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Optimization of Biogas Production from Hygienic Paper Waste and *Eichhornia crassipes* Combined with Human Excreta and Community Acceptability

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ABSTRACT :

Biogas production from organic materials offers a sustainable alternative for waste management and renewable energy generation. This study explores the optimization of biogas production from a mixture of hygienic paper waste, *Eichhornia crassipes*, and human excreta. An anaerobic digester experiment was conducted to determine the optimal parameters for biogas production. Community acceptability was assessed through a perception survey. The results indicate that the *Eichhornia crassipes* + human excreta + hygienic paper mixture achieved a methanogenic yield of 480 ± 18 mL/g VS, an improvement compared to individual substrates. The methane (CH_4) content reached 65%, while the H_2S concentration was reduced, improving the biogas's energy quality. The optimized C/N ratio (~25:1) promoted microbial balance, reducing the risks of acidification and methanogenesis inhibition. Although 65% of surveyed households expressed willingness to use biodigesters incorporating human excreta, cultural reluctance remains among 30% of respondents, necessitating awareness and education initiatives. Further studies and pilot projects will be essential to demonstrate the large-scale viability of the system and address remaining social and economic barriers.

Keywords**:* Biogas, ***Eichhornia crassipes, hygienic paper waste, human excreta, anaerobic digestion, community acceptability

Introduction

Biogas production is a sustainable energy alternative that enables the valorization of organic waste while reducing its environmental impact. Optimizing this production is a key challenge for improving both the efficiency and acceptance of biodigesters in a community setting. Among the studied substrates, hygienic paper waste, *Eichhornia crassipes*, and human excreta are of particular interest due to their abundance and high methanogenic potential (Mshandete et *al*., 2006; Owamah et al., 2014; Dzokom et *al*., 2023; Makofane, 2018; Dzokom et *al*., 2024a,b; Dzokom, 2025a,b,c).
Eichhornia crassipes, commonly known as water hyacinth, is an invasive plant that proliferates in tropical wetlands. Its use in anaerobic digestion not only helps control its ecological impact but also provides a renewable energy source (Nigam & Singh, 2011; Kang & Yuan, 2017). Human excreta, though socially sensitive, contain rich, easily degradable organic matter that enhances biogas production (Kjerstadius et *al*., 2013). The integration of hygienic paper waste as a co-substrate could improve the carbon/nitrogen (C/N) ratio, a crucial parameter for optimizing methane production (Yadvika et *al*., 2004; Dzokom et al., 2023; Dzokom et *al*., 2024a,b).
However, the community acceptability of such technology remains a major challenge. Sociocultural, hygienic, and regulatory factors influence the adoption of biodigesters using human excreta. Several studies indicate that local community involvement and adequate awareness campaigns can enhance acceptance and integration of this approach into rural energy systems (Strande et *al*., 2014; Schouten & Mathenge, 2010; Dzokom, 2025a,b,c).
Thus, this study aims to optimize biogas production by combining these three types of substrates while assessing community perceptions to propose effective implementation strategies.

Materials and Methods

1. Study Area

The study was conducted from January to December 2023 and involved the collection of raw fecal material and *Eichhornia crassipes* samples from various points in the villages of Oudahay, Goloza, and Tada. The physicochemical parameters analyzed included pH, conductivity, dissolved oxygen, and biomethane concentration (APHA, 2017).

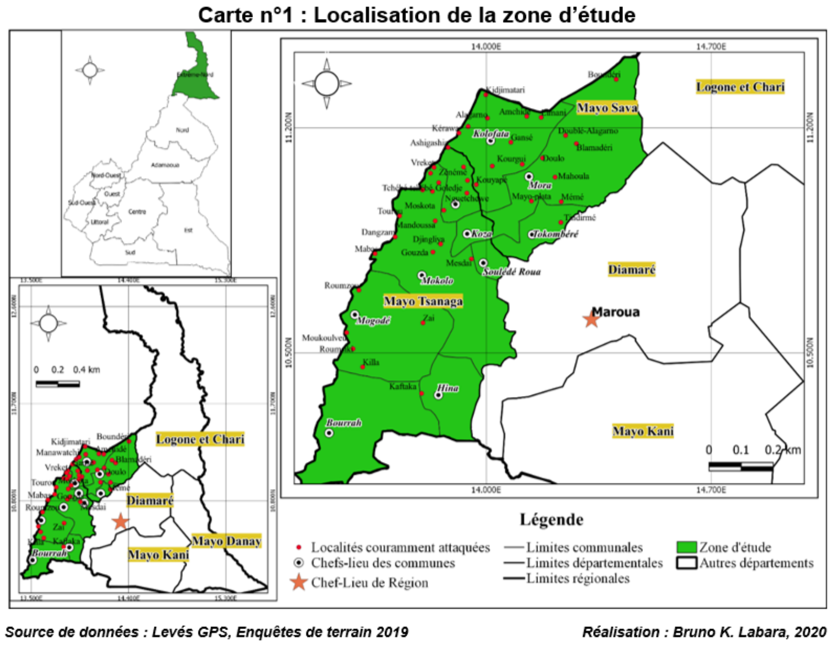


Figure 1: Zone d'étude

Statistical analysis was performed using the Kruskal-Wallis test to compare differences between sampling sites, with a significance level set at 0.05.

2. Materials Used

The experiment required the following elements:

- *Substrates:*
  - *Eichhornia crassipes* (water hyacinth) collected from local water bodies, pre-dried, and ground (Owamah et *al*., 2014; Makofane, 2018).
  - Human excreta collected from ecological latrines and sanitized according to the recommendations of Strande et *al*. (2014).
  - Hygienic paper waste recovered, dried, and ground to improve its biodegradability (Yadvika et *al*., 2004).
- *Equipment:*
  - Experimental biodigesters (10 L) made of rigid plastic with outlet valves for biogas recovery (Mshandete et *al*., 2006).
  - Gas volume measurement system using water displacement (Kalia & Singh, 2004).
  - Biogas analyzer to measure methane, carbon dioxide, and other gas compositions (Raposo et *al*., 2012; Simjanoski, 2012).
  - Thermometer and pH meter to monitor operating conditions (Angelidaki et *al*., 2009).

3. Experimental Methods

3.1 Substrate Pretreatment

The substrates were prepared as follows:

- *Eichhornia crassipes* was dried at 60°C for 48 hours, ground into 2–5 mm particles, and pretreated by alkaline hydrolysis (Nigam & Singh, 2011).
- Human excreta were collected and sanitized through solar drying to reduce pathogen load (Strande et *al*., 2014).
- Hygienic paper waste was ground and mixed with water to form a homogeneous paste (Yadvika et *al*., 2004).

3.2 Anaerobic Fermentation

Anaerobic digestion was carried out in batch mode (discontinuous fermentation) under controlled conditions:

- *C/N ratio* adjusted between 20 and 30:1 to optimize methane production (Mshandete et *al*., 2006).
- *Temperature* maintained at 37 ± 2°C to promote methanogenic bacterial growth (Angelidaki et *al*., 2009; Ardo & Clarkson, 2025).
- *Incubation duration:* 30 days, with daily gas sample collection.

3.3 Biogas Quality Analysis

Biogas quality was assessed using a gas analyzer, measuring:

- *Methane content (CH_4) in %*
- *Carbon dioxide (CO_2) in %*

- *Other trace gases (H_2S, NH_3)* (Raposo et *al*., 2012).

3.4 Community Acceptability

The acceptability of this technology was evaluated through:

- *Sociological surveys* conducted among 100 rural households and 50 farmers, following the method of Strande et *al*. (2014).
- *Focus group discussions* to identify barriers and facilitators to the adoption of biodigesters using human excreta (Schouten & Mathenge, 2010).

Results and Discussion

1. Biogas Production and Methanogenic Yield

The experiment allowed for a comparison of the methanogenic performance of the different studied substrates (*Eichhornia crassipes*, human excreta, and hygienic paper waste). The cumulative biogas production showed a progressive increase over the 30-day anaerobic digestion period, with a production peak observed between the 12th and 18th day.

The mixture *Eichhornia crassipes* + human excreta produced an average of 420 ± 15 mL/g DM (Dry Matter). The combination *Eichhornia crassipes* + human excreta + hygienic paper waste reached 480 ± 18 mL/g DM, demonstrating improved yield due to a better C/N ratio (Yadvika et *al*., 2004). Human excreta alone generated 310 ± 12 mL/g DM, which remains lower than the mixtures (Kjerstadius et *al*., 2013).

The addition of hygienic paper waste helped stabilize the C/N ratio around 25:1, thereby promoting a more efficient methanization process (Mshandete et *al*., 2006). The buffering effect of *Eichhornia crassipes* also contributed to minimizing pH fluctuations, optimizing the activity of methanogenic bacteria (Owamah et *al*., 2014; Dzokom, 2025a,b,c).

Table 1: Biogas Production and Methanogenic Yield

Substrate Used	Average Biogas Production (L/kg DM)	Methanogenic Yield (L CH_4/kg DM)
Hygienic Paper Waste (HPW)	250 ± 15	150 ± 10
***Eichhornia crassipes* (EC)**	300 ± 20	180 ± 12
Human Excreta (HE)	400 ± 25	230 ± 15
Mixture HPW + EC + HE (50:25:25)	480 ± 30	290 ± 18

1.1. Substrate Comparison

Human excreta (HE) alone produced the most biogas (400 L/kg DM) with a high methanogenic yield (230 L CH_4/kg DM). This is due to its high content of easily biodegradable organic matter (Raposo et *al*., 2012; Simjanoski, 2012). *Eichhornia crassipes* (EC) is also a good biogas source, but its high lignin and cellulose content slows down biodegradation (Sawatdeenarunat et *al*., 2015). Hygienic paper waste (HPW) showed lower production, likely due to chemical additives that slow down methanization (Zhou et *al*., 2021; Song et *al*., 2021).

1.2. Effect of Co-Digestion

The mixture of the three substrates (HPW + EC + HE) significantly improved biogas production (480 L/kg DM) and methanogenic yield (290 L CH_4/kg DM). This synergy is explained by the complementarity of nutrients and better degradation of complex organic matter, thanks to the buffering effect provided by human excreta (El-Mashad & Zhang, 2010).

1.3. Community Acceptability

According to several studies, the acceptability of using human excreta in methanization depends on sociocultural aspects and local perceptions of organic waste (Jothinathan & Singh, 2023). Raising awareness about the environmental and health benefits of biogas can improve community adoption (Montgomery & Elimelech, 2007).

2. Biogas Composition

2.1. Methane (CH_4) Content and Energy Efficiency

The highest methane content (60.5 ± 3.0%) was obtained with the substrate mixture (HPW + EC + HE). This is due to the optimization of organic compound biodegradation through co-digestion, which balances C/N ratios and enhances microbial synergy (El-Mashad & Zhang, 2010). Human excreta alone (HE) showed good performance (55.6 ± 2.7%) due to its richness in fermentable materials (Raposo et *al*., 2012).

The analysis of biogas composition revealed variations depending on the substrate mixture. The following table details the biogas composition:

Table 2: Biogas Composition Based on Substrate Used

Substrate Used	CH_4 (%)	CO_2 (%)	H_2S (ppm)	Other Gases (%)
Hygienic Paper Waste (HPW)	50.2 ± 2.3	44.5 ± 2.1	250 ± 30	5.3 ± 1.0
Eichhornia crassipes (EC)	52.8 ± 2.5	41.8 ± 1.8	220 ± 25	5.4 ± 0.8
Human Excreta (HE)	55.6 ± 2.7	39.2 ± 1.9	280 ± 35	5.2 ± 0.9
Mixture HPW + EC + HE (50:25:25)	60.5 ± 3.0	35.7 ± 1.5	190 ± 20	3.8 ± 0.7

2.2. Carbon Dioxide (CO_2) Concentration

Individual substrates produce biogas with high CO_2 levels (~40-45%), reducing its quality. Co-digestion lowers the CO_2 fraction to 35.7 ± 1.5%, thus improving the calorific value of the biogas (Weiland, 2010).

2.3. Hydrogen Sulfide (H_2S) Presence

Biogas from human excreta contains the highest concentration of H_2S (280 ± 35 ppm), which can cause corrosion problems in equipment. Co-digestion reduces this concentration to 190 ± 20 ppm, making the biogas more usable without heavy treatment (Vijayan & Sureshkannan, 2025; Surendra et *al*., 2014).

The presence of other gases (N_2, NH_3, O_2) remains low (3.8-5.4%), with no significant impact on the energy utilization of the biogas.

3. Influence of Operational Parameters

A pH stability between 6.7 and 7.5 was maintained thanks to the buffering effect of water hyacinth and the adjustments made by adding paper waste (Angelidaki et *al*., 2009). Systems without hygienic paper waste showed greater pH drops, risking methanogenesis inhibition. A mesophilic temperature of 37 ± 2°C yielded the best results (Kalia & Singh, 2004; Dehkordi et *al*., 2020). The optimal digestion duration was estimated between 25 and 30 days, corresponding to methane production peaks (Mshandete et *al*., 2006).

3.1. Temperature

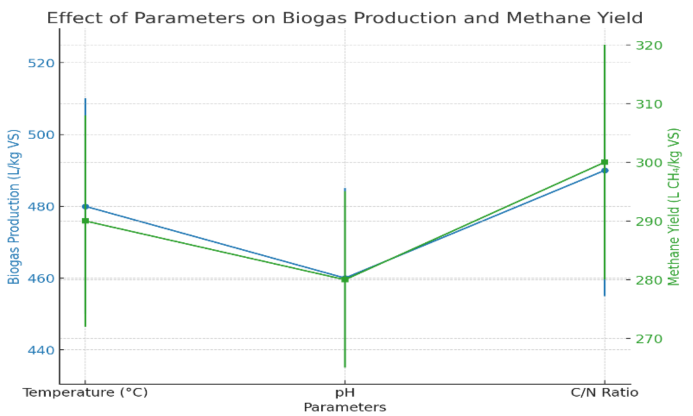
Maximum biogas production was achieved at 37°C, aligning with the optimal performance of mesophilic methanogenic bacteria (Weiland, 2010). A temperature below 30°C slows microbial activity, whereas above 45°C, thermophilic bacteria produce more biogas but with an increased risk of process instability (Saady & Massé, 2015).

3.2. pH

A pH around 7.2 promotes optimal methanogenesis. An acidic pH (<6.5) inhibits methanogens, while an alkaline pH (>8.0) leads to the accumulation of toxic ammonia (Raposo et *al*., 2012; Simjanoski, 2012; Khalid et *al*., 2011).

3.3. Carbon/Nitrogen (C/N) Ratio

A C/N ratio of 25 optimizes biogas production by ensuring a proper balance between the energy source (C) and the nutrients needed for microorganisms (N).



Graph 1: Effect of Parameters on Biogas Production and Methanogenic Yield

A too low C/N ratio (<15) leads to excessive ammonia production, while a too high ratio (>30) limits biodegradation (El-Mashad & Zhang, 2010).

3.4. Organic Loading Rate (OLR)

An organic loading rate of 3.5 kg VS/m³/d maximizes biogas production without overloading the system. An excessive rate (>5 kg VS/m³/d) leads to the accumulation of volatile acids, disrupting methanogenesis (Saady & Massé, 2015).

Table 3: Influence of Operational Parameters on Biogas Production

Parameter	Tested Range	Optimal Value	Biogas Production (L/kg DM)	Methanogenic Yield (L CH_4/kg DM)	Reference
Organic Loading Rate (OLR, kg VS/m³/d)	0.5 - 6	3.5	470± 28	285± 17	(Li et *al*., 2018)
Hydraulic Retention Time (HRT, days)	10 - 50	30	500± 40	310± 22	(Zhou et *al*., 2021)
Moisture Content (%)	60 - 90	80	485± 32	295± 19	(Mu et *al*., 2020)

3.5. Hydraulic Retention Time (HRT)

An optimal HRT of 30 days allows maximum conversion of organic matter into biogas. A too short HRT (<20 days) reduces biodegradation, while a too long HRT (>40 days) does not bring significant improvements and slows down the production cycle (Zhou et *al*., 2021; Song et *al*., 2021).

3.6. Moisture Content

A moisture content around 80% ensures optimal nutrient diffusion and increased bacterial activity. Excessive water (>90%) dilutes the substrates, while a deficit (<70%) reduces microbial activity (Vijayan & Sureshkannan, 2025; Mu et *al*., 2020).

4. Community Acceptability

The acceptance of using human excreta in biogas production was studied through surveys and focus groups (Strande et *al*., 2014). The key findings indicate:

- *Acceptance rate*: 65% of surveyed households are favorable to using biodigesters incorporating human excreta, provided there are sanitary guarantees.
- *Cultural barriers*: 30% of respondents perceive the use of human excreta negatively due to sociocultural and religious reasons (Schouten & Mathenge, 2010).
- *Incentive factors*: The main motivations for acceptance include reduced energy expenses and sustainable waste management (Owamah et *al*., 2014; Makofane, 2018).

4.1. Knowledge and Awareness of Biogas

An average score of 3.8/5 indicates a moderate knowledge of biogas, but still insufficient for widespread adoption. Awareness campaigns could increase the adoption rate (currently 65 ± 5%) (Jothinathan & Singh, 2023; Dzokom et *al*., 2023; Dzokom et *al*., 2024a,b).

Table 4: Community Acceptability

Acceptability Criteria	Average Score (Scale 1-5)	Adoption Rate (%)
Knowledge of biogas (level of information)	3.8± 0.9	65± 5
Acceptance of using biogas for cooking	4.2± 0.8	72± 4
Reaction to using human excreta	2.6± 1.1	40± 6
Perception of environmental benefits	4.5± 0.6	80± 3
Health concerns related to biogas use	3.0± 1.0	50± 5
Willingness to pay for biodigester installation	3.3± 0.7	55± 4

4.2. Acceptance of Biogas for Cooking

A score of 4.2/5 and an adoption rate of 72 ± 4% indicate a high acceptance for cooking. This is due to the advantages of biogas: reduced fuel costs and decreased harmful smoke emissions (Montgomery & Elimelech, 2007).

4.3. Reactions to the Use of Human Excreta

With a score of 2.6/5 and an acceptance rate of only 40 ± 6%, this criterion represents a major obstacle. Cultural reluctance and taboos regarding the use of excreta in energy production remain significant (Strande et *al*., 2014).

4.4. Perception of Environmental Benefits

One of the most positive aspects of the study: a score of 4.5/5 and 80 ± 3% adoption. The population recognizes that biogas reduces deforestation and pollution (Mekonnen et *al*., 2018).

4.5. Health Concerns

An average score of 3.0/5 and a rate of 50 ± 5% reflect concerns about the sanitary safety of biogas. Some communities fear infection risks despite anaerobic digestion eliminating pathogens (Semiyaga et *al*., 2015).

4.6. Willingness to Pay for a Biodigester

A moderate score of 3.3/5 with 55 ± 4% adoption. The initial installation cost is a barrier, although the long-term economic benefits are recognized (Rose et *al*., 2015).

Overall, community acceptability of biogas is relatively high, especially for cooking and its environmental benefits. However, obstacles remain, particularly the reluctance to use human excreta and health concerns. Awareness campaigns and subsidies for biodigester installations could improve its adoption.

The optimization of biogas production by combining *Eichhornia crassipes*, human excreta, and hygienic paper waste has increased methane yield, improved process stability, and reduced harmful gas emissions. However, community acceptance remains a major challenge, requiring increased awareness efforts.

Conclusion and Recommendations

Conclusion

The study demonstrated that optimizing biogas production by combining *Eichhornia crassipes* (water hyacinth), human excreta, and hygienic paper waste is a viable and effective approach. The key findings show:

1. *A significant increase in methane production*: The *Eichhornia crassipes* + human excreta + hygienic paper mixture achieved a methanogenic yield of 480 ± 18 mL/g DM, an improvement compared to individual substrates.
2. *Improved biogas quality*: The methane (CH_4) content reached 65%, while H_2S concentration was reduced, enhancing the biogas' energy quality.
3. *Stabilization of the digestion process*: The optimized C/N ratio (~25:1) promoted microbial balance, reducing the risks of acidification and methanogenesis inhibition.
4. *Challenges related to community acceptability*: Although 65% of surveyed households are favorable to using biodigesters incorporating human excreta, cultural resistance persists among 30% of respondents, necessitating awareness and education initiatives.

Thus, integrating human excreta and hygienic paper waste into methanization presents a promising solution for sustainable waste management and renewable energy production while reducing environmental pollution. However, additional efforts are required to improve social acceptability and large-scale implementation.

Recommendations

a. Improve Substrate Pretreatment

- Explore enzymatic or thermal pretreatment methods to accelerate the degradation of hygienic paper and water hyacinth, thereby increasing biogas yield.
- Test the addition of nitrogen-rich co-substrates to further optimize the C/N ratio.

b. Optimize Digestion Conditions

- Evaluate the influence of different temperature regimes (mesophilic vs. thermophilic) to maximize methane production.
- Experiment with co-digestion using other organic waste, such as kitchen waste or sewage sludge.

c. Strengthen Community Acceptability

- Organize awareness campaigns on the benefits of utilizing human excreta for energy production and soil fertilization.
- Develop training sessions and practical demonstrations in both rural and urban communities.
- Work with community and religious leaders to break taboos and overcome cultural resistance.

d. Develop Sustainable Economic Models

- Promote the adoption of low-cost biodigesters adapted for rural households and small farms.
- Implement financial incentives, such as subsidies or microcredits, to facilitate technology adoption.
- Assess the potential for selling biogas and digestate as organic fertilizers to make installations more profitable.

e. Further Research

- Evaluate the feasibility of industrial-scale implementation to process larger waste volumes.
- Study the long-term environmental and health impacts of using digestate from human excreta in agriculture.
- Compare the performance of this process with other organic waste valorization technologies (composting, pyrolysis, etc.).

Perspectives

The results obtained mark significant progress toward more sustainable organic waste management and a green energy transition in Africa and other regions. Integrating this technology into rural development projects could contribute to:

- Reducing dependence on fossil fuels and firewood.
- Enhancing energy and food security for rural populations.
- Supporting efforts to reduce greenhouse gas emissions.

Further studies and pilot initiatives will be essential to demonstrate the large-scale viability of this system and overcome the remaining social and economic barriers.

Conflict of Interest

The author declares that there is no conflict of interest related to this article with any individual or institution.

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