Biogas production from wastes from *Opuntia ficus indica* at different temperatures

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INTRODUCTION. Anaerobic digestion (AD) effectively produces clean energy from organic waste while generating digestates that can improve soil quality (Weiland, 2010). However, challenges like competition for agricultural land and inhibitory substances in waste limit its application. *Opuntia ficus-indica* (nopal) is a promising alternative since it thrives in arid climates without competing for farmland (Quiroz et al., 2021). In Mexico, nopal has significant economic and cultural value, with diverse uses in food, medicine, and industry, contributing to an annual production of over 812,000 tons for human consumption (INEGI, 2022). About 5% of the crop is discarded because the cladodes (leaves) do not comply with the required quality standards (Figure 1).

Opuntia ficus-indica is a low-cost, widely available plant with environmental benefits like soil regeneration and erosion prevention. It thrives in drought-prone areas without requiring much water or fertilizers, making it ideal for climate change adaptation (Belay et al., 2021). Its high carbohydrate and bioactive compound content makes it suitable for food and biofuel production, offering significant energy potential. However, optimizing anaerobic digestion (AD) at different temperatures remains a technical challenge affecting process efficiency. No studies have specifically analyzed temperature effects on AD of *Opuntia*, highlighting the need for research to maximize its energy use. The anaerobic digestion of *opuntia* varies with temperature, impacting efficiency. Psychrophilic conditions (15-20°C) have low energy consumption but slower conversion rates. Mesophilic conditions (35-40°C) offer an optimal balance between efficiency and cost, while thermophilic conditions (55°C) increase degradation speed but pose challenges like ammonia accumulation.

Figure 1. Waste from Opuntia ficus-indica harvesting.

This project evaluated methane production from *Opuntia* at 20 °C, 35 °C, and 55°C, aiming to enhance biogas production and provide system stability. Michaelis-Menten parameters were determined for detailed kinetic analysis.

METODOLOGY. The methodology included the physicochemical characterization of opuntia and inoculum, with parameters such as COD, pH, and total solids. UASB sludge from a large brewery in Mexico City was used as inoculum. As a first stage, the inoculum was acclimatized to 20 °C, 35 °C, and 55 °C in 2-liter reactors fed with synthetic wastewater (SWW) to stabilize microbial activity at each condition, monitoring pH, alkalinity, and methane content. Subsequently, anaerobic digestion was performed in 500 mL batch reactors, using different substrate/inoculum ratios to optimize methane production. Using the temperature-adapted inoculum, 15-day tests were conducted at each temperature (20, 35, and 55°C), and biogas production and methane content were measured using AMPTS II (Bioprocess Control, Sweden) and gas chromatography. Kinetic modeling of methane production was performed using the Michaelis-Menten model, estimating key parameters such as reaction rate and substrate affinity using the Lineweaver-Burk equation.

RESULTS. *Opuntia ficus-indica* was characterized as a substrate for methane production through anaerobic digestion. The results indicate a moisture content of 93.4%, total solids (TS) of 65.6 g/kg, volatile solids (VS) of 54.0 g/kg, and a COD of 1,338 gO_2/kg_{VS}, suggesting high potential for biodegradation and a theoretical methane production of 389 $mLCH_4/g_{VS}$. Ground to particles under 8 mm, *Opuntia* had a pH of 4.6, a suboptimal pH for anaerobic digestion, so a buffer solution was used in the following stages. Initially, the inoculum was anaerobic granular sludge with a VS/TS ratio 0.76.

Phase 1 of the experiment involved acclimatizing the anaerobic reactors at 20 °C, 35 °C, and 55 °C to adapt microbial consortia to operate under the selected thermal conditions. The parameters monitored included pH, alkalinity, alpha and BI indices, methane percentage (greater than 60%), and dissolved COD, which helped assess operational stability. At this stage, the reactor acclimatized at 35 °C adapted more quickly than the reactors at 20 °C and 55 °C.

Phase 2 consisted of determining the biogas and methane production for the three different temperatures and initial substrate concentrations. Eight reactors were run at each temperature with 1, 2, 3, 4, 5, 6, and 7 g_{VS} of *Opuntia* with 8 g_{VS} of inoculum acclimatized in the previous phase. Figure 2 shows that biogas and methane production were directly proportional to the initial substrate concentration of opuntia at 35 °C. At this temperature, the maximum cumulative biogas production reached 3,200 NmL for 7 g_{VS} (17.5 g_{VS}/L) of opuntia, while the maximum cumulative CH_4 production reached 2,000 NmL (average 63% CH_4 in biogas). At 35 °C, a positive correlation (figure 3) is obtained by plotting the methane production vs. the substrate mass; The slope corresponds to the specific methane production of 198 NmLCH_4/g_{VS}, and the intercept to the theoretical endogenous methane production (blank) with 236 NmL. Because of limited space, only the results for 35°C are shown in this abstract. All results for the other temperatures will be shown in the full paper.

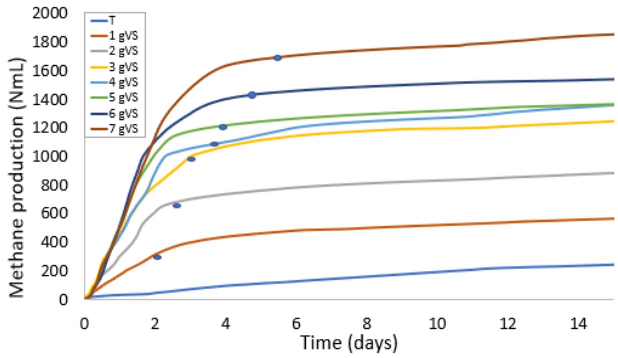

Figure 2. Cumulative methane production for fresh Opuntia at 35°C and different substrate concentrations.

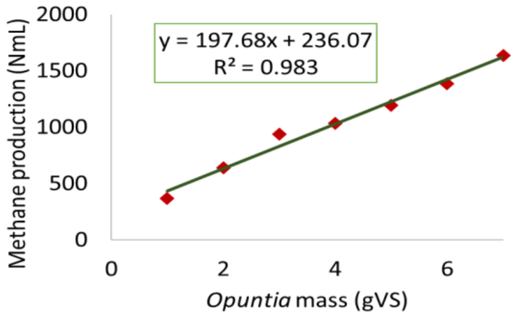

Figure 3. Specific methane production calculation from the methane production curves at 35°C.

Phase 3 consisted of determining kinetic analysis using the Michaeli-Menten model. Figure 4 shows the Lineweaver-Burk plot for the determination of Vmax and Km. The kinetic analysis at 35 °C showed a maximum methane production rate of 1,787 NmLCH_4/g_{VS}·d and a Km of 27 g_{VS}/L, reflecting an efficient process under mesophilic conditions.

CONCLUSIONS

Opuntia ficus-indica is a promising substrate for biogas production due to its high biodegradability and availability. Independently of the substrate concentration, the highest specific methane production was recorded at 35°C. Although the methane production at 20 °C and 55 °C proved less stable than at 35°C a detailed explanation will be provided in the full-text article; the preliminary results show inhibition or unstable process conditions. This research contributes to the development of sustainable systems for the use of agricultural waste as a renewable energy source.

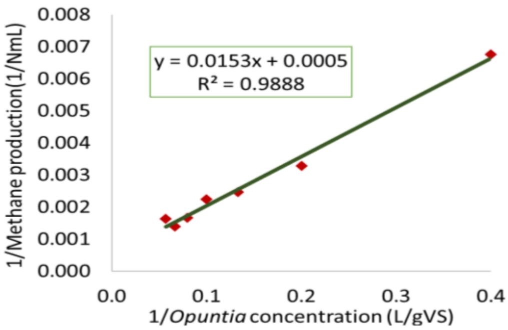

Figure 4. Lineweaver-Burk plot for the determination of kinetic parameters at 35°C.

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