LCA and market analysis of a novel bioaugmentation strategy for co-digesting lignocellulosic- and ammonia-rich biomasses

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Full-scale biogas plants worldwide face two major challenges: inhibition of hydrolysis and methanogenesis due to lignocellulosic-and ammonia-rich substrates, respectively, which result in up to 50% of practical methane potential remaining unexploited, leading to environmental and economic consequences for biogas plants (Nielsen and Angelidaki, 2008). To address this problem, bioaugmentation with complex lyophilised specialized methanogenic consortia (Yan et al., 2022a, 2022b), has recently proposed in the MicroPower project (HFRI Pr. No. 15547, https://micropower.gr/), as a promising new strategy to improve biogas production without altering feedstock composition or reactor operational conditions (Fotidis et al., 2014), by enhancing hydrolysis and methanogenesis, and thus the overall AD process efficiency. However, bioaugmentation of lyophilised inocula, which combine specialized hydrolytic bacteria and methanogenic archaea, to simultaneously improve hydrolysis and methanogenesis, is only recently proposed and tested thus there is no comprehensive research of the technology's environmental effects and market acceptance. Therefore, the current study aims, using the unpublished experimental data of the MicroPower project, to provide a preliminary life cycle assessment (LCA) and a basic market analysis of this novel bioaugmentation strategy to initiate the scientific and stakeholder discussion on efficiently co-digesting lignocellulosic- and ammonia-rich biomasses.

The LCA was designed and realized in accordance with the international reference life cycle data systems, technical reports and technical specification bio-based products (CEN/TC 411, 2024; ISO 14040, 2006; ISO 14044, 2006). The goal and scope of the LCA were defined, followed by the collection and quantification of data through the life cycle inventory analysis. The life cycle impact assessment then evaluated the potential environmental impacts associated with the identified inputs and outputs. The results were interpreted to draw conclusions and provide recommendations for improving environmental performance. The system boundaries for the MicroPower LCA were established to assess the environmental impact of the novel bioaugmentation process. These boundaries included all the essential activities required to produce and apply the advanced lyophilized bioaugmentation inocula in continuous anaerobic digestion (AD) reactors using lignocellulose and ammonia-rich substrates. A bioaugmentation-scenario was developed covering microbiome acclimatization, lyophilization, logistics, pasteurization, biomethanation, digestate and energy production etc., all within a unified process for sustainability evaluation compared to a basic-scenario (i.e. conventional AD of unwanted biomasses under "inhibited steady state" (Yan et al., 2019)), and a null-scenario (no treatment of the unwanted biomasses). Sensitivity analyses were conducted to assess the importance of these parameters on overall system performance. The main process steps, material flows, and transformation boundaries were defined, resulting in a material flow scheme of the bioaugmentation and the basic scenarios (Figure 1).

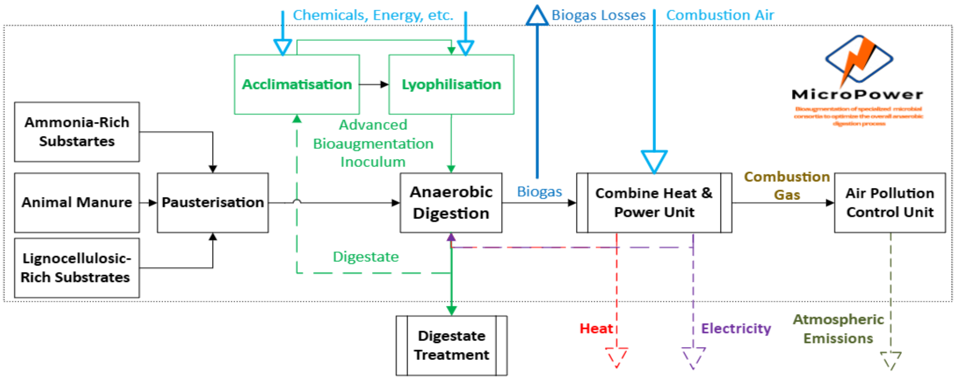

Figure. 1 The MicroPower system process and boundaries basic-scenario (only black boxes) and bioaugmentation-scenario (black and green boxes)

The analysis of the advanced bioaugmentation-scenario revealed that the most significant contributors to the carbon footprint, measured as global warming potential, were digestate production (33%) and the biomethanation process (22%). Biomass sourcing and combined heat and power (CHP) processes also played notable roles, contributing 20% and 12%, respectively. In terms of energy resource consumption, CHP emerged as the dominant factor, accounting for 46% of the total. Digestate, a crucial byproduct of the process, was found to be the primary driver of eutrophication (62%), freshwater use (60%), and nutrient recovery impacts (52%). Given these findings, efforts to enhance the environmental sustainability of bioaugmentation should prioritize reducing the impacts associated with digestate, CHP, and biomethanation. Strategies aimed at optimizing these stages could lead to significant reductions in global warming, acidification, and eutrophication effects, ultimately fostering a more sustainable bioaugmentation process. By improving efficiency and implementing targeted mitigation measures, it is possible to minimize the environmental footprint of these critical processes, contributing to a cleaner and more resource-efficient bioaugmentation system.

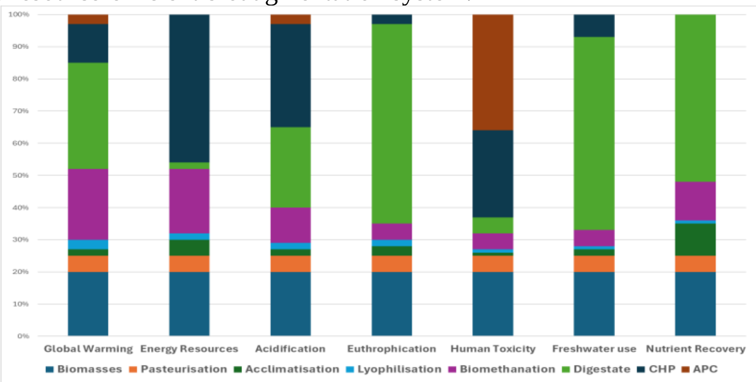

Figure 2. Relative contribution (in %) per MicroPower process to impact category

A sensitivity analysis has been carried out for both the basic and the bioaugmentation scenarios to evaluate the potential reductions in the environmental impacts compared to the null-scenario (Figure 3). The results showed that the basic-scenario, even if it was suboptimal, was expected to contribute significantly to the reduction of different environmental impacts in all categories in the range of approx. 30-50%. The contributions causing the main part of the reductions were different in each impact category of the basic-scenario. For example, the reduction of nutrient recovery, to create and enhance circular economy waste management concepts, is a major concern in many regions producing lignocellulosic- and ammonia-rich substrates. Comparatively, the advanced bioaugmentation-scenario reached reductions in environmental impacts of approx. 40-80% in many impact categories. Especially in the nutrient recovery category, it amounted to more than 30 base units, compared to the basic-scenario due to its ability to efficiently catabolize high nutrient content biomasses (e.g., ammonia-rich).

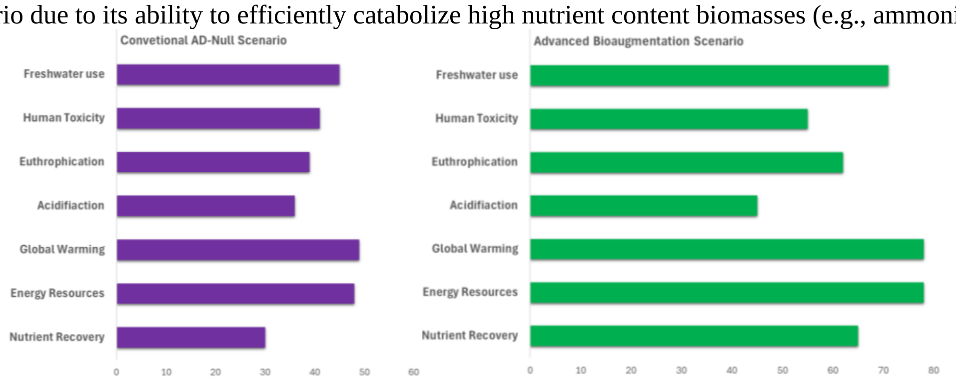

Figure 3. Reduction of environmental impacts for the basic-scenario (left) and the advanced bioaugmentation scenario (right)

The market analysis explored the potential opportunities, stakeholders, and prospects of the MicroPower proposed bioaugmentation technology (Figure 4). The global biogas market, driven by the rising demand for renewable energy and sustainable waste management, is expected to experience significant growth. Key regions such as the European Union, North America, and Asia are providing strong support for this expansion. Between 2010 and 2019, the biogas industry saw an estimated 90% increase in size, with Europe contributing over 70% of global biogas production by 2017, a trend that has continued positively (Abanades et al., 2022). To sustain this growth, new biomass sources with high methane potential are needed. Simultaneously, the growing demand for sustainable treatment of agricultural, industrial, and municipal organic waste, including materials rich in lignocellulose and ammonia, presents a strong market for biogas plants. However, many biogas plants struggle with underperformance due to inefficient lignocellulose hydrolysis and ammonia inhibition. The MicroPower bioaugmentation technology has emerged as an effective solution, enhancing methane yield by 25-40% and improving plant efficiency and profitability. Thus, MicroPower technology is particularly effective for processing lignocellulose- and ammonia-rich waste, attracting industries handling food waste, manure, and agro-industrial residues. Additionally, lyophilized microbial consortia, which can be stored long-term and reactivated as needed, reduce operational costs and simplify implementation. This adaptability makes the technology suitable for both existing and new biogas plants, benefiting a wide range of stakeholders. Key stakeholders that were identified include biogas plant operators, waste management companies, farmers, agricultural cooperatives, industrial partners in food processing and paper industries, research institutions, and policy makers. The competitive landscape reveals that traditional biogas plants often suffer from inefficiencies and methane losses, while the MicroPower technology offers long-term production stability and targeted performance improvements. Future commercialization strategies involve partnerships with biogas plant operators, licensing to manufacturers, and creating standardized products (e.g., ready-to-use lyophilized bioaugmentation inocula) for distribution. Technological advancements will focus on optimizing microbial consortia and developing automated delivery systems. With the potential for deployment in different markets, the MicroPower bioaugmentation technology holds a significant market potential in biogas, agriculture, and waste management sectors, and future efforts will focus on partnerships, technological optimization, and regulatory alignment to maximize impact.

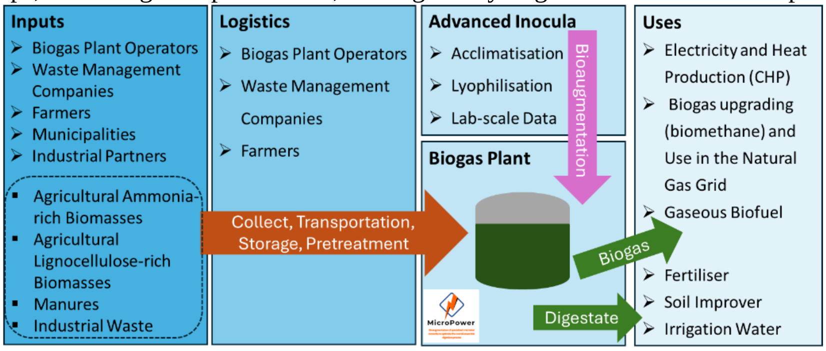

Figure 4. Simplified illustration of a potential the biogas production chain with advanced bioaugmentation implemented. Adjusted from (Emmann et al., 2013)

Acknowledgements

MicroPower-Bioaugmentation of specialized microbial consortia to optimize the overall anaerobic digestion process. The research project is implemented in the framework of H.F.R.I call "Basic research Financing (Horizontal support of all Sciences)" under the National Recovery and Resilience Plan "Greece 2.0" funded by the European Union – NextGenerationEU (H.F.R.I. Project Number: 15547).

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