Electrohydrolysis as a strategy to unlock biomethane production from concentrated waste-activated sludge

J.A. Gutiérrez-González[1], J.K Chenwi-Minang[1], A. Ramírez[1], M. Muñoz-Morales[1], J. Llanos[1], J. Villaseñor[1].

[1]Department of Chemical Engineering, Research Institute for Chemical and Environmental Technology, University of Castilla – La Mancha, Av. Camilo José Cela, Ciudad Real, 13071, Spain

Keywords: biomethane, electrohydrolysis, waste activated sludge, carbon felt, Gompertz model
Presenting author email: alvaro.ramirez@uclm.es

Introduction

The transition toward sustainable energy systems is a key objective of the European Long-Term Decarbonisation Strategy (ELP 2050), which targets a 90% reduction in greenhouse gas emissions by 2050. In this context, biomethane production from waste streams represents an attractive alternative to fossil fuels while addressing waste management challenges. Waste activated sludge (WAS), a byproduct of wastewater treatment plants, is rich in organic matter but exhibits low biodegradability due to its complex floccular structure, limiting anaerobic digestion (AD) efficiency (Yi et al., 2013).

This study evaluates electrohydrolysis (EH) as an innovative electrochemical pretreatment to enhance WAS hydrolysis and subsequent biomethane production through anaerobic digestion process. The effects of applied energy, cathode material, and current density on sludge solubilization, biodegradability, and biochemical methane potential (BMP) were assessed. EH pretreatment was carried out in a galvanostatic stirred reactor using an Iridium–Tantalum mixed metal oxide (MMO) anode combined with either a conventional carbon felt cathode (CF) or a valorized hydrochar-coated carbon felt (HC-CF) developed after coating a hydrochar obtained from a hydrothermal carbonization of lignocellulosic biomass and further activation process with KOH and pyrolysis (Ramírez et al., 2023).

Materials and methods

Waste concentrated sludge was supplied by a wastewater treatment plant located in Ciudad Real. This sludge was collected after the biological treatment after filtration with a high moisture content (≈ 96%). Physicochemical characterization was carried out including pH, conductivity, total solid, volatile solids and elemental analysis.
Electrochemical pretreatment was carried out in galvanostatic mode with electrodes of 36 cm^2 and interelectrode gap of 3 cm using 1L beakers under magnetic stirring (730 rpm). Experiments with different energy applied and different current density were assessed. Chemical oxygen demand (COD) and biological oxygen demand (BOD_5) was measured to evaluate the organic matter available for biomethane production.

Anaerobic digestion assays were subsequently performed in closed batch reactors (Oxitop® , 1L) measuring the increase of pressure under mesophilic conditions of 35 ºC. Experiments were done over 30 days using an inoculum substrate (I/S) ratio of 2:1. pH was set to 7. BMP kinetics was analysed using a modified Gompertz model (Barrios et al., 2021).

Results and Discussion

EH pretreatment significantly improved organic matter solubilization and biodegradability, as evidenced by increases in soluble COD, BOD_5, and sludge disintegration degree (DDCOD). In addition to COD-related improvements, the EH pretreatment also led to positive effects on extracellular polymeric substances (EPS) disruption and a reduction in sludge particle size, further enhancing sludge disintegration and substrate accessibility for anaerobic microorganisms. An optimal DDCOD of 3.80% ± 0.01 was achieved using carbon felt cathodes at 15 $mA \cdot cm^{-2}$. The CF electrode showed the highest BMP enhancement, reaching up to a 79.27% increase, while the HC-CF electrode performed more efficiently at lower specific energy inputs, with a maximum BMP increase of 68.61% from untreated substrate.

Optimal operating conditions were achieved at intermediate energy inputs (~1000 $kJ \cdot kg^{-1}$ TS) and current intensities of 0.35–0.4 A. Methane production kinetics were accurately described by the modified Gompertz model (R^2 = 0.95–0.99; Fig. 1), consistent with previous reports (Veluchamy et al., 2018). At low energy inputs, the HC-CF cathode exhibited a higher methane yield than the CF cathode (214 vs. 185 g $CH_4 \cdot kg^{-1}$ inoculum$\cdot kg^{-1}$ VS), whereas at higher energy inputs this advantage diminished, and slightly higher yields were observed for the CF cathode. This behavior is likely associated with mass transfer limitations, which are more pronounced in the casted HC-CF electrode. Increasing current density enhanced BMP; however, at higher energy inputs—particularly for HC-CF—the effect became marginal, indicating that lower energy levels are sufficient to maximize methane production while minimizing energy consumption during pretreatment. Overall, these results demonstrate the technical feasibility of the EH process for biomethane production.

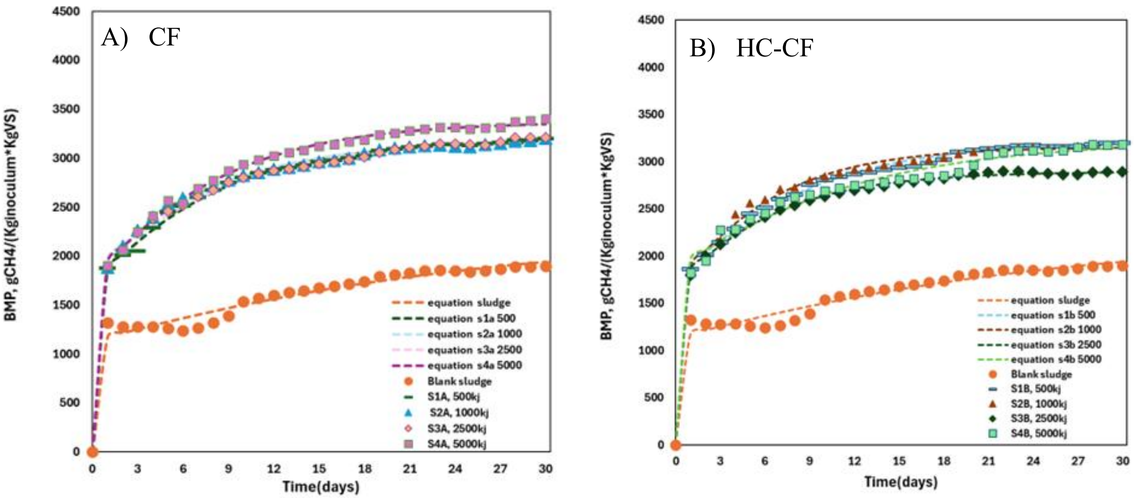

Figure 1. Mathematical fitting of the BMP model for AD tests for 30 days using a MMO anode and A) CF cathode; B) HC-CF cathode.

Conclusions

These results demonstrate the strong potential of electrohydrolysis (EH) pretreatment to enhance anaerobic digestion (AD) performance and support the sustainable valorization of waste activated sludge (WAS) produced within wastewater treatment plants. Parameters as electrode surface chemistry and optimized current density were found to play a decisive role to improve methane yields and process predictability.

Better results were shown with lower energy applied and higher current densities that reduces the treatment time required to obtain AD substrate and good fittings obtained with the Gompertz modified kinetics model let us to validate BMP data and to predict AD performance.

References

Barrios, J. A., Cano, A., Rivera, F. F., Cisneros, M. E., & Durán, U. (2021). Efficiency of integrated electrooxidation and anaerobic digestion of waste activated sludge. *Biotechnology for Biofuels*, *14*(1), 81. https://doi.org/10.1186/s13068-021-01929-7

Ramírez, Á., Muñoz-Morales, M., Fernández-Morales, F. J., & Llanos, J. (2023). Valorization of polluted biomass waste for manufacturing sustainable cathode materials for the production of hydrogen peroxide. *Electrochimica Acta*, *456*, 142383. https://doi.org/https://doi.org/10.1016/j.electacta.2023.142383

Veluchamy, C., Raju, V. W., & Kalamdhad, A. S. (2018). Electrohydrolysis pretreatment for enhanced methane production from lignocellulose waste pulp and paper mill sludge and its kinetics. *Bioresource Technology*, *252*, 52–58. https://doi.org/10.1016/J.BIORTECH.2017.12.093

Yi, H., Han, Y., & Zhuo, Y. (2013). Effect of Combined Pretreatment of Waste Activated Sludge for Anaerobic Digestion Process. *Procedia Environmental Sciences*, *18*, 716–721. https://doi.org/10.1016/J.PROENV.2013.04.097

Acknowledgements

Authors gratefully acknowledge the financial support of (1) the project PID2022-141265OB-I00 funded by MCIU/AEI/10.13039/501100011033 and FEDER, UE; (2) the Project 2025-GRIN-38454 from Universidad de Castilla La Mancha-FEDER, and (3) Julio A. Gutiérrez gratefully acknowledges the grant PREP2022-000820 funded by MCIU/AEI/10.13039/501100011033.