Análisis del potencial bioquímico de metano como herramienta para evaluar el desempeño de la planta de biodigestores de Ikiam

Analysis of the biochemical methane potential as a tool to assess the performance of Ikiam's biodigester plant

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Resumen

El crecimiento poblacional y la limitada cobertura del tratamiento de aguas residuales en la Amazonía ecuatoriana representan un desafío ambiental y de salud pública, agravado además por la falta de acceso a agua potable en comunidades rurales. En este contexto, los biodigestores tubulares se propusieron como una alternativa sostenible para integrar el saneamiento con la generación de energía renovable. El presente estudio tuvo como objetivo aplicar ensayos de Potencial Bioquímico de Metano (BMP, por sus siglas en inglés) como herramienta diagnóstica para evaluar la eficiencia de la planta piloto de biodigestores de la Universidad Regional Amazónica Ikiam. Se recolectaron muestras en cuatro puntos y se caracterizaron parámetros fisicoquímicos (pH, sólidos, DQO, alcalinidad y conductividad). Los ensayos de BMP se realizaron en modo discontinuo bajo condiciones controladas. Los resultados preliminares revelaron variaciones inesperadas en el BMP entre los puntos de muestreo, atribuidas al efecto del inóculo, mientras que el pH, la alcalinidad y la conductividad se mantuvieron estables. En conclusión, el BMP demostró ser una herramienta diagnóstica valiosa para identificar limitaciones microbianas y orientar estrategias de optimización en biodigestores rurales.

Palabras Clave: Saneamiento en la Amazonía; Biodigestores de bajo costo; Digestión

anaerobia; Potencial Bioquímico de Metano; Tratamiento de aguas residuales domésticas.

Abstract

Population growth and the limited coverage of wastewater treatment in the Ecuadorian Amazon posed an environmental and public health challenge, further exacerbated by the lack of access to drinking water in rural communities. In this context, tubular biodigesters were proposed as a sustainable alternative to integrate sanitation with renewable energy generation. The present study aimed to apply Biochemical Methane Potential (BMP) assays as a diagnostic tool to assess the efficiency of the pilot biodigester plant at Universidad Regional Amazónica Ikiam. Samples were collected from four points, and physicochemical parameters (pH, solids, COD, alkalinity, and conductivity) were characterized. BMP assays were conducted in batch mode under controlled conditions. Preliminary results revealed unexpected variations in BMP among sampling points, attributed to the inoculum effect, while pH, alkalinity, and conductivity remained stable. In conclusion, BMP proved to be a valuable diagnostic tool for identifying microbial limitations and guiding optimization strategies in rural biodigesters.

Keywords: Sanitation in the Amazon; Low-cost biodigesters; Anaerobic Digestion; Biochemical Methane Potential; Domestic wastewater treatment.

Introduction

Wastewater treatment remains a significant challenge in developing countries. Globally, more than 80% of wastewater generated by human activities is discharged untreated, leading to increased water body pollution and posing risks to public health (Sánchez et al., 2023). In Latin America, only 20% of wastewater receives adequate treatment, while in Europe the figure reaches 71% (Sato et al., 2013; Jiménez-Paute et al., 2025). In Ecuador, fewer than half of the municipalities have treatment systems, and many of these systems operate only partially or inefficiently. This situation particularly affects rural regions such as the Amazon, where geographical conditions, population dispersion, and economic limitations hinder the implementation of conventional systems (INEC, 2020).

In this regard, the search for sustainable sanitation alternatives in rural and decentralized contexts is a priority, in line with the Sustainable Development Goals (SDGs), particularly SDG 6 (clean water and sanitation). Within this framework, tubular biodigesters have emerged as a low-cost and easily implemented technology, capable of integrating decentralized sanitation and biogas production as an energy source (Kinyua et al., 2016; Martí-Herrero et al., 2019). However, their performance depends on factors such as flow rate, temperature, and microbiological stability. In this sense, Biochemical Methane Potential (BMP) assays

enable the estimation of maximum methane generation under controlled conditions, making them a valuable diagnostic tool for rural systems (Holliger et al., 2016; Jaimes-Estévez et al., 2021). Against this background, the present study applied BMP assays as a diagnostic tool to evaluate the efficiency of the pilot plant of tubular biodigesters in series at Amazon Regional University Ikiam (URAI). This plant, implemented six years ago in Tena (Napo province), represents a model of decentralized domestic wastewater treatment in the Ecuadorian Amazon and a unique opportunity to analyze the performance of these technologies under real operating conditions.

Methodology

The study employed a quantitative experimental design to evaluate the Biochemical Methane Potential (BMP) as an indicator of the biodigester plant's performance at Amazon Regional University Ikiam, which consists of three tubular digesters in series (20 m^3). Composite samples were collected at four points in the system (B0–B3): influent to the first biodigester (raw wastewater, B0), effluent from the first/influent to the second (B1), effluent from the second/influent to the third (B2), and effluent from the third biodigester (B3). Samples were obtained by subsampling every two hours between 08:30 and 16:30, twice per week for four weeks, and then homogenized into 2 L samples. Active sludge from biodigester three was used as inoculum due to its prior adaptation. Physicochemical characterization was performed according to APHA (2017), including pH, temperature, solids, COD, alkalinity, dissolved oxygen, and conductivity. BMP assays were carried out in batch mode using 250 mL bottles with an ISR of 2:1, incubated at 25 ± 3 °C for 30 days, with a blank and a cellulose control included. Methane production was quantified by NaOH displacement, and all assays were conducted in triplicate.

Results and Discussion

Preliminary results show that the Biochemical Methane Potential (BMP) of the samples varies across the sampling points, with a progressive increase from the initial influent to the final effluent (Figure 1). The highest value was recorded in sample B3, while the lowest was observed in B0. This behavior was unexpected, since the measurements of VS and COD indicate a progressive reduction of organic matter through the biodigesters, which should be reflected in a lower BMP (Figures 2 and 5). This result cannot be attributed to experimental setup errors, as the positive control with cellulose yielded a production of 378.49 NmL CH_4/g VS, within the range reported in the literature (Holliger et al., 2016).

Regarding operating conditions, parameters such as pH, conductivity, and alkalinity showed a decreasing trend, confirming that the biodigester system is functioning correctly. The most

likely explanation for the atypical BMP behavior is related to the inoculum used, which was sourced from the third biodigester that has been operating under low organic loads for six years. This suggests microbial adaptation that limits its ability to respond to higher substrate concentrations, leading to a partial inhibition effect.

The temperature remained stable during the assays, although it was below the optimal range for maximizing methanogenic activity, while the pH showed a progressive decrease from the influent to the final effluent (Figure 3). This trend could be associated with the accumulation of volatile fatty acids; nevertheless, the values remained within the range considered suitable for methanogenic activity (7.0–8.0) (Oliveira et al., 2024).

Alkalinity decreased from 0.63 g/L in B0 to 0.50 g/L in B3, attributable to bicarbonate consumption during acid neutralization, while remaining within the recommended range (500–3000 mg/L $CaCO_3$) to ensure stability (Appels et al., 2008; Holliger et al., 2016). Similarly, electrical conductivity decreased by 13% (1533.24 → 1337.44 $\mu S/cm^{-1}$), likely due to salt precipitation and nutrient assimilation by the biomass (Figure 4).

These trends support the efficiency of the tubular biodigester system, in agreement with studies in tropical regions reporting simultaneous reductions in alkalinity and electrical conductivity associated with organic stabilization (Jaimes-Estévez et al., 2021; Jiménez-Paute et al., 2025). However, at full scale, more pronounced reductions in COD (67%) and VS (78%) have been reported, with methane contents of 63% v/v (Jaimes-Estévez et al., 2021). In this context, the differentiated BMP behavior confirms that this tool is susceptible to the origin and conditions of the inoculum, as previously noted in inter-laboratory studies (Holliger et al., 2016; De Vrieze et al., 2015).

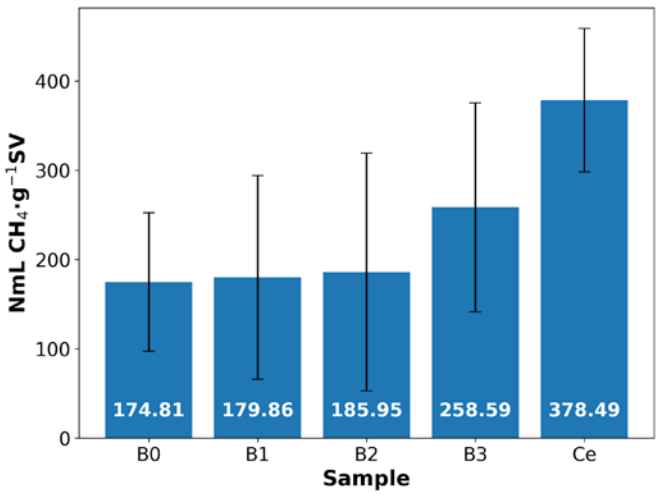

Figure 1. Total biogas production of wastewater samples B0 to B3 from the biodigester

system.

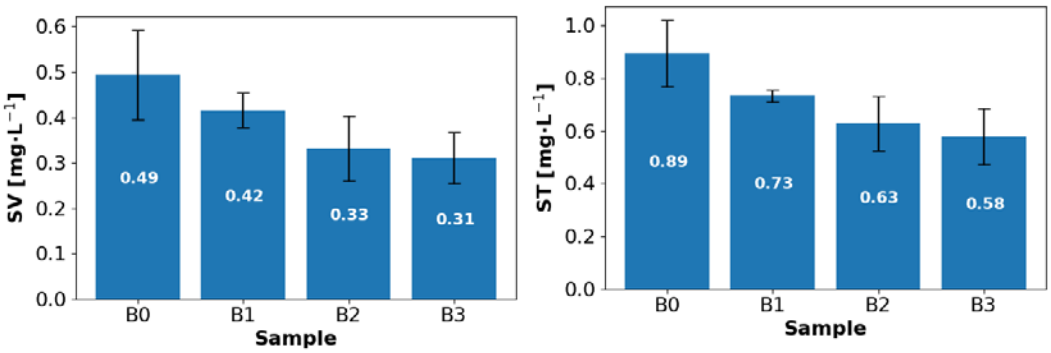

Figure 2. Average total solids and volatile solids of wastewater samples from the biodigester system (influent and effluent).

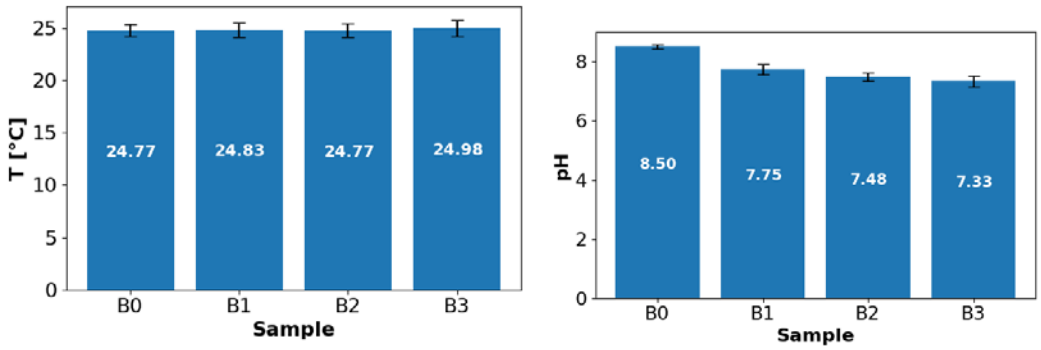

Figure 3. Overall average temperature and pH of wastewater samples from the biodigester system.

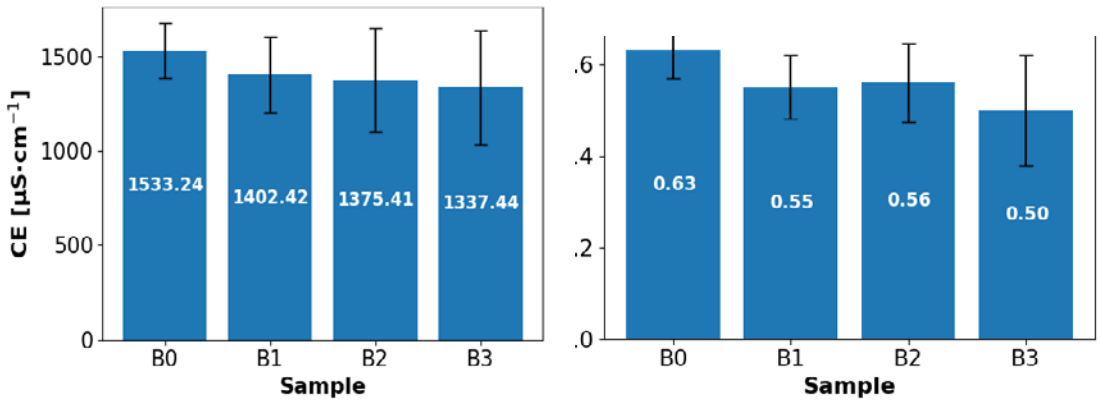

Figure 4. Total electrical conductivity and alkalinity of wastewater samples B0 to B3.

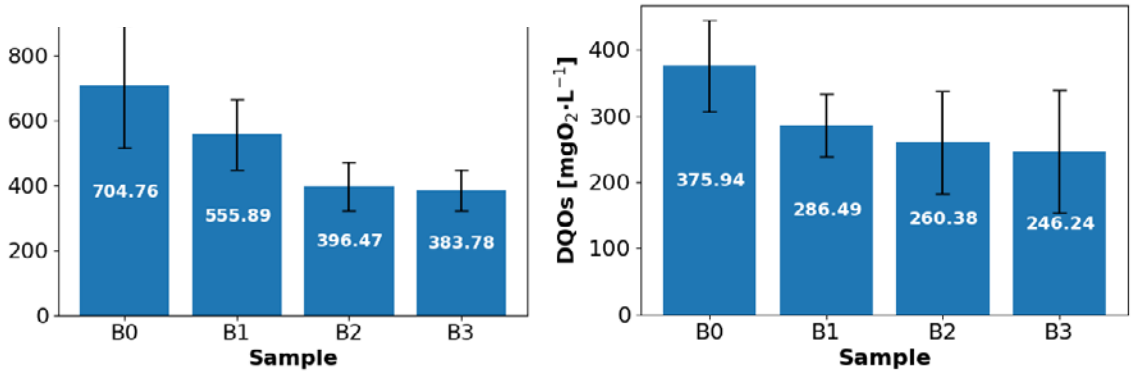

Figure 5. Total CODt_tt and CODs_ss of wastewater samples B0 to B3.

Conclusions

The study demonstrated that BMP is an effective diagnostic tool for evaluating the performance of tubular biodigesters in Amazonian contexts, enabling the identification of the relationship between stabilization parameters and potential methane production. Preliminary results showed stability in pH, alkalinity, and electrical conductivity, confirming the system's efficiency, while also highlighting the sensitivity of BMP in revealing microbial limitations and inoculum-related biases. As a contribution, a replicable baseline was established for the URAI pilot plant under real operating conditions. It is recommended to standardize and compare inocula (by sampling point and/or external sources) and their preconditioning, as the application of BMP complemented with physicochemical parameters constitutes a valuable strategy for optimizing the operation of rural biodigesters. The continuation of the study will allow the incorporation of additional experimental data to refine conclusions and strengthen recommendations.

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