Opinion

Microalgal Cultivation in Treating Liquid Digestate from Biogas Systems

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Biogas production via anaerobic digestion (AD) has rapidly developed in recent years. In addition to biogas, digestate is an important byproduct. Liquid digestate is the major fraction of digestate and may contain high levels of ammonia nitrogen. Traditional processing technologies (such as land application) require significant energy inputs and raise environmental risks (such as eutrophication). Alternatively, microalgae can efficiently remove the nutrients from digestate while producing high-value biomass that can be used for the production of biochemicals and biofuels. Both inorganic and organic carbon sources derived from biogas production can significantly improve microalgal production. Land requirement for microalgal cultivation is estimated as 3% of traditional direct land application of digestate.

Trends

Biogas production has developed rapidly in recent years. Digestate is an important byproduct of the biogas system. However, digestate processing has become a major bottleneck in the development of a biogas industry.

Biofuels and bioproducts from microalgae are promising for the future; nevertheless, the current microalgal cultivation cost is too high to allow commercial applications. Nutrient use may account for half of the cost in microalgal cultivation. The combining of on-site liquid digestate treatment and microalgal cultivation can significant reduce the nutrient cost for cultivation.

Study of microalga-based digestate treatment has become a topic of much interest in the past few years. Microalgae can efficiently remove various nutrients from digestate, particularly nitrogen and phosphorus. However, there remain numerous challenges for such a process.

Development of Biogas Industry

The global industry of **biogas** (see Glossary) has developed significantly in the past 10 years [1–3]. In Europe, Germany leads the biogas industry. A total of 10 020 biogas plants were in operation in 2014, generating over 144 PJ of energy; biogas produced 4.7% of electricity and 1% of heat demand in Germany [1]. In Asia, China is the largest biogas producer; in 2014, 41.5 million household digesters were in operation, annually generating 13.7 billion m^3 of biogas (293 PJ) [2]. The number of medium/large-scale biogas plants is also growing. In 2014, 99 957 biogas plants produced 2.1 billion m^3 of biogas (45 PJ) [2].

Currently, most biogas is used as a source for generation of heat and/or electricity. However, the use of upgraded biogas (biomethane after removal of CO_2 and impurities) as a transport fuel is growing. In Sweden, 54% of biogas was used as transport biofuel in 2013 [1]. Other countries, such as Switzerland, Germany, China, the USA, and France, are developing biogas-fuelled transport systems [4].

In addition to biogas, **digestate** is another important byproduct [5]. Digestate processing has become a major bottleneck in the development of a biogas industry [6]. Digestate may be separated into solid (10–20% by mass) and liquid (80–90% by mass) fractions by screw press or decanter centrifuge [6]. Solid digestate contains less water and is more stable; it can be easily transported and stored. Solid digestate can either be used as agricultural biofertiliser or be further converted to heat and/or value-added products (e.g., pyrochar, nanocellulose) via thermal processes [6,7]. By contrast, liquid digestate processing is more difficult. The simplest treatment method is to directly spread on local agricultural land; land application of liquid digestate, however, has some disadvantages. First, it leads to NH_3 volatilisation and nutrient loss, which may cause **eutrophication** of nearby water systems [8]. Second, it may cause chemical (e.g., heavy metals), biological (e.g., pathogens), or physical (e.g., plastics) contamination, which reduces the long-term crop productivity of soil [5,9]. Furthermore, the increasing

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number and capacity of biogas plants may lead to an oversupply of digestate for local agricultural land; the value of liquid digestate after long-distance transport may become negative. Digestate is continuously produced. Land application is dependent on the crop growth stage, soil type, and time of year; it is not applied in winter months or in poor weather. Thus, digestate needs to be stored. The storage process can emit additional greenhouse gases (e.g., CH_4, N_2O) [7,9] as the digestion process rarely destroys all volatile solids. Other digestate treatment technologies, such as membrane separation and evaporation, can efficiently concentrate the nutrients; however, they require high energy input. For example, at an industrial scale, membrane separation consumes 16–25 kW_eh (58–90 MJ) of electricity per m^3 treated digestate, while evaporation requires 300–350 kWh (1080–1260 MJ) of thermal energy per ton of water evaporated [6].

There are huge demands on agricultural land for application of digestate (in countries such as Germany) and in a number of countries (such as Ireland) authorisation for the application of digestate produced from the digestion of animal byproducts and wastes is very difficult to obtain. Solutions whereby digestate is not land applied are extremely beneficial to a biogas system. Aquatic **microalgae** may offer an alternative solution for digestate treatment [7,10]. The initial attempt to cultivate microalgae in digestate was conducted by Golueke and Oswald in the 1950s [11]. However, this process was not built upon until very recently. The primary driver for this work is the increasing demand for digestate processing from the biogas industry [1,6].

This opinion article aims to provide a perspective on microalgal cultivation for liquid digestate treatment. Recent trends of microalgae grown in digestate are reviewed. A quantitative model is proposed for a 2-MW_e biogas plant to establish the savings in land area needed provided by a microalgal cultivation system as opposed to land application of digestate. The potential and the challenges associated with such a process are highlighted.

Microalgae Grown in Liquid Digestate

Microalga-based biofuels and bioproducts are promising for the future; however, the current cultivation cost is too high to allow commercial applications [10,12,13]. Nutrient use (e.g., nitrogen, phosphorus) can account for half of the cost and energy input in cultivation [8,14]. The combining of on-site liquid digestate treatment and microalgal cultivation can significantly reduce the nutrient cost.

There are three main cultivation modes for microalgae: photoautotrophic, heterotrophic, and mixotrophic, as described in Box 1. For liquid digestate treatment, mixotrophic microalgae not only improve the biomass productivity and enhance nitrogen and phosphorus removal but also enable inorganic and organic carbon removal. Mixotrophic cultivation has higher biomass concentration and productivity and less photoinhibition/limitation than photoautotrophic cultivation [14–16]. Mixotrophic microalgae can achieve one to two magnitudes higher productivities than photoautotrophic cultures in outdoor photobioreactors [15].

Box 2 presents the effects of the main components of liquid digestate on microalgal growth. The composition of liquid digestate varies significantly and is mainly dependent on feedstock characteristics, the microbial community, **AD** process control (e.g., temperature, organic loading rate, trace element supply), and the configuration (e.g., batch or continuous, single stage or two stage).

Trends in Microalgae Treating Liquid Digestate

Table 1 summarises recent studies of microalgal cultivation using liquid digestate. Most of the reported microalgae are naturally grown in either a freshwater environment (e.g., *Chlorella pyrenoidosa*, *Scenedesmus obliquus*) or a marine environment (e.g., *Nannochloropsis salina*) [17–19]. Alternatively, a mutant strain obtained by nuclear irradiation (e.g., *Chlorella* PY-ZU1)

Glossary

Anaerobic digestion (AD): an anaerobic biological process comprising hydrolysis, acidogenesis, acetogenesis, and methanogenesis. AD degrades organic components such as animal manure, agricultural residues, energy crops, industrial wastes, and food wastes while producing biogas and digestate via a complex microorganism community. AD is efficient in organic component removal; however, it has minimal effect in removal of the inorganic component [14].

Biogas: a gas mixture mainly comprising CH_4 (ca. 60% by volume) and CO_2 (ca. 40% by volume). The gas usually contains trace amounts of water, H_2S, NH_3, N_2, O_2, CO, halogenated hydrocarbons, and siloxanes. Biogas has various applications, such as electricity, vehicle fuel, and heat.

Biorefinery: a sustainable process converting biomass to various products (such as chemicals, materials, and feeds) and energy (including electricity and/or heat and biofuels).

Combined heat and power (CHP) generation: simultaneous generation of electricity and heat via biogas combustion. Efficiencies of 35% and 50% respectively would be typical.

Digestate: a mixture of undigested substrates, microbial biomass, and metabolic products. Digestate contains high levels of nitrogen, phosphorous, and stabilised carbon [7].

Eutrophication: a phenomenon whereby an aquatic system is enriched with natural or artificial nutrients. This may cause explosive growth of algae and plants.

Microalgae: microscopic photosynthetic eukaryotic organisms (usually 1–10 μm in size) that live in freshwater and marine environments. They convert CO_2 and water to organic carbon components (e.g., glucose) and produce O_2 through photosynthesis. Cyanobacteria may also be referred to as microalgae, as they share many features [44,45,47].

Two-stage fermentation: separate hydrolytic and methanogenic reactors. The two reactors operate at the optimal pH for each stage (hydrolysis and methanation). In the first, hydrolytic reactor much of the organic component is hydrolysed and fermented to VFAs, while in the