

Assessment and Optimization of In-situ Hydrogen Biomethanation to Enhance Anaerobic Digestion Process

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Abstract

The rising global demand for sustainable energy and effective waste management necessitates advancements in waste-to-energy systems. Anaerobic digestion (AD) is a well-established process for the sustainable treatment of organic waste and the generation of biogas. However, further advancements are required to upgrade the biomethane generated from AD systems. Hydrogen biomethanation (HBM) offers a promising approach to upgrade the methane (CH₄) content in biogas via the biological conversion of exogenous hydrogen (H₂) and the carbon dioxide (CO₂) produced from the AD process. One of the main bottlenecks in HBM is the low solubility of H₂, which limits its bioavailability for microbial conversion.

In order to address the challenges related to the optimization of the HBM process, this study aims to enhance the biomethane yield within AD systems through the evaluation of varying CO₂:H₂ ratios, hydrogen injection parameters (dosage and frequency), and temperature conditions. The performance of the process will be assessed through biogas quantity and quality, as well as treatment efficiency. This research is focused on optimizing the hydrogen injection parameters, including dosage (H₂:CO₂ ratios) and frequency, under mesophilic conditions in batch biomethane potential assays. The experimental work was focused on studying H₂ micro-dispersion under mesophilic conditions (32°C and 37°C) with CO₂:H₂ mole ratios of 1:3 and 1:5 to assess impacts on biogas and biomethane production.

Table 1 summarizes the results of the examined scenarios. The treatment efficiency of the examined scenarios was influenced by both temperature and CO₂:H₂ ratios. At 32°C, the control achieved 89% soluble chemical oxygen demand (sCOD) removal, which increased to 91% under the 1:3 CO₂:H₂ ratio. However, the 1:5 ratio reduced efficiency slightly to 85%. At 37°C, the 1:5 CO₂:H₂ ratio exhibited the highest sCOD removal efficiency (90.9%), outperforming both the 1:3 ratio (76.7%) and the control (84.9%). Alkalinity levels were significantly enhanced at 37°C, peaking at 2,217 mg/L CaCO₃ under the 1:3 ratio, compared to 855 mg/L in the control at 32°C. Similarly, total Kjeldahl nitrogen (TKN) values were higher at 37°C, reaching 463 mg/L under the 1:3 ratio, reflecting improved microbial nitrogen retention.

Table 1. Summary of the main findings for the examined hydrogen biomethanation scenarios

Parameter	32°C (1:3 CO ₂ :H ₂)	32°C (1:5 CO ₂ :H ₂)	37°C (1:3 CO ₂ :H ₂)	37°C (1:5 CO ₂ :H ₂)
sCOD Removal (%)	91	85	76.7	90.9
Biogas Yield (mL/gVS)	580	530	678	884
Methane Yield (mL/gVS)	389	358	475	626
Alkalinity (mg/L CaCO ₃)	1,084	783	2,217	1,480
TKN (mg/L)	144	134	463	405
H ₂ Utilization (mL/mmol H ₂)	33	20	55	30

Biogas and methane production followed similar trends as shown in Figure 1 Table 1, with yields increasing with both temperature and H₂ supplementation. At 32°C, the control yielded 429.3 mL/gVS of biogas, which increased

to 580.6 mL/gVS and 530 mL/gVS under the 1:3 and 1:5 ratios, respectively. At 37°C, biogas production was highest under the 1:5 CO₂:H₂ ratio, reaching 884.3 mL/gVS—a 100% increase over the control. Methane production mirrored these results, with yields at 32°C of 242.37 mL/gVS (control), 389 mL/gVS (1:3 ratio), and 358 mL/gVS (1:5 ratio). At 37°C, methane yields increased to 332.67 mL/gVS (control), 475 mL/gVS (1:3 ratio), and 626 mL/gVS (1:5 ratio), representing an 88% improvement over the control.

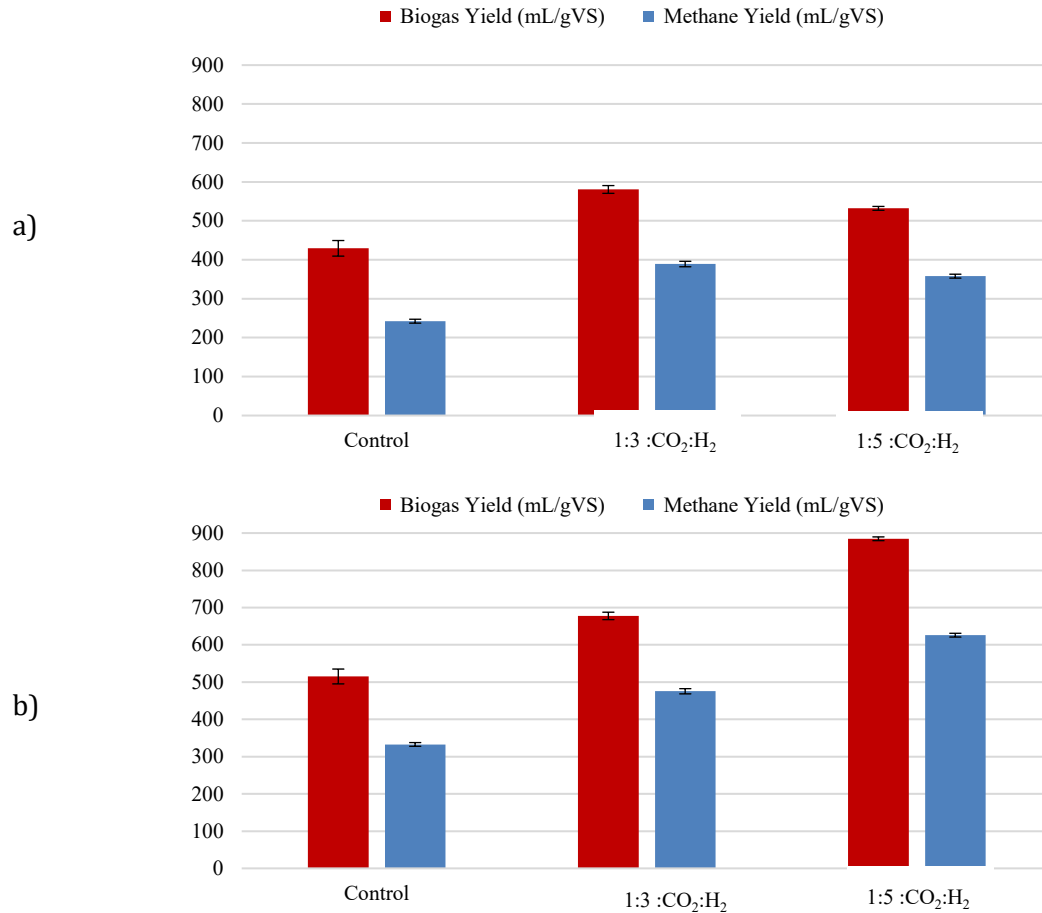


Figure 1. Biogas and methane yields (mL/gVS) at 1:3 and 1:5 CO₂:H₂ ratio under a) 32 and b) 37°C mesophilic temperatures.

Moreover, hydrogen utilization efficiency was highest at the 1:3 CO₂:H₂ ratio, particularly at 37°C, with methane yields of 55 mL/mmol H₂. While the 1:5 ratio provided higher absolute methane yields, the efficiency of H₂ conversion was lower. Overall, the 1:3 CO₂:H₂ ratio proved most efficient for H₂ utilization, while the 1:5 ratio at 37°C delivered the highest biogas and methane outputs. These findings highlight the importance of optimizing temperature and H₂ injection parameters to enhance biomethane production efficiency, demonstrating that the 1:5 ratio at 37°C is optimal for maximizing biogas and methane yields.