D5.6 Scientific publications

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1. BIOMETHAVERSE in a nutshell

BIOMETHAVERSE aims to diversify the technology basis for biomethane production in Europe, increase its cost-effectiveness, contribute to the uptake of biomethane technologies, and support the priorities of the SET Plan Action 8.

To meet these goals, **five innovative biomethane production pathways** will be demonstrated in five European countries: France, Greece, Italy, Sweden, and Ukraine.

The five selected demonstrators go beyond the state of the art and thus beyond technologies already implemented at commercial scale and rely on:

- In-situ and Ex-Situ ElectroMethanoGenesis (EMG): Electricity enhanced biomethane production (by ENGIE, France);
- Ex-situ Thermochemical/catalytic Methanation (ETM): Thermochemical/catalytic upgrading of biogas using hydrogen (by BLAG, Greece);
- Ex-Situ Biological Methanation (EBM): Biological upgrading of biogas using hydrogen, including feed-stock pre-treatment via ozonolysis (by CAP, Italy);
- Ex-Situ Syngas Biological methanation (ESB): Biological methanation of syngas from thermal gasification (by RISE, Sweden);
- In-situ Biological Methanation (IBM): Hydrogen integration in the AD reactor (by MHP, Ukraine).

The project's objectives will be achieved through the implementation and consolidation of the following founding pillars:

- Demonstration of Innovative Biomethane Pathways;
- Assessment and Optimisation of Innovative Biomethane Pathways;
- Replicability, Planning Decisions, Market Penetration, and Policy Dimension;
- Dissemination, Exploitation & Communication.

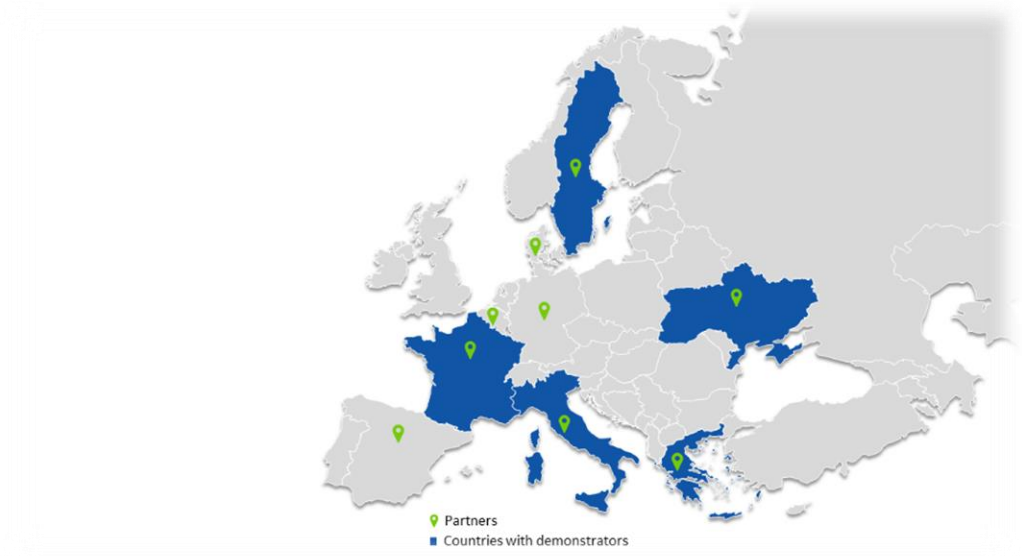

Figure 1 - BIOMETHAVERSE Countries and Partners

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2. Scientific publications indexed in Scopus

As part of the dissemination and exploitation activities of the project, scientific outputs have been produced. Specifically, the consortium has contributed to three peer-reviewed scientific papers in 2025, all directly related to the project's research activities and results.

The list below provides the relevant references of the peer-reviewed papers:

1. M. Xu, M.FA. Cobo, D. Zeng, Y. Zhang, Leveraging 3D printing in microbial electrochemistry research: current progress and future opportunities. Front. Environ. Sci. Eng. 19, 1 (2025). https://doi.org/10.1007/s11783-025-1921-y
2. S. Rossi, M. Mantovani, F. Marazzi, V. Mezzanotte, E. Ficara, Long-term outdoor operation of microalgae-based digestate treatment: impact of external drivers on process performances and techno-economic assessment, Bioresource Technology, Volume 427, 2025, 132406, ISSN 0960-8524, https://doi.org/10.1016/j.biortech.2025.132406.
3. M.FA Cobo, B. Rezaei, S.S. Keller, Y. Zhang, Electromethanogenesis with 3D printed carbon electrodes: Effects of surface properties and geometries on H2 generation and CO2 reduction, Chemical Engineering Journal, 2025, 168495, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2025.168495.
4. S. Feilner, M. Espejo, M. Garcia, D. Molognoni, E. Borràs und K. Herkendell, „CFD simulation for optimizing flow dynamics in a bioelectrochemically enhanced single-chamber anaerobic digester“, *Journal of Thermofluids*, 2025 (accepted for publication, in production).

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Table 1 – List of scientific publications indexed in Scopus with abstract

Authors	**BIOMETHAVERSE Partner**
M. Xu, M.FA. Cobo, D. Zeng, Y. Zhang	DTU
year	**DOI**
2025	https://doi.org/10.1007/s11783-025-1921-y
Title	
Leveraging 3D printing in microbial electrochemistry research: current progress and future opportunities	
Abstract	
Microbial electrochemical system (MES) offers sustainable solutions for environmental applications such as wastewater treatment, energy generation, and chemical synthesis by leveraging microbial metabolism and electrochemical processes. This review explores the transformative role of 3D printing in MES research, focusing on reactor body design, electrode fabrication, and bioprinting applications. Rapid prototyping facilitated by 3D printing expedites MES development while unlocking design flexibility, which enhances performance in optimising fluid dynamics and mass transfer efficiency. Tailored ink materials further improve the conductivity and biocompatibility of electrodes, paving the way for environmental applications. 3D-printed bio-anodes and bio-cathodes offer enhanced electrogenesis and boosted electron acceptance processes, respectively, by fine-tuning electrode architectures. Additionally, 3D bioprinting presents opportunities for scaffold fabrication and bioink formulation, enhancing biofilm stability and electron transfer efficiency. Despite current challenges, including material selection and cost, the integration of 3D printing in MES holds immense promise for advancing energy generation, wastewater treatment, resource recovery, carbon utilisation, and biosensing technologies.	

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Authors	BIOMETHAVERSE Partner
S. Rossi, M. Mantovani, F. Marazzi, V. Mezzanotte, E. Ficara	PoliMI

year	DOI
2025	https://doi.org/10.1016/j.biortech.2025.132406.

Title

Long-term outdoor operation of microalgae-based digestate treatment: impact of external drivers on process performances and techno-economic assessment

Abstract

A pilot-scale algal pond for liquid digestate treatment (5.8 m2, 0.75–1.83 m3) was operated outdoor for 1145 cumulative days. Key performance indicators were correlated with relevant external drivers including influent characteristics, weather conditions, and operational parameters, gaining information for management and optimisation. A techno-economic assessment allowed to calculate and validate process costs for a scaled-up plant (2-ha). Despite external factors, thanks to consistent nitrification, ammonium removal was high and stable during all trials (85 ± 8%). Environmental and operational conditions strongly influenced phosphate removal (51 ± 21%) and biomass productivity (10.4 ± 6.6 g TSS/m2/d). High biomass productivities were mostly associated to global radiation, while phosphate removal was influenced by digestate characteristics. The relatively low biomass production costs (6.9 €/kg or 7.4 $/kg) and substantial savings for liquid digestate bioremediation (3.4 €/m3 or 3.7 $/m3) and N removal (15.1 €/kg N or 16.2 $/kg N) confirmed the high potential of microalgae-based technologies as a cost-effective and sustainable alternative to conventional approaches for wastewater bioremediation and resource recovery.

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Authors	BIOMETHAVERSE Partner
M.FA Cobo, B. Rezaei, S.S. Keller, Y. Zhang	DTU

year	DOI
2025	https://doi.org/10.1016/j.cej.2025.168495

Title

Electromethanogenesis with 3D printed carbon electrodes: Effects of surface properties and geometries on H2 generation and CO2 reduction

Abstract

Electromethanogenesis offers a promising approach to the sustainable conversion of CO_2 into CH_4, yet enhancing its efficiency remains a key challenge. One strategy involves developing more conductive, biocompatible electrodes with increased surface area. In this study, 3D pyrolytic carbon electrodes fabricated by 3D printing and subsequent pyrolysis were proposed as cathodes for electromethanogenesis systems. The results revealed a successful implementation of these 3D printed cathodes for CO2 reduction, with comparable performance to the one of carbon felt. Moreover, the effect of surface charge and porosity was evaluated by modifying the surface, resulting in a much more porous and neutrally charged electrode. Negatively charged surfaces favoured hydrogen evolution reaction, while increased porosity and neutrally charged electrodes enhanced microbial activity. Finally, the impact of lattice size was studied by fabricating modified electrodes with different designs. The study of the different designs showed that a more compact lattice structure reduced the internal resistance of the electrode, enhancing H_2 and CH4 production, while larger lattice sizes presented larger internal resistance, reducing current and H2 and CH4 generation. This research underlines the importance of optimizing surface properties and geometry when designing 3D electrodes for electromethanogenesis.

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Authors	BIOMETHAVERSE Partner
S. Feilner, M. Espejo, M. Garcia, D. Molognoni, E. Borrás and K. Herkendell	FAU

year	DOI
2025	In production: Journal of Thermofluids,

Title

CFD simulation for optimizing flow dynamics in a bioelectrochemically enhanced single-chamber anaerobic digester

Abstract

The combination of anaerobic digestion (AD) and bioelectrochemical systems (BES) for improved biogas production makes a significant contribution to the conversion of organic waste materials into a usable, renewable energy source. This study employs computational fluid dynamics (CFD) to examine the performance of a bioelectrochemically enhanced single-chamber anaerobic digester (AD-BES). Flow conditions in a laboratory-scale stirred tank reactor are compared with those in an identical AD-BES reactor equipped with carbon fiber brush electrodes. Two configurations of the BES reactor, AD-BES-1 and AD-BES-2, were examined. The overarching aim of the analysis is to develop suitable fluid dynamic models for the simulation of the AD-BES reactor system. Particular emphasis is placed on modeling the turbulence and the rotational movement of the stirrer. With a realistic representation of the reactor system, the influence of the electrodes on the operating dynamics of the reactor, the mixing behavior and the formation of dead zones can be described and optimized. The simulation results were validated with experimental tests in an acrylic glass model reactor. Operating the included stirrer at 200 and 300 revolutions per minute (rpm) reveals that, with higher rotational speed the extension of dead zones is decreasing. The brush electrodes significantly influence the flow patterns, acting as obstacles. The arrangement of the electrodes determines the extent of the dead zones that occur between them and the reactor wall. In presence of the electrodes, the radial component of the flow velocity is decreasing, while the axial component is increasing.

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3. Other scientific publications

In addition to scientific articles indexed in Scopus, the following scientific outputs have been produced which are directly related to the project's research activities and results.

The list below provides the relevant references of the scientific outputs non indexed in Scopus:

1. S. Åström, The Effect of Pyrolysis Water on Different Levels of a Reactor for Biological Syngas Methanation, SLU, Sveriges lantbruksuniversitet; Institutionen för energi och teknik; Bioenergiteknik, Independent thesis Advanced level, 2024, Series UPTEC X ; 24039, available at https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1892779&dswid=1379

Table 2 – List of other scientific publications with abstract

Authors	**BIOMETHAVERSE partner**
Stina Åström	RISE
year	**DOI or WebLink**
2024	https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1892779&dswid=1379, https://www.diva-portal.org/smash/get/diva2:1892779/FULLTEXT03.pdf
Title	
The Effect of Pyrolysis Water on Different Levels of a Reactor for Biological Syngas Methanation	
Abstract	
Thermophilic biological syngas methanation has the potential to become an important factor to reduce the usage of fossil fuels and contribute to a resilient energy production in Europe. The technology is built on the complex syntropy of different groups of microbes that together convert syngas (CO, H_2, CO_2, and some CH_4) to CH_4 through a variety of pathways. The pathway for CO conversion to CH_4 has been less studied than the conversion for H_2 and CO_2, but several studies have observed that species that perform hydrogenotrophic methanogenesis and the water-gas shift reaction (WGSR) seem to be dominating in biological syngas methanation in thermophilic temperatures. In future commercial plants for biological syngas methanation, the process will perhaps be disturbed by varying amounts of pyrolysis water, a condensate that might enter the reactor with the syngas. Research Institutes of Sweden (RISE) has conducted an experiment where a trickle bed reactor (TBR) has been exposed to pyrolysis water without seeing any apparent effect on the CH_4 production. However, after conducting a qPCR analysis, targeting the genera Methanobacterium, on samples from the TBR, it is possible to conclude that the introduction of the contamination indeed had an effect on the methanogenic community since the population decreased at the top of the reactor, where the contamination was decreased. The reason why this was not apparent on the data gathered from the experiment might be because an inoculum which had been thoughtfully chosen with the diversity in mind had been used, and there were plenty of species that could convert the harmful components. This might have protected the lower parts of the reactor while other methanogenic species than Methanobacterium maintained the CH_4 production.	

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