Integrated Anaerobic Digestion and *Chlorella vulgaris* Cultivation for Biogas Upgrading and Biomass Valorization

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In the context of the global energy transition, there is an urgent need to develop integrated and sustainable technologies that reduce carbon emissions, promote circular resource use, and support renewable energy production. Anaerobic digestion is a prevalent biological process in which a consortium of microorganisms breaks down organic matter in the absence of oxygen, yielding biogas that is mostly composed of methane and carbon dioxide (CO_2). However, to effectively use biogas as a renewable energy source, it needs to be upgraded to biomethane by the removal of CO_2. In this work, a biologically integrated process was studied for simultaneously producing valuable algal biomass and biomethane. A 6-liter anaerobic digester was operated semi-continuously with four-day feeding intervals using 250 mL of municipal organic waste having a chemical oxygen demand (COD) of 157,000 mg/L. The produced biogas was led through a gas monitoring unit and then supplied to a 1-liter photobioreactor with *Chlorella vulgaris*. In this setup, CO_2 produced from biogas was utilized as the sole carbon source for photosynthesis by microalgae, which enabled CO_2 fixation and methane enrichment without resorting to external aeration. The upgrading of biogas yielded high-purity biomethane, which was CH_4-rich, and the COD of digestate stabilized to approximately 23,000 mg/L at the end of each feeding cycle. It may be noted that the COD of the sludge before feeding was nearly 24,500 mg/L. The microalgae reached a maximum biomass concentration of 0.7 g/L, with a biomass productivity of 0.043 g/L/day. Gas composition was determined by micro gas chromatography, and digestate quality was measured through COD, total solids, and suspended solids. The harvested algal biomass was dried, and biochemical composition was analyzed as lipids, proteins, carbohydrates, and photosynthetic pigments. This integrated system not only upgrades the methane value of biogas by CO_2 bio-sequestration but also valorizes waste streams by producing high-value microalgal biomass. The dual benefit of biogas upgrading and biomass production is a model example of a circular bioeconomy and provides value addition towards zero-waste, and carbon-neutral energy systems. This study demonstrates a viable alternative to conventional biogas upgrading technologies and indicates the potential of algae-based systems in application to renewable energy and resource recovery processes.

Keywords: *CO2 fixation, Biogas, Algae cultivation, Anaerobic digestion*