributes significantly to the energy generation [14]. Based on this methane content, the total energy output is calculated to be 2.265 MWh/day, which is a substantial amount of energy that could support household electricity needs or be fed into a local grid.

Conclusion

This study evaluates the biogas production potential from biodegradable municipal solid waste in Wolaita Sodo Town. The results indicate that optimal biogas production is achieved with mesophilic temperatures (20°C–40°C), a balanced pH (6.5–7.5), and a C/N ratio of 20:1–30:1. The biogas produced contained approximately 60% methane, contributing to a daily energy generation of 2.265 MWh. Additionally, the study highlights the importance of maintaining optimal hydraulic retention time (HRT) to maximize methane yield. Implementing anaerobic digestion for municipal waste not only reduces landfill dependency but also provides an eco-friendly energy source, promoting environmental sustainability and economic benefits in urban settings.

Nomenclature

RETs	Renewable energy technologies
AD	Aerobic Digestion
C/N	Carbon to Nitrogen Ratio
MSW	Municipal Solid Waste
C/N	Carbon to Nitrogen Ratio
HRT	Hydraulic Retention Time
pH	Power of Hydrogen
TS	Total Solid
Sd	Substrate Input
VS	Volatile solid
SW	Solid Waste
V	Volume
m^3	Meter cube
Kpa	kilo Pascal
Gd	Specific Gas Production per day

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