Algal Research 28 (2017) 235–243

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Towards energy neutral microalgae-based wastewater treatment plants

Fabiana Passos[a,b,1], Raquel Gutiérrez[a,1], Enrica Uggetti[a,*], Marianna Garfí[a], Joan García[a], Ivet Ferrer[a]

[a] GEMMA – Group of Environmental Engineering and Microbiology, Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya·BarcelonaTech, c/Jordi Girona 1-3, Building D1, E-08034 Barcelona, Spain
[b] Department of Sanitary and Environmental Engineering, Federal University of Minas Gerais, Antonio Carlos Avenue 6627, 31270-090 Belo Horizonte, Brazil

ARTICLE INFO

Keywords:
Anaerobic co-digestion
Energy balance
High rate algal pond
Microalgal biomass
Wastewater

ABSTRACT

The aim of this study was to assess the energy balance of a hypothetical microalgae-based wastewater treatment plant (10,000 PE) located in the Mediterranean Region, where harvested microalgal biomass and primary sludge would be co-digested to produce biogas and bioenergy. The assessment was based on experimental results obtained over one year in pilot high rate algal ponds followed by anaerobic digesters for biogas production from harvested microalgal biomass and primary sludge. The energy balance compared four scenarios: 1) anaerobic co-digestion of microalgal biomass and primary sludge, and cogeneration from biogas in a combined with heat and power (CHP) unit; 2) co-digestion with thermal pretreatment of microalgal biomass, and cogeneration from biogas in a CHP unit; 3) co-digestion and heat generation from biogas in a boiler; and 4) co-digestion with thermal pretreatment of microalgal biomass, and heat generation from biogas in a boiler. According to the results, when biogas was used to cogenerate electricity and heat (scenarios 1 and 2), the electricity balance was always positive, and the best results were obtained with pretreated microalgal biomass (scenario 2). Similarly, the heat balance was always positive when biomass was thermally pretreated (scenario 2). On the other hand, when biogas was only used to produce heat (scenarios 3 and 4), heat requirements were covered during the whole year. The sensibility analysis of the scenarios with pretreatment (2 and 4) confirmed that the microalgae-based WWTP would be energy neutral or even net energy producer.

1. Introduction

The wastewater treatment sector has considerably evolved over the past decades showing a huge increase in treatment facilities based on conventional wastewater treatment systems [1]. However, energy requirements for these conventional technologies (such as activated sludge) are about 1 kWh/m^3 [2], which represents a high energy consumption. Furthermore, it has been estimated that aeration is responsible for > 60% of the total energy consumption of activated sludge processes [3]. Thus, energy devoted to wastewater treatment must be significantly reduced to cut down both environmental impacts and costs. Besides, the final effluent and by-products from wastewater treatment facilities are currently regarded as wastes with no value. To make wastewater treatment self-sufficient, it is necessary to shift from the current model of sanitation towards a new one in which wastewater treatment systems will become a low energy demanding industry, able to generate marketable products rather than wastes.

In this new scenario, microalgae-based wastewater treatment systems (such as high rate algal ponds (HRAPs)) are an alternative in suitable cases (e.g. enough surface area available and high solar radiation) with low-energy demand, which produces microalgal biomass that could be used as bioenergy feedstock [4]. HRAPs were developed in the late 1950s in California [5] and used since then to treat a wide variety of municipal, industrial and agricultural wastewaters [6]. In such systems, microalgae photosynthesis provides the oxygen required by heterotrophic bacteria to oxidise organic matter without external aeration [7]. Since these systems do not require mechanical aeration, they only consume around 0.02 kWh/m^3 [8]. This corresponds to a saving of > 50% of the energy applied to the mechanical aeration of an activated sludge reactor. Furthermore, microalgal biomass produced in HRAPs could be digested to produce biogas and cover the energy requirements for wastewater treatment [9]. It was estimated that between 800 and 1400 GJ/ha year could be produced from microalgae-based wastewater treatment plants (WWTPs), which could be used to provide sufficient energy for medium (10,000 PE) and small-scale systems (2000 PE) [10]. Furthermore, the sludge from the primary treatment

---

[*] Corresponding author.
E-mail address: enrica.uggetti@upc.edu (E. Uggetti).
[1] Both authors contributed equally.

https://doi.org/10.1016/j.algal.2017.11.006
Received 8 May 2017; Received in revised form 13 September 2017; Accepted 5 November 2017

could be co-digested to increase the biogas and bioenergy production. In spite of the increasing interest in HRAPs and anaerobic digestion of microalgal biomass, their full-scale implementation for bioenergy generation in WWTPs has yet to be exploited. Since the wastewater treatment capacity has been widely proved, the following step towards the dissemination of these systems is the evaluation of energy aspects in an integrated system, including biogas production from by-products (microalgae and sludge).

The aim of this study was to assess the energy balance of a hypothetical microalgae-based WWTP (10,000 PE) with anaerobic co-digestion of harvested microalgal biomass and primary sludge. For the first time, a year-round energy assessment of a microalgae-based WWTP was undertaken based on experimental data on biomass and biogas production. These data were gathered over one year in pilot HRAPs followed by anaerobic digesters, and were used to evaluate the energy balance of four different scenarios (with or without microalgae biomass thermal pretreatment, and a cogeneration unit or a boiler for biogas conversion). This scenario analysis allows establishing the conditions for the WWTP to be energy self-sufficient. To the best of the authors' knowledge, this is the first study evaluating the energy balance of a microalgae-based wastewater treatment system, including the co-digestion of microalgae and primary sludge with or without microalgae thermal pretreatment.

2. Experimental section

2.1. Pilot plant

Two pilot HRAPs located outdoors on the roof of the building of the Group of Environmental Engineering and Microbiology-GEMMA (Department of Civil and Environmental Engineering of the Universitat Politècnica de Catalunya·BarcelonaTech (Barcelona, Spain)) were monitored over one and a half years (from July 2012 to December 2013). In this pilot plant, wastewater from a municipal sewer was daily pumped to a homogenisation tank (1.2 m^3), where it was screened and stored for a few hours (not relevant for wastewater quality). From this tank, wastewater flowed continuously (180 L/d) to a primary settler (7 L, 0.0255 m^2), with a critical settling velocity of 7 m/d and a hydraulic retention time (HRT) of 1 h. Following, the primary effluent was pumped to the two parallel HRAPs working each at different HRT (4 and 8 days), corresponding to flow rates of 120 and 60 L/d. Both HRAPs (from now on referred to as 4 days-HRAP and 8 days-HRAP) were built in PVC and had a surface area of 1.54 m^2, a water depth of 0.3 m and a useful volume of 0.47 m^3. A paddle-wheel driven by an engine operated at 5 rpm ensured a flow velocity of 10 cm/s. Microalgal biomass grown in the HRAPs was harvested in two secondary settlers with a useful volume of 10 L, a surface area of 0.0255 m^2, a critical settling velocity of 4.7 and 2.4 m⁄d, and a HRT of 2 and 4 h for the 4 days-HRAP and 8 days-HRAP, respectively. Around 1–1.5 L of biomass with a total solids concentration of 0.7–1.5% (w/w) (depending on the period of the year) was harvested from each settler every weekday. More details on the microalgae composition can be found in Gutiérrez et al. [11]. Subsequently, harvested microalgal biomass was thickened in gravity settling cones for 24 h to increase the solids concentration to 2.5% (w/w), before undergoing anaerobic co-digestion. A fraction of this thickened microalgae biomass was thermally pretreated. To this end, a 250 mL-glass bottle was filled with 150 mL of thickened biomass and placed in an incubator at 75 °C under continuous stirring for 10 h [12]. Afterwards, pretreated and non-pretreated thickened biomass was co-digested with primary sludge in two identical lab-scale anaerobic digesters (1.5 L). Due to the low flow rate of primary sludge of the pilot-scale primary settlers, primary sludge was collected from a municipal WWTP near Barcelona and had an average volatile solids (VS) concentration of 28.5 g/L. The reactors were fed with a mixture of 75% primary sludge and 25% microalgal biomass (pretreated and non-pretreated) on a VS basis. This proportion was selected based on the optimal one among several conditions of co-digestion in biochemical methane potential (BMP) tests [13]. Continuous lab-scale reactors were operated under mesophilic conditions (37 ± 1 °C) by an electric heating cover (Selecta, Spain) at a HRT of 20 days. The biomass flow rate varied from 14.6 (December) to 110 m^3/d (April). Constant mixing was provided by a magnetic stirrer (Thermo Scientific).

2.2. Experimental procedures

Microalgal biomass production was quantified once a week by determining the concentration of total suspended solids (TSS) from a grab sample of the HRAPs mixed liquor collected at 10 am. Monthly average biomass production was calculated in terms of g TSS/m^2·d, from daily production estimated for each week (Eq. (1)).

$$\text{Microalgal biomass production} = \frac{\mathrm{TSS}(Q - Q_E + Q_P)}{A} \tag{1}$$

where TSS is the total suspended solids concentration of the HRAPs mixed liquor (mg TSS/L), Q is the wastewater flow rate (L/d), Q_E is the evaporation rate (L/d), Q_P is the precipitation rate (L/d) and A is the surface area of the pilot HRAPs (m^2). The evaporation rate was calculated following Eq. (2).

$$Q_E = \frac{E_p A}{7} \tag{2}$$

where E_p is the potential evaporation between weekly samples (mm), calculated from Turc's formula (Eq. (3)). Note that the 7 in Eq. (2) is necessary to change from weekly to daily evaporation rate.

$$E_p = a(R + 50)\frac{Ta}{Ta + 15} \tag{3}$$

where R is the average solar radiation in a week (cal/cm^2d), T_a is the average air temperature in a week (°C), and a is the dimensionless coefficient verying depending on the numbers of days elapsed between sampling (in this case 0.091, which is the value corresponding to 7 days between sapling). In general the precipitation rate was negligible in comparison to the other flows.

Filtered HRAPs mixed liquor, which has the same nutrients and dissolved organic matter concentrations as the secondary settler effluent, was used to analyse the soluble chemical oxygen demand (sCOD) and ammonium nitrogen (NH_4^+-N) concentrations, as indicators of wastewater treatment efficiency. Thus, COD removal was calculated from the difference between the concentrations in unfiltered samples of the primary effluent and filtered samples of the HRAPs mixed liquor (glass fiber filters of 47 mm and average pore size 1 μm). The wastewater treatment efficiency was weekly monitored during the whole experimental period. COD was analysed according to Standard Methods [14] and NH_4^+-N was measured according to the Solorzano method [15]. All analyses were performed in triplicate and averages were used to give data shown in this paper.

Solar radiation, air temperature and precipitation data were obtained from a nearby meteorological station (Department of Astronomy and Meteorology, University of Barcelona, http://infomet.am.ub.es).

Experimental results were used to determine the best HRT for wastewater treatment (which is the primary goal of the HRAPs) and the linked microalgal biomass production over the year. In general, as lower the HRT the higher the biomass production, but effluent water quality has to be maintained.

2.3. Energy assessment

The best HRAPs operation conditions (4 days of HRT from March to October and 8 days of HRT from November to February) were then used to perform the year-round energy assessment of a hypothetical full-scale WWTP located in the Mediterranean region.

To this aim, four scenarios were considered: