Circular Bioeconomy for Sustainable Livestock: Integrated Bioelectrochemical and Microalgal Technologies for Pig Slurry Valorization

E. Iniesta-López, A. Hernández Fernández, M.A. Sánchez Muñoz, I. Alfaro Abarca, A. Sánchez-Zurano, F.J. Hernández Fernández, and A. Pérez de los Ríos

Department of Chemical Engineering, Faculty of Chemistry, University of Murcia (UMU), Campus de Espinardo, E-30100 Murcia, Spain

Abstract

The increasing environmental impact of intensive livestock production requires innovative technologies capable of simultaneously reducing pollution, recovering valuable resources, and contributing to climate-neutral agricultural systems. This study presents an integrated circular bioeconomy approach that combines microbial fuel cells (MFCs) equipped with ionic-liquid-based proton exchange membranes and microalgae-bacteria (MB) consortia for the sustainable valorization of raw pig slurry. The process consists of a two-stage treatment in which high-strength pig slurry is first processed in a single-chamber microbial fuel cell, where organic matter is partially removed while renewable bioelectricity is generated. The pretreated effluent is subsequently cultivated in microalgae-bacteria photobioreactors to recover nutrients as valuable biomass and produce a cleaner effluent suitable for further reuse. Unlike conventional MFC systems based on PFAS-containing membranes, the proposed technology employs a non-perfluorinated ionic-liquid membrane, contributing to the development of more sustainable electrochemical treatment systems.

The integrated process achieved more than 50% chemical oxygen demand removal during the bioelectrochemical stage while simultaneously producing electricity. The subsequent biological stage recovered more than 99% of ammonium, 78–87% of total nitrogen, 61–70% of phosphate, and up to 72% of residual organic matter, while producing microalgal biomass with productivities comparable to conventional fertilizer-based cultures. Overall, the combined system demonstrated efficient conversion of livestock waste into renewable energy, biomass, recovered nutrients, and treated water.

These results highlight the potential of integrated bioelectrochemical–microalgal platforms as nature-based circular solutions for sustainable livestock management. Beyond wastewater treatment, the proposed technology contributes to greenhouse gas mitigation, nutrient recycling, reduced dependence on synthetic fertilizers, and decentralized resource recovery, supporting the transition toward resilient agricultural systems and the objectives of the European Green Deal.

Keywords: circular bioeconomy; microbial fuel cells; microalgae; pig slurry; nutrient recovery; sustainable agriculture