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Nutrient removal from agricultural run-off in demonstrative full scale tubular photobioreactors for microalgae growth

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ABSTRACT

The objective of this paper is to present the design, construction and operation (during one year) of 3 full scale semi-closed, horizontal tubular photobioreactors (PBR, 11.7 m^3 of volume each) used to remove nutrients of a mixture of agricultural run-off (90%) and treated domestic wastewater (10%). PBRs were located outdoor and have 2 paddlewheels (engines of 0.25 kW) to ensure the movement of the mixed liquor. The microalgal biomass produced in the PBRs was harvested in a static lamella settling tank in which a polyaluminium chloride coagulant is applied. Each PBR treated in average 2.3 m^3/d, being the actual mean hydraulic retention time 5 d. PBRs were submitted to strong seasonal changes regarding solar radiation and temperature, which had a direct impact in the activity of microalgae and the efficiency of the system. Higher mixed liquor pH values were registered in summer (daily average > 10). These high values were not observed in the effluents because the system was designed to discharge the mixed liquor (effluent) only at the end of night, when pH reached the lowest daily values (around 8.5). Most of the influent and effluent nitrogen content was inorganic (average of 9.0 mg N/L and 3.17 mg N/L, respectively), and in the form of nitrate (62% and 50%, respectively). Average nitrogen removal efficiency was 65%, with values of around 90% in summer, 80% in autumn, 50% in winter and 60% in spring. Most of the influent and effluent phosphorus content was in the form of orthophosphate. Influent average was 0.62 mg P/L, but with great variations and in a considerable number of samples not detected. Removal efficiency (when influent values were detected) was very high during all the study, usually greater than 95%, and there were not clear seasonal trends for efficiency as observed for TIN. Volumetric biomass production greatly changed between seasons with much lower values in winter (7 g VSS (volatile suspended solids)/m^3·d) than in summer (43 g VSS/m^3·d). Biomass separation efficiency of the settler was very good in either terms of turbidity and total suspended solids, being most of the time lower than 5 UNT and 25 mg/L, respectively. Overall this study demonstrated the reliable and good effectiveness of microalgae based technologies such as the PBR to remove nutrients at a full scale size.

1. Introduction

Changes in the nutrient biochemical flows due to anthropogenic activities are one of the main environmental challenges that humanity must face in the coming decades. The alteration of the cycles of nitrogen and phosphorus (N and P) is already considered of high global risk, with unfavourable effects leading to unknown impacts (Steffen et al., 2015). Urban and agricultural discharges of contaminated or insufficiently treated water are the main cause for the imbalance of these biochemical cycles. Nowadays, most of the aquatic ecosystems are receiving these nutrient enriched discharges, being their eutrophication an unequivocal signal of it. Globally, more than 450 coastal areas are affected by severe eutrophication (Selman et al., 2008).

Ecological engineering techniques can be used to reverse this contamination situation in many cases, allowing also for the restoration of these aquatic ecosystems. In particular, treatment wetlands have been extensively used in recent decades as effective systems for the treatment of urban, agricultural and even industrial wastewater; a vast array of literature with hundreds of examples at full scale is available (Ávila et al., 2013; García et al., 2010). There is much less experience with

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other types of ecological engineering techniques such as microalgae systems, despite the fact that microalgae based wastewater treatment systems were developed more than 50 years ago, specifically to treat urban wastewaters (García et al., 2006). Therefore, it is necessary to show and demonstrate the potential of these microalgae technologies at full-scale. One of the most powerful advantage of microalgae systems in comparison to other technologies is that harvested microalgae biomass can easily be valorised as a bioproduct and/or energy, which is extremely interesting within the framework of the circular economy.

Up to date, most of the studies devoted to phytoremediation of agricultural-related wastes by means of microalgae have focused on lab-scale experiments to treat industrial effluents, such as those from dairy farms (Labbé et al., 2017), palm oil mills (Kamyab et al., 2015) or rice mills (Kumar et al., 2016). The treatment of aquaculture effluents and diluted pig slurry treatments were also investigated in different works (Ansari et al., 2017; Lananan et al., 2014; Ledda et al., 2016). The capacity of microalgae to remove pesticides from agriculture run-off was also evaluated by Matamoros and Rodríguez (2016). In all cases, however, only lab-scale experiments were performed, usually with microalgae cultures grown on synthetic media and aseptic conditions. To the authors' knowledge, only two recent studies have evaluated the feasibility of integrating agricultural run-off treatment and biomass production at real scale. Bohutskyi et al., (2016) studied the phytoremediation of agricultural run-off by filamentous green microalgae (*Cladophor*a sp. and *Rhizoclonium* sp.) in an Algal Turf Scrubber (ATS®), treating 10 million gallons per day. The authors obtained a maximum monthly productivity of 22 g/m^2·d (measured as volatile suspended solids) and a suitable feedstock to obtain biogas after anaerobic digestion. Furthermore, diluted digestate from anaerobic digestion was used as nutrients supplement to cultivate more valuable microalgae species. The second study by García-Galán et al. (2018) evaluated the efficiency of a large-scale photobioreactor treating agriculture run-off and also obtaining microalgae biomass as added-value product. Results showed a maximum biomass production of 76.4 g/m^3·d (measured as total suspended solids) in April, and a total N elimination ranging from 84% to 95%.

In the present paper we describe the experience gained on the design, construction and operation during the first year after the start-up (from May 2017 to May 2018) of 3 full scale photobioreactors (PBRs) fed with a mixture of agricultural run-off and treated domestic wastewater. The microalgae biomass produced in the photobioreactors was harvested in a static lamella settling tank. All these units were constructed in the framework of the innovation European project INCOVER (http://incover-project.eu/). These PBRs are part of a complex installation aiming to efficiently treat wastewater and produce bioenergy, bioproducts and reclaimed water for irrigation. A brief description of the entire experimental site can be found in Uggetti et al. (2018). This study is exclusively focused on the PBRs functioning and their auxiliary elements. The INCOVER project will be operative till May 2019.

2. Materials and methods

2.1. Photobioreactors design

The PBRs are located in the Agròpolis experimental campus of the Universitat Politècnica de Catalunya-BarcelonaTech (UPC) (41.288N, and 2.043 E UTM), very near to Barcelona's airport (Figs. 1 and S1 in the Supplementary materials). The PBRs and their auxiliary elements were conceived, designed and constructed by the GEMMA Research Group of the UPC in collaboration with the company Disoltech S.L after several previous investigations (García-Galán et al., 2018; Solimeno et al., 2017; Uggetti et al., 2018). These PBRs are tubular horizontal semi-closed reactors, each consisting of 2 lateral open tanks made from 10 mm polypropylene (5 m width, 1 m length and 0.6 m height, nominal volume of 1.25 m^3 each at design water depth). Both tanks are connected through 16 low density polyethylene tubes (0.3 mm thick, 125 mm diameter and 47 m length, nominal volume of 9.2 m^3 for all tubes together) (Figs. 2 and S2). These tubes lie down on a plastic covering sheet in order to ensure separation from the ground, and they are protected by agricultural anti-birds nets. The total useful volume of each PBR is 11.7 m^3 (approximately 20% corresponding to the tanks, and 80% to the tubes). In each open tank, a paddlewheel with eight blades (1 m width, 0.35 m long) is installed 1.8 m away from the external edge and at 3 cm height from the bottom. An engine (0.25 kW) connected to each paddlewheel provides a turning speed which can be changed from 0 to 12 rpm. Rotation of the paddlewheel makes the mixed liquor contained in the tank move from a shallow water sector to a deep one. Difference in pressure head causes a gravity flow through 8 tubes from the deep side of one tank to the shallow side of the opposite one. Then again, the flow is moved by the paddlewheels to the deeper side part of the tank, and then it returns to the shallow side of the first tank through the other 8 tubes, and so on (Fig. S2). Each tank has an inclined dam in the deep sector, which assists in maintaining the two different surface water levels and avoids big waves within the tank (Fig. 2). Both open tanks ensure and favour the homogenous distribution and mixing of the liquor and also the release of the exceeding dissolved oxygen accumulated along the closed tubes.

Each PBR is equipped with online sensors of pH (Hatch Lange SL., Spain), dissolved oxygen (DO) (Neurtek, Spain) and temperature (Campbell Scientific Inc., USA) in one of the two open tanks. Data of these parameters are taken every 5 s and recorded and stored each 60 s in a datalogger (Campbell Scientific Inc., USA). PBRs also include a water level sensor (Wras, UK) to control filling and emptying operations. They also have an automatic CO_2 injection system (tubing, valves and pressure sensor), but at the time of the present work it was not being used.

The three PBRs were installed in winter 2016–17, and were inoculated at the end of April 2017 with a mixed culture grown in experimental high rate algal ponds fed with urban wastewater (Gutiérrez et al., 2016a,b). A volume of 10 L was added to each PBR, with a volatile suspended solids (VSS) concentration of approximately 220 mg/L. The inoculum consisted of a community of bacteria, microalgae, protozoa and small metazoa, but mostly dominated by green microalgae *Chlorella* sp. and *Stigeoclonium* sp., and diatoms *Nitzschia* sp. and *Navicula* sp. (Gutiérrez et al., 2016a,b). Note that *Stigeoclonium* is a branched filamentous microalgae which in natural aquatic environments usually grows attached to submerged surfaces. In the particular case of the inoculum used here, it was growing in the form of flocs submerged in the mixed liquor of the high rate algal ponds. After inoculation, the three PBRs were operating in parallel and fed with a mixture of agricultural run-off and domestic wastewater (design ratio of 6:1 respectively, although the actual ratio was slightly higher). Total design flow was 7 m^3/d (6 m^3/d of agricultural run-off and 1 m^3/d of treated domestic wastewater) (see Supplementary Materials, Methods section).

2.2. Auxiliary elements description and system operation

Treated domestic effluent is obtained from an aerated septic tank which receives the wastewater of the main building of the campus Agròpolis (~20 persons, without overnight stay), whereas agricultural wastewater comes from a drainage collection channel (see Fig. 1). Fig. 3 shows a process flow diagram of the PBR and their auxiliary elements. Daily operation cycle starts at 4:30 AM when the treated domestic wastewater, stored in a cylindrical glass fiber tank (TK-103, 1 m^3) discharges in a cylindrical polyethylene homogenization tank (HT-102, 10 m^3, provided with a sampling port) through stream line 3. This operation is done by means of a centrifugal pump P-104 (14.4 m^3/h) during a maximum time of 30 min. Treated domestic wastewater continuously reaches TK-103 by the stream line 2, that conveys treated wastewater to the tank thanks to a submersible pump located in the aerated septic tank. When more than 1 m^3 domestic wastewater is produced per day, TK-103 remains full and the remaining wastewater