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Biogas production from microalgae grown in wastewater: Effect of microwave pretreatment

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HIGHLIGHTS

- Microwave irradiation enhanced the disintegration and digestibility of microalgae.
- Algal biomass solubilisation increased by 800% with microwave pretreatment.
- The main parameter influencing biomass solubilisation was the applied specific energy.
- Increased biogas production rate (27–75%) and yield (12–78%) with pretreated biomass.
- Linear correlation between microalgae solubilisation and biogas yield.

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ABSTRACT

The aim of this study was to evaluate the effect of microwave pretreatment on the solubilisation and anaerobic digestion of microalgae–bacterial biomass cultivated in high rate algal ponds for wastewater treatment. The microwave pretreatment comprised three specific energies (21,800, 43,600 and 65,400 kJ/kg TS), combining three output power values with different exposure times. Response surface analysis showed that the main parameter influencing biomass solubilisation was the applied specific energy. Indeed, a similar solubilisation increase was obtained for the same specific energy, regardless of the output power and exposure time (280–350% for 21,800 kJ/kg TS, 580–610% for 43,600 kJ/kg TS and 730–800% for 65,400 kJ/kg TS). In biochemical methane potential tests, the initial biogas production rate (27–75% increase) and final biogas yield (12–78% increase) were higher with pretreated biomass. A linear correlation was found between biomass solubilisation and biogas yield. It can be concluded that microwave irradiation enhanced the disintegration and digestibility of microalgae.

1. Introduction

During the last decade, there has been a growing interest in investigating the energy potential of biofuels obtained from microalgae cultures [1]. The high lipid content of microalgae makes them an alternative to terrestrial energy crops for biodiesel production. However, microalgae cultures and energy production are at an initial research phase. According to the literature, the cultivation of microalgae to produce biofuels has a number of requirements that limit its current implementation at industrial scale [2]. To make it economically feasible, massive biomass production and energy generation technologies must be addressed.

The cultivation of certain specific strains of microalgae is not viable in economic and environmental terms, since freshwater and fertilizers are needed. In contrast, if microalgal biomass is grown as a by-product of high rate algal ponds (HRAPs) operated for wastewater treatment, the economic and ecological footprint are more realistic if used at large-scale [3,4]. High rate ponds are shallow, open raceway ponds, with continued mixing provided by paddle-wheels. This system works by a symbiosis between heterotrophic bacteria, which oxidize organic matter contained in wastewater, and the phytoplankton, which by photosynthesis consumes the CO_2 derived from organic matter mineralization. Microalgae–bacterial biomass grown in this environment assimilates nutrients and subsequently, its separation from the final effluent eliminates nutrients from the wastewater [5].

Anaerobic digestion of microalgae was first studied in the 1950s [6,7]. These authors used microalgal biomass from HRAP, pointing out biomass separation from the liquor as a major limitation of the process. Up to date, the literature on microalgae digestion is very limited. The review by González-Fernández et al. [1] reports a specific methane production of 0.1–0.5 L CH_4/g VS, with 60–80% CH_4 in biogas, depending on process temperature (15–52 °C) and

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hydraulic retention time (HRT) (3–64 days). This value is commensurate with biogas production from other substrates. For instance, the specific methane production of waste activated sludge, another by-product of wastewater treatment, ranges between 0.15 and 0.3 L CH_4/g VS [8]; and that of lignocellulosic agricultural crops, such as maize, wheat, rice and sugarcane wastes, between 0.28 and 0.34 L CH_4/g VS [9].

The complex cell wall structure of microalgae, composed by cellulose, hemicellulose and pectin, makes bacteria attack difficult [1]; suggesting that biomass pretreatment is necessary for the feasibility of microalgae anaerobic digestion [10]. The pretreatment of substrates to increase the anaerobic biodegradability has been the subject of intense research in recent years. Physical, chemical and biological processes have proven successful at improving the disintegration and anaerobic biodegradability of lignocellulosic biomass [11]. Furthermore, waste activated sludge pretreatment using mechanical, thermal and biological processes increased the specific methane production, leading to positive energy balances, and is currently applied in full scale facilities [12]. The few studies that have so far been conducted with microalgae show an increased methane yield after thermal and ultrasound pretreatments [13–16].

The electromagnetic radiation of microwaves has also been investigated as a pretreatment process [17–19]. Microwaves are short waves of electromagnetic energy varying in a frequency from 300 MHz to 300 GHz, which can increase the kinetic energy of the water leading to a boiling state [17]. The quantum energy applied by microwave irradiation is not capable of breaking down chemical bonds, however hydrogen bonds are or can be broken [20]. Induction heating and dielectric polarization result in changes in the secondary and tertiary structure of proteins and cause cell hydrolysis. The polarization of macromolecules occurs by a consistent rotation through an alternating electric field. This process is influenced by microwave frequency, radiation time, biomass concentration and penetration depth [18].

The literature on microwave pretreatment of waste activated sludge under different conditions [18,21–25], shows how the process enhanced sludge solubilisation and/or cumulative gas production in anaerobic batch tests (Table 1). Microwave irradiation can produce both thermal and athermal effects. Some authors have compared microwave and thermal pretreatments, observing higher volatile solids and hemicellulose solubilisation [19] and biogas production [26] with the former. So far, the effect of microwave irradiation on microalgae remains unexplored.

Thus, the objective of this study was to evaluate the effect of microwave pretreatment on the disruption and anaerobic biodegradability of microalgal biomass from HRAP for wastewater treatment.

2. Materials and methods

2.1. Microalgal biomass production system

The experimental set-up was located at the laboratory of the GEMMA research group (Universitat Politècnica de Catalunya. BarcelonaTech, Spain). The system had been in operation since March 2010. The microalgae production system was composed of a hydrolytic up-flow sludge blanket reactor (HUSB), a high rate algal pond and a settler. Urban wastewater was pumped from a municipal sewer and stored in a tank (1.2 m^3), which was continuously stirred to avoid solids sedimentation. From the storage tank, pretreated wastewater was conveyed to the primary treatment: a cylindrical PVC HUSB, with an internal diameter of 0.3 m, a total height of 1.9 m and an effective volume of 0.105 m^3; operated at an HRT of 5 h. The sludge blanket inside the HUSB reactor was kept at a total volatile solids (VS) concentration below 10 g/L by periodical purge. A detailed description of the operation and performance of the HUSB reactor can be found in Pedescoll et al. [27].

The primary effluent of the HUSB reactor was stored in a 50 L regulation tank and pumped to the HRAP by means of peristaltic pumps. The experimental HRAP was a PVC raceway pond with a paddle wheel for stirring the mixed liquor. The HRAP had a nominal volume of 0.5 m^3, a surface area of 1.5 m^2 and a water depth of 0.3 m. The HRAP treated 62.5 L/day corresponding to an HRT of 8 days. Average surface loading rates were 24 g COD/m^2 day and 4 g NH_4–N/m^2 day. The daily biomass production potential was calculated from Eq. (1), where TSS is the concentration of total suspended solids in the mixed liquor of the HRAP, A is the HRAP surface area and Q is the flow rate.

$$\text{Biomass production} = [\text{TSS (g/L)}/A\ (\text{m}^2)] \times Q(L/d) \quad (1)$$

Microalgal biomass was harvested from the HRAP by means of a conventional settling tank, with a nominal volume of 0.01 m^3 (0.16 days HRT). Purged biomass was then settled in laboratory Imhoff cones stored at 4 °C for 24 h. The HRAP performance was monitored by taking weekly samples at 2 PM from March 2011 to March 2012. Average characteristics of the HRAP influent, effluent and harvested biomass are summarized in Tables 2 and 3.

2.2. Microwave pretreatment

To study the effect of microwave pretreatment on microalgal biomass a household type microwave (Samsung M1914, 2450 MHz frequency) was used. The output power range of the equipment was 100–1000 W (Microwave test procedure IEC-705). Three target specific energies were applied: 21,800; 43,600 and 65,400 kJ/kg TS. Considering the following output power

Table 1
Effect of microwave pretreatment on activated sludge solubilisation and biochemical methane potential tests.

Pretreatment conditions	Batch test conditions	Results	References
14.3 min; 400 W; 102 °C; 2.3% TS		Increase of 17.9% in the COD_s/COD ratio*	[18]
5 min; 800 W; 13,000 kJ/kg SS	55 °C; 32 d	Increase of 311% in the VS_s/VS ratio and no difference in biogas production and production rate*	[21]
5 min; 96 °C; 5.5% TS	33 °C; 23 d	Increase of 143% in the COD_s/COD ratio and 211% in the cumulative biogas production*	[22]
Progressive heating 1.2–1.4 °C/min; 175 °C	33 °C; 18 d	Increase of 74.3% in COD solubilisation and 34% in biogas production*	[23]
0.83 kJ/ml; 1000 W; 7–8% TS	35 °C; 20–25 d	Decreased solubilisation (COD_s/COD) and increase of 15.4% in methane production*	[24]
1168 W; 90 °C; 4% TS	35 °C; 22 d	Increase of 2.5% in the COD_s/COD ratio, 37% in the digestion rate and no impact on methane production*	[25]

Note: TS: total solids, SS: suspended solids, VS: volatile solids, VSs: soluble volatile solids, COD: chemical oxygen demand, CODs: soluble chemical oxygen demand.
* Compared to control.