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## Performance of a membrane-coupled high-rate algal pond for urban wastewater treatment at demonstration scale

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Abstract: The objective of this study was to evaluate the performance of an outdoor membrane-coupled high-rate algal pond equipped with industrial-scale membranes for treating urban wastewater. Decoupling biomass retention time (BRT) and hydraulic retention time (HRT) by membrane filtration resulted in improved process efficiencies, with higher biomass productivities and nutrient removal rates when operating at low HRTs. At 6 days of BRT, biomass productivity increased from 30 to 65 and to 90 g·m<sup>-3</sup>·d<sup>-1</sup> when operating at HRTs of 6, 4 and 2.5 days, respectively. The correspondent nitrogen removal rates were 4, 8 and 11 g N·m<sup>-3</sup>·d<sup>-1</sup> and the phosphorous removal rates were 0.5, 1.3 and 1.6 g P·m<sup>-3</sup>·d<sup>-1</sup>. The system was operated keeping moderate specific air demands (0.25 m<sup>3</sup>·m<sup>-2</sup>·h<sup>-1</sup>), resulting in reasonable operating and maintenance costs (€0.04 per m<sup>3</sup>) and energy requirements (0.287 kWh per m<sup>3</sup>). The produced water was free of pathogens and could be directly used for reusing purposes.

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Dear Editor,

Attached you will find the manuscript entitled “**Performance of a membrane-coupled high-rate algal pond for urban wastewater treatment at demonstration scale**” submitted for possible publication as an original research article in the Special Issue on Biological Nutrients Removal and Recovery (BNR) in *Bioresource Technology*.

The objective of this study was to evaluate the performance of an outdoor membrane-coupled high-rate algal pond equipped with industrial-scale membranes for treating urban wastewater. The important findings that must be highlighted are:

- Decoupling biomass retention time and hydraulic retention time by membrane filtration resulted in improved process efficiencies.
- Higher biomass productivities and nutrient removal rates were achieved when operating at low hydraulic retention times.
- The system was operated keeping moderate specific air demands, resulting in reasonable operating and maintenance costs and energy requirements.
- The produced water was free of pathogens and could be directly used for reusing

Yours sincerely,

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## Performance of a membrane-coupled high-rate algal pond for urban wastewater treatment at demonstration scale

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### Highlights

- Decoupling hydraulic and biomass retention times increased the system performance
- N and P removal rates enhanced at lower hydraulic retention times
- Efficient operation achieved at low specific air demands
- Relatively low operational energy requirements

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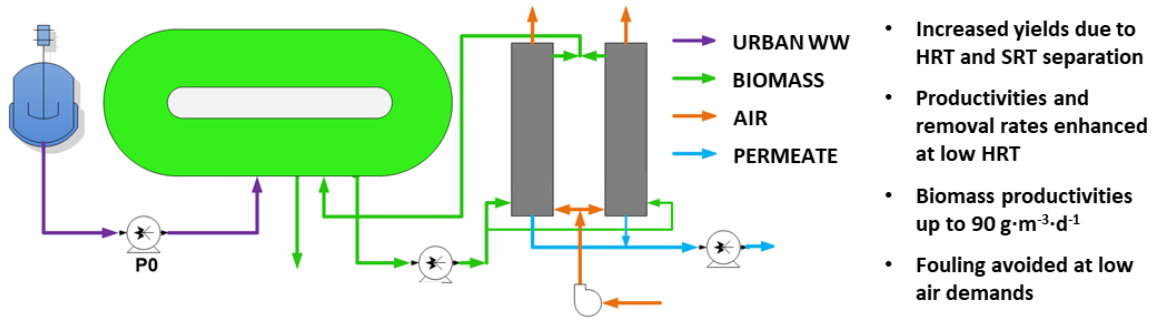
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### Abstract

The objective of this study was to evaluate the performance of an outdoor membrane-coupled high-rate algal pond equipped with industrial-scale membranes for treating urban wastewater. Decoupling biomass retention time (BRT) and hydraulic retention time (HRT) by membrane filtration resulted in improved process efficiencies, with higher biomass productivities and nutrient removal rates when operating at low HRTs. At 6 days of BRT, biomass productivity increased from 30 to 65 and to 90  $\text{g}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$  when operating at HRTs of 6, 4 and 2.5 days, respectively. The correspondent nitrogen removal rates were 4, 8 and 11  $\text{g N}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$  and the phosphorous removal rates were 0.5, 1.3 and 1.6  $\text{g P}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ . The system was operated keeping moderate specific air demands ( $0.25 \text{ m}^3\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ), resulting in reasonable operating

and maintenance costs (€0.04 per m<sup>3</sup>) and energy requirements (0.287 kWh per m<sup>3</sup>). The produced water was free of pathogens and could be directly used for reusing purposes.

## Graphical abstract



## Keywords

High-rate algal pond (HRAP); industrial-scale hollow-fibre membranes; nutrient recovery; secondary urban wastewater treatment; ultrafiltration

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## 1. Introduction

The concept of circular economy relies on the recovery of valuable compounds from waste streams. To implement this approach, wastewater treatment plants are nowadays being shifted towards modern water resource recovery facilities (WRRFs), where the wastewater is not only

1 treated and disposed, but also transformed into valuable products (*e.g.* energy, nutrients and  
2 reclaimed water).

3  
4 The recovery of nutrients from urban wastewater (UWW) is a key goal to be achieved in  
5  
6 future WRRFs due to its essential role in achieving a sustainable food production-  
7  
8 consumption network. Microalgae-based processes have a huge potential as main actors for  
9  
10 this purpose (Salama et al., 2017). Autotrophic microalgae are organisms able to grow using  
11  
12 carbon dioxide as carbon source and light as energy source, assimilating at the same time the  
13  
14 nutrients required for their growth (*i.e.* inorganic nitrogen and phosphorous). They convert  
15  
16 these materials into biomass and a series of valuable organic compounds which are  
17  
18 precursors of different forms of bio-energy (*e.g.* biogas, biodiesel, bio-ethanol, and bio-  
19  
20 butanol) and other value-added products (*e.g.* products for livestock or fertilizers) (Wang et  
21  
22 al., 2016). The cultivation of microalgae in wastewaters could reduce the production costs,  
23  
24 generating at the same time clean water, recovering the nutrients initially present in the  
25  
26 wastewater and capturing carbon dioxide during their growth by harvesting solar energy, thus  
27  
28 reducing the environmental impact of the process (Wang et al., 2016). However, while these  
29  
30 autotrophic microorganisms can efficiently reduce the concentrations of nutrients present in  
31  
32 wastewater to very low values (*e.g.*  $2.20 \text{ mg NH}_4\text{-N}\cdot\text{L}^{-1}$  and  $0.15 \text{ mg PO}_4\text{-P}\cdot\text{L}^{-1}$  (Boelee et al.,  
33  
34 2011)), they cannot remove organic matter, thus not being able to provide a complete  
35  
36 wastewater treatment. Because of this, microalgae-based treatment systems are generally  
37  
38 applied for tertiary wastewater treatment or are often combined with anaerobic pretreatments  
39  
40 (Wang et al., 2015).

41  
42 The utilization of microalgae-bacteria consortia to provide a complete single-stage treatment  
43  
44 of wastewater is regarded as a potential solution for this problem. This wastewater treatment  
45  
46 approach is based upon a synergetic interaction: the organic matter is degraded by  
47  
48 heterotrophic bacteria, producing carbon dioxide, which is consumed by microalgae during  
49  
50

1 photosynthesis, assimilating nutrients during this process and generating the oxygen that  
2 bacteria need to carry out aerobic respiration. In addition, other advantages of this mixed-  
3 culture systems have been postulated when compared to sole-microalgae cultures: (i) algae  
4 and bacteria produce vitamins and other organic compounds which can be beneficial for the  
5 growth of the partners, (ii) some microalgae generate a extracellular matrix that can provide  
6 attachment sites for bacteria and be used as carbon source, (iii) bacteria have been found to  
7 favour the flocculation of algae, enhancing biomass harvesting and (iv) the spatial distance for  
8 oxygen and carbon dioxide exchange is decreased (Arbib et al., 2017; Fernández-Sevilla et  
9 al., 2018; Galès et al., 2019; Liao et al., 2018; Shoener et al., 2019; Wang et al., 2016). Recent  
10 studies have demonstrated the feasibility of microalgae-bacteria consortia for UWW  
11 treatment. Removals of 92% of the biological chemical demand (BOD), 75% of the total  
12 nitrogen ( $N_T$ ) and 93% of total phosphorus ( $P_T$ ) have been reported using offshore  
13 photobioreactors (PBRs) (Novoveská et al., 2016). Photo-sequencing batch reactors reached  
14 removals of 87% of the chemical oxygen demand (COD) and 98% of the total Kjeldahl  
15 nitrogen (TKN), without the need of external aeration (Foladori et al., 2018). In high-rate  
16 algal ponds (HRAPs), removal efficiencies of 40-80% of the soluble COD, 80-100% of the  
17  $NH_4^+$  and 30-80% of the  $PO_4^{3-}$  have been reported (Galès et al., 2019). Therefore, these  
18 systems have appeared as an environmental-friendly wastewater treatment option able to  
19 remove both COD and nutrients while avoiding the need of supplying external oxygen or  
20 carbon dioxide.

21 Two key factors are limiting the application of microalgae-bacteria consortia for UWW  
22 treatment: (i) high amounts of total suspended solids (TSS) in the effluent (washout of  
23 microorganisms) and (ii) expensive biomass harvesting methods (Craggs et al., 2011;  
24 Solimeno and García, 2017; Wang et al., 2016). Both of these issues could be overcome by  
25 using membranes for biomass retention, enabling the decoupling of the biomass retention time



1 (BRT) and the hydraulic retention time (HRT) (Bhave et al., 2012; González-Camejo et al.,  
2 2019; Liao et al., 2018; Seco et al., 2018; Viruela et al., 2018). The application of membranes  
3  
4 also provides an efficient solid-liquid separation, acting as biomass harvesting process and  
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6 resulting in increased biomass concentrations and higher productivities due to enhanced  
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8 nutrient removal efficiencies and higher organic loading rates (Bilad et al., 2014b; Honda et  
9  
10 al., 2012; Luo et al., 2017). Furthermore, the addition of ultrafiltration membranes allows  
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12 producing reclaimed water (*i.e.* with negligible levels of pathogens and suspended solids)  
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14 from wastewater, directly applicable for several purposes (*e.g.* irrigation or fertirrigation,  
15  
16 aquifer recharge or urban/industrial uses).  
17  
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19  
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21 HRAPs have been widely applied for large-scale cultivation of microalgae worldwide, mainly  
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23 due to their low investment and operational costs, their easy operation and maintenance and  
24  
25 their low specific energy demand (Craggs et al., 2011; Kumar et al., 2015). Coupling  
26  
27 membranes and HRAP can also help to overcome the low biomass productivities achieved,  
28  
29 which has been recognised as a key challenge in HRAPs (Craggs et al., 2011; Dalrymple et  
30  
31 al., 2013; Drexler and Yeh, 2014). Nevertheless, before membrane-coupled high-rate algal  
32  
33 ponds (M-HRAP) can be applied industrially, research must still be carried out to ensure the  
34  
35 feasibility of this technology (Bilad et al., 2014a). A key challenge that this technology may  
36  
37 face is membrane fouling (Bilad et al., 2012; Marbelia et al., 2014; Sun et al., 2013;  
38  
39 Wicaksana et al., 2012). In addition, the performance of M-HRAPs for wastewater treatment  
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41 is significantly sensitive to the environmental and operating conditions, which must be  
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43 optimized for each particular case. The available literature dealing with urban wastewater  
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45 treatment via microalgae-bacteria consortia using membranes for decoupling BRT and HRT is  
46  
47 limited, with no pilot/demonstration-scale studies available using HRAPs. Therefore, the  
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49 performance and feasibility of this process must be evaluated, determining the achievable  
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51 biomass productivities and the resulting nutrient recoveries. Potential operational issues must  
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still be identified, setting the baselines for future optimization.

The objective of this study was to evaluate the performance of an outdoor M-HRAP equipped with industrial-scale membranes for treating UWW. The effect of the membrane addition to the HRAP system (decoupling of BRT and HRT) on the treatment performance was assessed. In addition, the effect of naturally varying environmental conditions (*i.e.* temperature and light intensity) on the outdoor M-HRAP performance were also studied. The capability of the process for UWW treatment was evaluated by determining the biomass productivities, the nutrient removal rates and the COD removal efficiencies, all of them being crucial parameters for these systems. After assessing the filtration performance, energetic and economic analyses were carried out to study the potential feasibility on the proposed process.

## **2. Materials and methods**

### *2.1. Self-inoculation of the HRAP and influent wastewater*

The plant was self-inoculated after starting feeding it with UWW. The start-up period for inoculation lasted for 1-2 weeks. An initial natural selection of the predominant microorganisms occurred naturally, facilitating the potential application of this technology.

The main characteristics of the synthetic UWW used as substrate for microbial growth are shown in Table 1. This UWW was prepared according to Nopens et al. (2001). It was continuously fed to the HRAP from a refrigerated tank (kept at 4 °C) with a volume of 500 L.

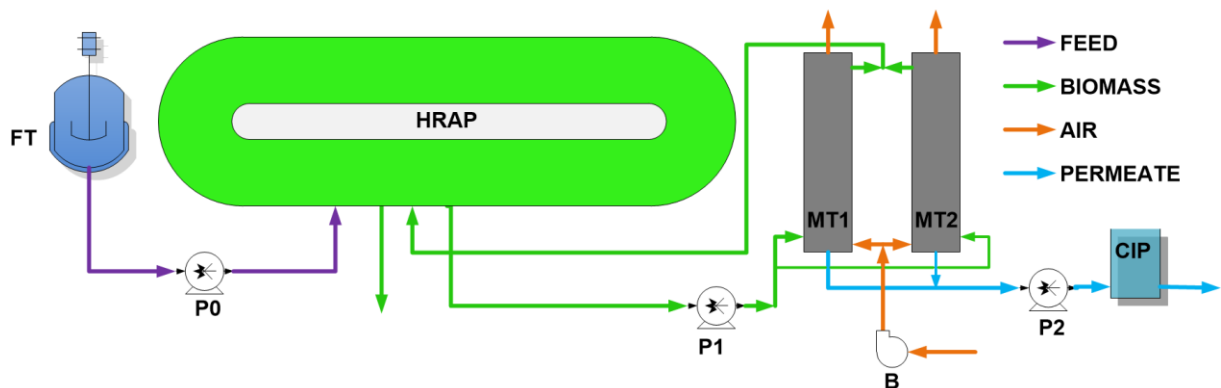
**Table 1.** Characteristics of the synthetic urban wastewater

Parameter	Units	Mean $\pm$ SD
NH <sub>4</sub> -N	mg N·L <sup>-1</sup>	17.3 $\pm$ 8.1
N <sub>T</sub>	mg N·L <sup>-1</sup>	45.5 $\pm$ 24.2
PO <sub>4</sub> -P	mg P·L <sup>-1</sup>	3.9 $\pm$ 1.6
P <sub>T</sub>	mg P·L <sup>-1</sup>	6.1 $\pm$ 2.2
COD <sub>T</sub>	mg·L <sup>-1</sup>	332 $\pm$ 55
VSS	mg·L <sup>-1</sup>	89 $\pm$ 24

SD stands for standard deviation, NH<sub>4</sub>-N for ammonium-N, N<sub>T</sub> for total nitrogen, PO<sub>4</sub>-P for phosphate-P, P<sub>T</sub> for total phosphorous, COD<sub>T</sub> for total chemical oxygen demand and VSS for volatile suspended solids.

## 2.2. Description of the demonstration plant (M-HRAP)

A continuously-operated M-HRAP was used in this study. Its working volume was 22 m<sup>3</sup>, with a depth of 0.3 m and a solar irradiance area of approximately 73.4 m<sup>2</sup>. The HRAP (located in the south of France, Lat. 43.156711, Long. 2.995075) was continuously mixed by a paddlewheel. As it can be observed in Figure 1, showing a flow diagram of the system, the HRAP was connected to two membrane tanks (MT1 and MT2), each of them including one membrane bundle (with a filtration area of 3.44 m<sup>2</sup>) that was obtained from one industrial-scale hollow-fibre ultrafiltration membrane unit (PURON<sup>®</sup> Koch Membrane Systems (PUR-PSH31), 0.03  $\mu$ m).



**Figure 1.** Flow diagram of the membrane-coupled high-rate algal pond. Nomenclature: FT: feeding tank; HRAP: high-rate algal pond; MT: membrane tank; CIP: clean-in-place; P:

pump; and B: blower

### 2.3. Monitoring of the plant operation

Different on-line sensors were installed in the M-HRAP to obtain real-time information of the state of the process. The on-line sensors placed in the HRAP were: (i) a pH-T transmitter (METTLER TOLEDO InPro® 4260 SG), (ii) a dissolved oxygen probe (METTLER TOLEDO InPro® 6800 G Amperometric Oxygen Sensor), (iii) an ultrasonic flowmeter for determining the influent flowrate (Titan Enterprises Ltd. atrato), and (iv) an irradiation sensor (Skye PAR Quantum Sensor) for measuring the photosynthetic active radiation (PAR).

Moreover, several sensors were installed to monitor the membrane performance: two liquid flow-rate transmitters (one after the mixed liquor recycling pump and another after the permeate pump), three level transmitters (one for each membrane tank and another for the clean-in-place unit), one pressure transmitter for monitoring the transmembrane pressure in the membrane tanks, one air pressure transmitter (in the blower outlet) and one air flowmeter for measuring the air sparging for membrane scouring. The T and PAR values provided in this work refer to daily averages of the continuous PAR measurements, considering both daylight and night-time hours.

In addition to the on-line process monitoring, samples were taken three times per week from the influent, the mixed liquor and the effluent streams to evaluate the performance of the biological processes. The concentrations of the total and soluble COD ( $COD_T$  and  $COD_S$ , respectively),  $N_T$ ,  $P_T$ , inorganic nutrients ( $NH_4^+$ ,  $NO_2^-$ ,  $NO_3^-$  and  $PO_4^{-3}$ ), total suspended solids (TSS) and volatile suspended solids (VSS) were periodically measured. In addition, the optical density at 680 nm ( $OD_{680}$ ) was used for VSS estimation ( $VSS_{680}$ ). The structure of the microbial community was studied via quantitative polymerase chain reaction (qPCR), estimating the copies per liter of 18S rDNA (from chlorophyte) and bacterial 16S rDNA.

## 2.4. Operation of the plant

The M-HRAP was operated outdoors (*i.e.* under ambient temperature and solar irradiance conditions) at a constant BRT of 6 days and three different HRTs: 6 days (run I; no membrane operation), 4 days (run II) and 2.5 days (run III). As the temperature and the light irradiation are known to affect significantly the performance of microalgae-based wastewater treatment processes (Perin et al., 2016; Ras et al., 2013), the influence of these variables on the M-HRAP was studied during run IV (at equivalent BRT and HRT as run III). Table 2 shows the particular objective of each run period, as well as the applied working conditions and the daily average solar irradiances and culture temperatures.

**Table 2.** Average operating conditions and objectives of the different run periods

Run	Objective	BRT (d)	HRT (d)	J ( $L \cdot m^{-2} \cdot h^{-1}$ )	SAD <sub>m</sub> ( $m^3 \cdot m^{-2} \cdot h^{-1}$ )	Solar irradiance ( $\mu E \cdot m^{-2} \cdot s^{-1}$ )	Temperature (°C)
I	Evaluate effect of BRT and HRT decoupling	6	6	NA	NA	433±113	22.0±3.1
II		6	4	28, 14	0.3, 0.6	395±72	21.2±2.0
III		6	2.5	28	0.12 – 1.0	420±90	24.5±1.8
IV	Evaluate effect of light and temperature changes	6	2.5	27-31	0.6 – 1.2	253±195	14.1±1.1

BRT stands for biological retention time, HRT for hydraulic retention time, J for transmembrane flux, SAD<sub>m</sub> for the specific air demand per membrane unit and NA not applicable

The membrane was operated with a gross transmembrane flux (J) of 28  $L \cdot m^{-2} \cdot h^{-1}$  (LMH) at the beginning of run II, lowering its value to 14 LMH afterwards. The value of J was fixed at 28 LMH during run III, varying between 27-31 LMH in run IV. During run II, the average specific air demand per square meter of membrane area (SAD<sub>m</sub>) was set to 0.3  $m^3 \cdot m^{-2} \cdot h^{-1}$  and

then increased to  $0.6 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$  to maintain the desired  $J$ . The  $\text{SAD}_m$  varied from 0.12-1.0  $\text{m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$  and 0.6-1.2  $\text{m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$  during run III and IV, respectively. The pH varied freely according to variations in the carbon dioxide concentrations, related to the activity of microorganisms.

## 2.5. Analytical methods and microbial analysis

The concentrations of  $\text{COD}_T$ ,  $\text{COD}_S$ ,  $\text{N}_T$ ,  $\text{P}_T$  and VSS were measured according to the Standard Methods (APHA, 2005). The concentrations of nutrients, *i.e.*  $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$ , were determined by ion chromatography, according to Capson-Tojo et al. (2017).

## 2.6. Data treatment and calculations

To evaluate the performance of the M-HRAP treatment process, the nitrogen removal rate (NRR), the phosphorus removal rate (PRR) and the biomass productivity were calculated according to Equations 1 to 3:

$$\text{NRR} = \frac{Q \cdot (N_i - N_e)}{V_{\text{MHRAP}}} \quad \text{Eq. 1}$$

$$\text{PRR} = \frac{Q \cdot (P_i - P_e)}{V_{\text{MHRAP}}} \quad \text{Eq. 2}$$

$$\text{Biomass productivity} = \frac{Q_w \cdot X_{\text{VSS}}}{V_{\text{MHRAP}}} \quad \text{Eq. 3}$$

Where,  $Q$  is the treatment flow rate ( $\text{m}^3 \cdot \text{d}^{-1}$ ),  $N_i$  is the concentration of nitrogen in the influent ( $\text{g N} \cdot \text{m}^{-3}$ ),  $N_e$  is the concentration of nitrogen in the effluent ( $\text{g N} \cdot \text{m}^{-3}$ ),  $V_{\text{MHRAP}}$  ( $\text{m}^3$ ) is the total volume of the M-HRAP,  $P_i$  is the concentration of phosphorus in the influent ( $\text{g P} \cdot \text{m}^{-3}$ ),  $P_e$  is the concentration of phosphorus in the effluent ( $\text{g P} \cdot \text{m}^{-3}$ ),  $Q_w$  ( $\text{m}^3 \cdot \text{d}^{-1}$ ) is the flow rate of wasted biomass and  $X_{\text{VSS}}$  ( $\text{g VSS} \cdot \text{m}^{-3}$ ) is the VSS concentration in the HRAP.

The photosynthetic efficiency (PE), and the carbon dioxide biofixation ( $CO_{2BF}$ ) (kg  $CO_2$  per  $m^3$  of treated water) were also used as indicator of the biological activity. They were calculated according to Eq. 4, and Eq. 5, respectively.

$$PE (\%) = \frac{r_G \cdot H_B}{I \cdot S \cdot f} \cdot 100 \quad \text{Eq. 4}$$

$$CO_{2BF} = \frac{r_G}{Y_{CO_2} \cdot Q} \quad \text{Eq. 5}$$

Where  $r_G$  is the daily microalgae growth (kg VSS·d<sup>-1</sup>),  $H_B$  is the lower heating value of dry biomass (22,900 kJ·kg VSS<sup>-1</sup>),  $I$  is the PAR ( $\mu\text{mol photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ),  $f$  is a conversion factor (18.78 kJ·s· $\mu\text{mol photons}^{-1} \cdot \text{d}^{-1}$ ),  $S$  is the surface of the open pond ( $\text{m}^2$ ) and  $Y_{CO_2}$  is the stoichiometric  $CO_2$  capture for microalgae growth (0.52 kg VSS·kg  $CO_2^{-1}$ ). For stoichiometric calculations of microalgae biomass composition, the chemical formula used in Viruela et al. (2018) was applied in this study (*i.e.* C<sub>106</sub>H<sub>181</sub>O<sub>45</sub>N<sub>16</sub>P).

The measured  $J$  values were standardized to 20 °C, according to Eq. 6:

$$J_{20} = J \cdot e^{-0.0239 \cdot (T-20)} \quad \text{Eq. 6}$$

Where,  $J_{20}$  is the 20 °C-standardized gross flux,  $J$  is the gross flux and  $T$  is the temperature in degrees Celsius.

## 2.7. Energy and economic analysis

### 2.7.1. Power requirements

The energy consumption of the M-HRAP unit was assumed to be mainly related to blowers (air sparging), pumps (culture media and permeate), and paddlewheel. The power requirements for pumps and blower were calculated as (Pretel et al., 2016). On the other hand,

an energy demand of  $0.4 \text{ W/m}^2$  was set for the paddlewheel.

### 2.7.2. Estimation of the operational and maintenance costs

The energy requirements of the blower, sludge recycling pump and permeate pump for filtration or back-flushing were calculated as explained in Robles et al. (2014). The costs related to energy consumption assumed an energy cost of 0.07 € per kWh, similarly to average electricity prices for industrial installations in Spain.

Other than the energy consumption due to air sparging and permeate and culture pumping, the costs related to membrane replacement and membrane chemical cleaning were considered.

The useful membrane lifetime was estimated from the total chlorine contact specified by the manufacturer and the recommended membrane chemical cleaning frequency.

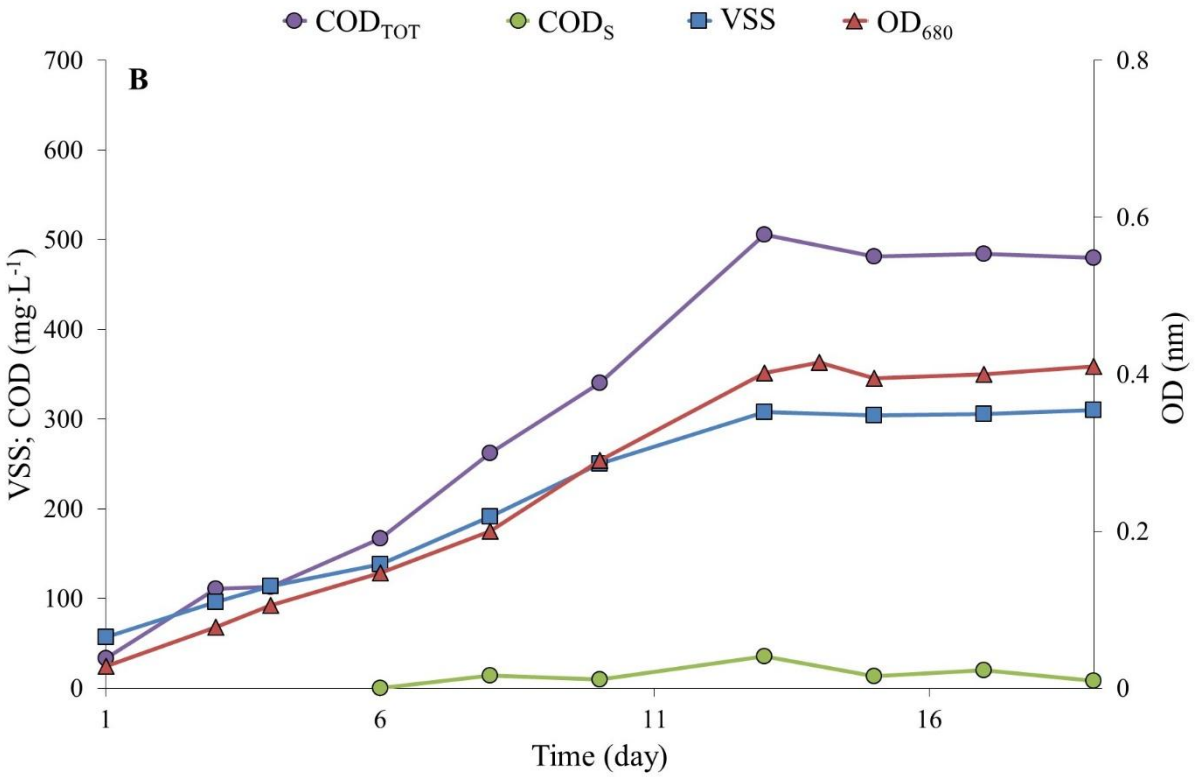
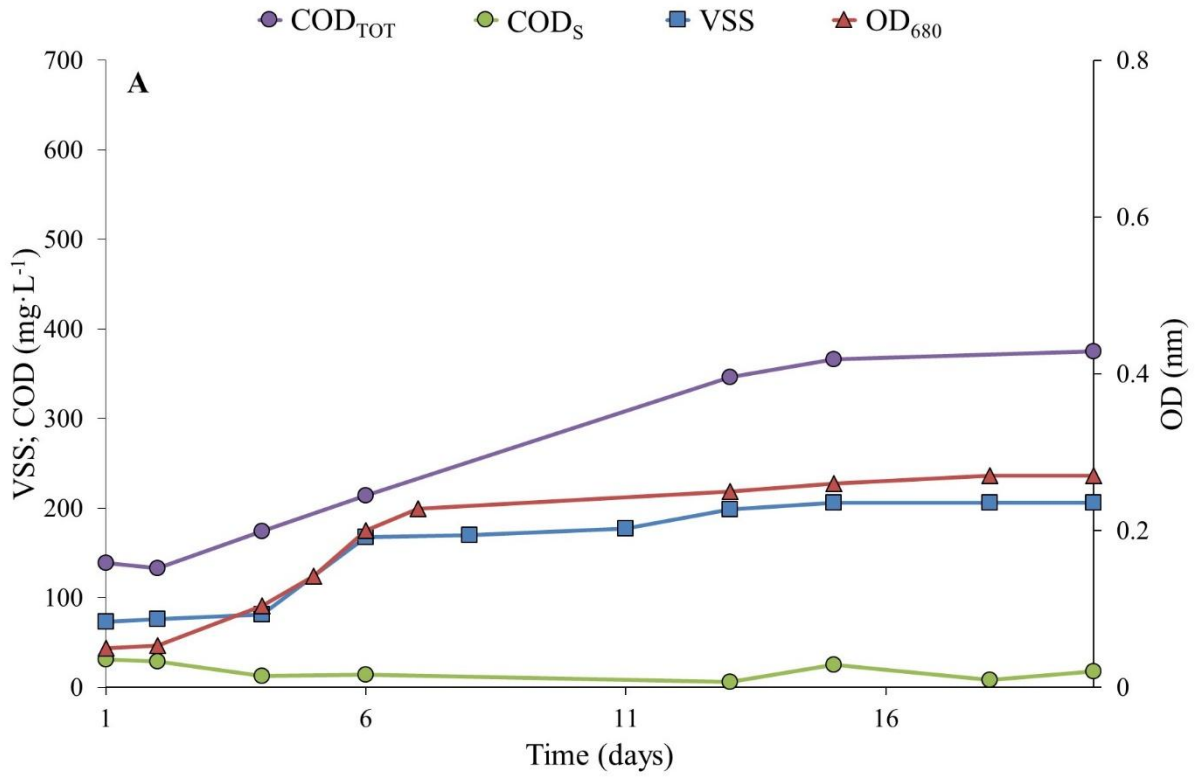
A more precise description of the costing methodology can be found in Robles et al. (2018).

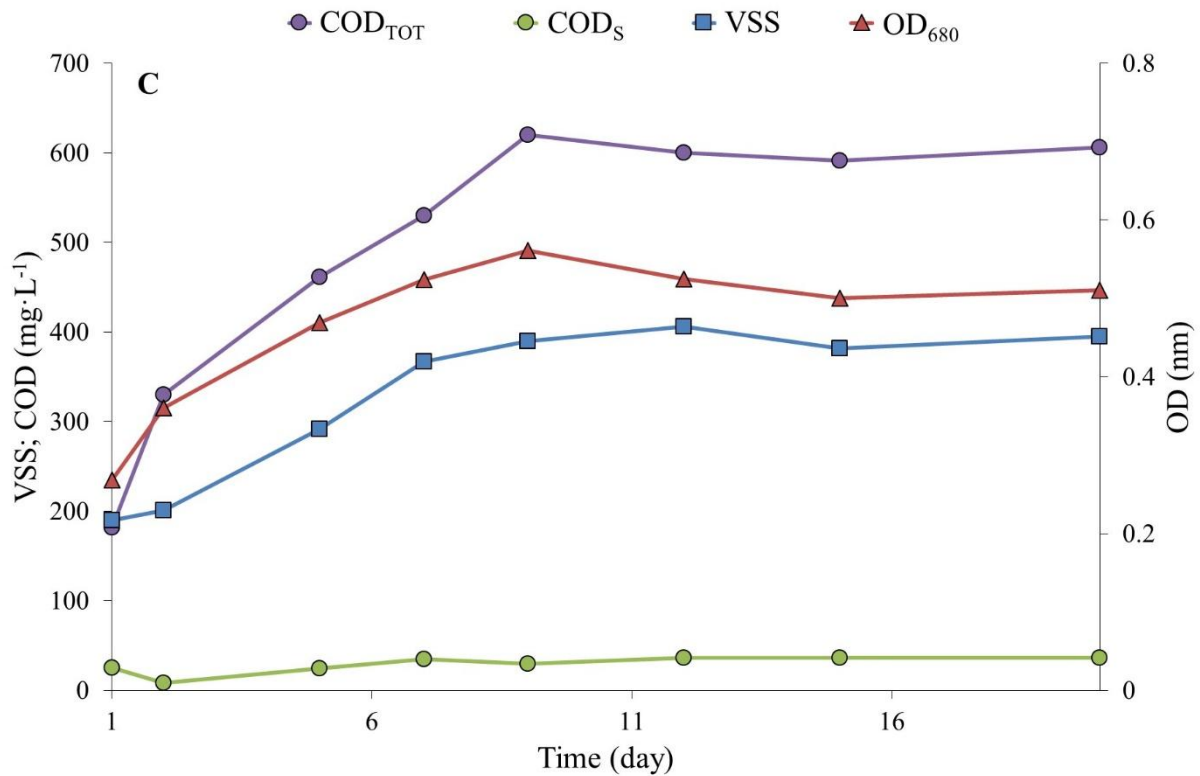
## 3. Results and discussion

### 3.1. Influence of the BRT and HRT decoupling on the M-HRAP performance

As aforementioned, runs I-III were dedicated to study the influence of decoupling the HRT and the BRT, i.e. testing different HRTs for a given BRT. Starting with runs I to III, the corresponding evolutions of the concentration of  $\text{COD}_T$ ,  $\text{COD}_S$ , VSS and the OD measurements (together with the estimated VSS) are presented in Figure 2.







**Figure 2.** M-HRAP performance when operating at a BRT of 6 days and HRTs of (A) 6, (B) 4, and (C) 2.5 days. COD<sub>T</sub>: total chemical oxygen demand; COD<sub>S</sub>: soluble chemical oxygen demand; VSS: volatile suspended solids; OD<sub>680</sub>: optical density at 680 nm.

The first observation to point out is the negligible values of the COD<sub>S</sub> that existed in all the conditions after the incubation period (always below 50 mg COD·L<sup>-1</sup>). This indicates that heterotrophic bacteria grew very rapidly initially, without any limitation for their growth in the applied working conditions. Nevertheless, the increasing VSS and COD<sub>T</sub> concentrations that can be observed in all the figures suggest that the biomass concentration augmented in the M-HRAP (considering stable COD<sub>S</sub> in the influent). This suggests the further development of an adapted microbial population, mainly due to growth of microalgae at this point. Although the raising COD<sub>T</sub> concentrations occurred in the three run periods studied, the behaviours were clearly different. When comparing the biomass concentrations in the reactors at pseudo-

steady state, it can be observed higher values when lowering HRTs (*i.e.* around 400, 500 and 600 mg VSS·L<sup>-1</sup> at HRTs of 6, 4 and 2.5 days, respectively). This resulted in an enhanced general performance of the biochemical system, decreasing also the time to reach a stable community. The favoured biomass growth when decoupling the BRT and HRT can be attributed to two main factors: (i) the membrane avoided the wash-out of microorganisms, which otherwise would have left the reactor (improving the start-up process) and (ii) the increased mass flow rate of both COD and nutrients at lower HRTs allowed a faster development of the microorganisms.

This improvement can be easily appreciated in the results presented in Table 3, where the NRRs, PRRs and biomass productivities are given for each run period.

**Table 3.** Average results in runs I to III at pseudo-steady state for: nitrogen and phosphorous removal rates, biomass productivities, photosynthetic efficiency, and carbon dioxide biofixation

Run	BRT (d)	HRT (d)	NRR (g N·m <sup>-3</sup> ·d <sup>-1</sup> )	PRR (g P·m <sup>-3</sup> ·d <sup>-1</sup> )	Biomass productivity (g VSS·m <sup>-3</sup> ·d <sup>-1</sup> )	PE (%)	CO <sub>2BF</sub> (kg CO <sub>2</sub> ·m <sup>-3</sup> )
I	6	6	4	0.5	30	1.0	0.2
II	6	4	8	1.3	65	4.0	0.3
III	6	2.5	11	1.6	95	3.5	0.4

BRT stands for biological retention time, HRT for hydraulic retention time, NRR for nitrogen removal rate, PRR for phosphorous removal rate, PE for photosynthetic efficiency, CO<sub>2BF</sub> for carbon dioxide biofixation, and VSS for volatile suspended solids

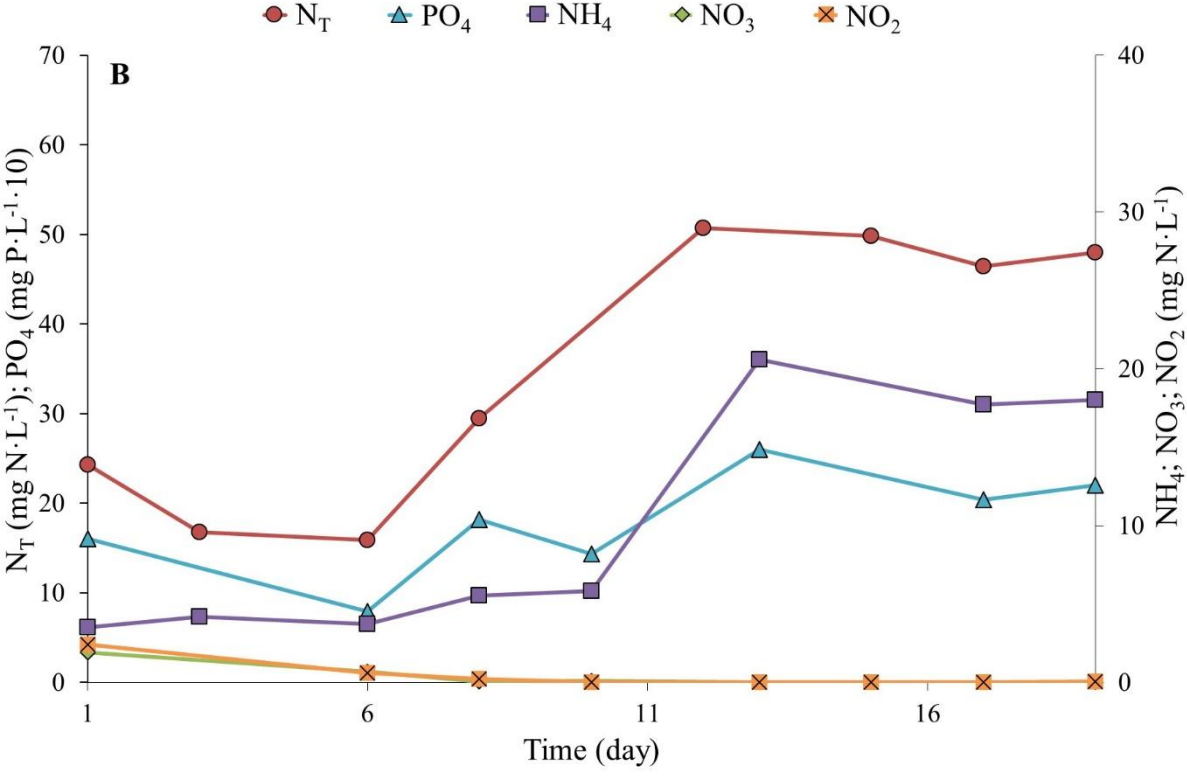
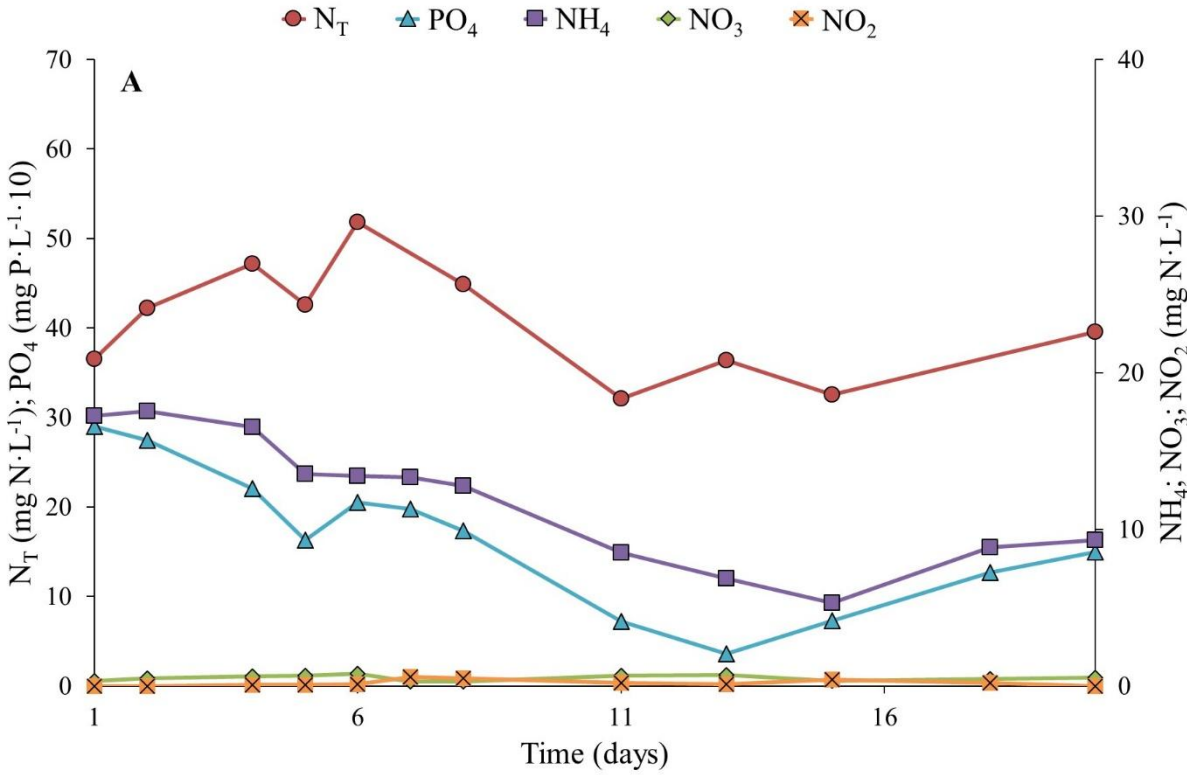
As this table illustrates, decoupling the BRT and the HRT increased significantly the nutrient removal rates and the biomass productivities. Decreasing the HRT by a factor of 2.4 (*i.e.* from 6 to 2.5 days) resulted in 3-folded NRRs and PRRs when comparing runs I and III. In addition, the biomass productivity increased from 30 to 65 and to 90 g VSS·m<sup>-3</sup>·d<sup>-1</sup> at decreasing HRTs of 6, 4 and 2.5 days, respectively. The increased biological activity due to

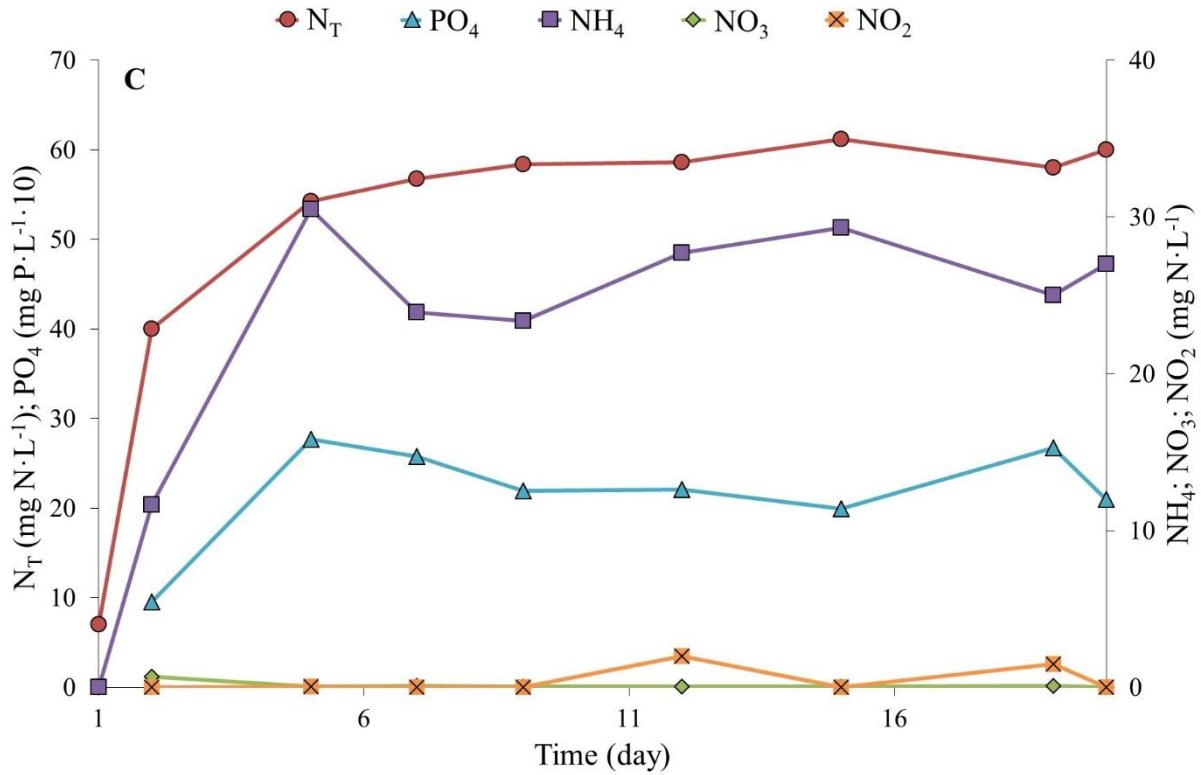
1 BRT/HRT decoupling can also be appreciated when looking at the average pseudo-steady  
2 state values of PE and CO<sub>2BF</sub> during the different run periods, of 1% and 0.2 kg CO<sub>2</sub>·m<sup>-3</sup> in  
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4 run I, 4% and 0.3 kg CO<sub>2</sub>·m<sup>-3</sup> in run II and 3.5 % and 0.4 kg CO<sub>2</sub>·m<sup>-3</sup> in run III. Both the PE  
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6 and CO<sub>2BF</sub> increased during the run periods following an asymptotic pattern until reaching a  
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8 maximum value, corresponding to the presence of a well-established microalgal community in  
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10 the HRAP. Interestingly, when comparing these maximum values, the PE was 4-folded and  
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12 the CO<sub>2BF</sub> increased by 50 % between runs I and II, confirming the positive effect of biomass  
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14 retention. The maximum CO<sub>2BF</sub> was even further increased in run III. However, the PE was  
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16 lower during run III when compared to run II. This is very likely caused by a shading effect  
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18 related to the higher biomass concentrations, decreasing the light uptake efficiency. Similar  
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20 phenomena have been reported previously at high HRTs (Viruela et al., 2018). This suggests  
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22 that an optimum combination of BRT and HRT exists, allowing to optimize the performance  
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24 of the system establishing efficient light uptake rates.  
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31 The results presented above are in agreement with previous studies dealing with membrane  
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33 filtration coupled to outdoors microalgae-based treatment systems. Using a PBR for tertiary  
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35 sewage treatment at BRT of 4.5 days and HRT of 3.5 days, optimum conditions were  
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37 achieved, with a CO<sub>2BF</sub> of 0.55 kg CO<sub>2</sub>·m<sup>-3</sup> and a PE of 2.7 % (González-Camejo et al.,  
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39 2019). Viruela *et al.* (2018) also achieved maximum biomass productivities, NRR and PRR  
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41 (66 mg VSS·L<sup>-1</sup>·d<sup>-1</sup>, 7.7 mg N·L<sup>-1</sup>·d<sup>-1</sup> and 1.2 mg P·L<sup>-1</sup>·d<sup>-1</sup>, respectively) at a BRT of 4.5  
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43 days. These results suggest that M-HRAPs can achieve similar (or even higher) productivities  
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45 and nutrient removal rates than MPBRs with lower power requirements.  
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51 Despite the positive effect of HRT reduction, the high nutrient loading rates into the system  
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53 resulted in higher concentrations of nutrients in the effluent. This fact can be appreciated in  
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55 Figure 3, where the evolutions of the concentrations of N<sub>T</sub>, NH<sub>4</sub>-N, PO<sub>4</sub>-P, NO<sub>3</sub>-N and NO<sub>2</sub>-N  
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57 during runs I to III are given. Nevertheless, it must be pointed out that this result was obtained  
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at a fixed BRT of 6 days. By optimizing this parameter, discharge limits could be obtained by favoring a faster algae growth (González-Camejo et al., 2019).





**Figure 3.** M-HRAP performance when operating at a BRT of 6 days and HRTs of (A) 6, (B) 4, and (C) 2.5 days. The evolutions of the concentrations of total nitrogen ( $N_T$ ) in the mixed liquor and the inorganic nutrients ( $NH_4$ -N,  $PO_4$ -P,  $NO_3$ -N and  $NO_2$ -N) in the effluent are given

As it can be observed, while the concentrations of  $NH_4$ -N and  $PO_4$ -P were far below 15 mg  $N \cdot L^{-1}$  and 2 mg  $P \cdot L^{-1}$ , respectively, at the end of run I, the concentrations of these species were 18 mg  $N \cdot L^{-1}$  and 1.2 mg  $P \cdot L^{-1}$  at the end of run II and of 28 mg  $N \cdot L^{-1}$  and over 2 mg  $P \cdot L^{-1}$  at the end of run III ( $N_T$  concentrations over 40 mg  $L^{-1}$ ). This was simply related to the higher nutrient loading rates caused by the lower HRTs. Besides these higher nutrient concentrations in the effluent in run II, the achieved values were nearby the limits imposed by European effluent nutrient standards (European directive 91/271/CEE). Considering this and the negligible amounts of solids and microorganisms in the effluent from the M-HRAP, it is

1 important to highlight that this high-quality effluent is suitable for its application in multiple  
2 reuse purposes, such as irrigation, fertigation, urban utilization, etc.  
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4 Although it can be concluded that the M-HRAP (at the conditions applied) treated the UWW  
5 successfully, it is clear that there is a great room for improvement. Control strategies aiming  
6 at optimizing the BRT and HRT for the given operating conditions (*i.e.* environmental  
7 conditions and influent characteristics) have a huge potential for improving the process  
8 performance (*e.g.* by minimizing the values of the BRT required to maximize the biomass  
9 productivities and nutrient removal rates while fulfilling the nutrients limits in the effluent).  
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21 Run IV served for evaluating the influence of the temperature and the light irradiation on the  
22 M-HRAP performance. The weather conditions (mainly T and solar irradiance) are known to  
23 have a significant effect on the performance of outdoors algae-based treatment systems, with  
24 open ponds being particularly affected by seasonal variations (Mata et al., 2010). The M-  
25 HRAP used in this study was run outdoors for several months, which allowed to obtain results  
26 at different ambient temperatures and natural irradiances. The results presented in Table 4  
27 correspond to the plant performance during runs III and IV, with equivalent working  
28 conditions but under different meteorological conditions.  
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43 **Table 4.** Average nitrogen and phosphorous removal rates and biomass productivities in runs  
44 III and IV at pseudo-steady state  
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run	Solar irradiance ( $\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ )	Temperature ( $^{\circ}\text{C}$ )	NRR ( $\text{g N}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ )	PRR ( $\text{g P}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ )	Biomass productivity ( $\text{g VSS}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ )
III	420±90	24.5±1.8	11	1.6	95
IV	253±195	14.1±1.1	8	1.1	65

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56 BRT stands for biological retention time, HRT for hydraulic retention time, NRR for nitrogen removal rate, PRR  
57 for phosphorous removal rate and VSS for volatile suspended solids  
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As expected, the lower solar irradiances and temperatures during run IV (average values of 253  $\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  and 14.1 °C, respectively) when compared with run III (420  $\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  and 24.5 °C) reduced nutrients removal rates and biomass productivities. The reduction on light lowered ATP production via photophosphorylation by algae. The lower temperatures are known to affect the algae growth rates (Ras et al., 2013). The combined effects of these parameters led to the reduction in the evaluated yields.

Although the effect of weather patterns on the performance of the M-HRAP cannot be neglected, it is interesting to consider that all the parameters used to evaluate the plant performance were higher during run IV when compared to run I (see Table 3 and Table 4). Therefore, the enhanced behaviour related to BRT/HRT decoupling (avoiding biomass wash-out) was able to overcome the negative effect of lower temperatures and light availabilities. This implies that M-HRAP technology can be applied in temperate climates to maintain acceptable performances during low temperature seasons.

### 3.2. Membrane filtration performance: energy and economic analysis

To assess the energy performance of the system (and thus its economic feasibility), it is essential to study the membrane filtration performance. The values of  $J$ ,  $J_{20}$ ,  $\text{SAD}_m$ , the specific air demand per permeate volume ( $\text{SAD}_p$ ), the TMP and the VSS concentrations during runs II and III are presented in Figure 4.

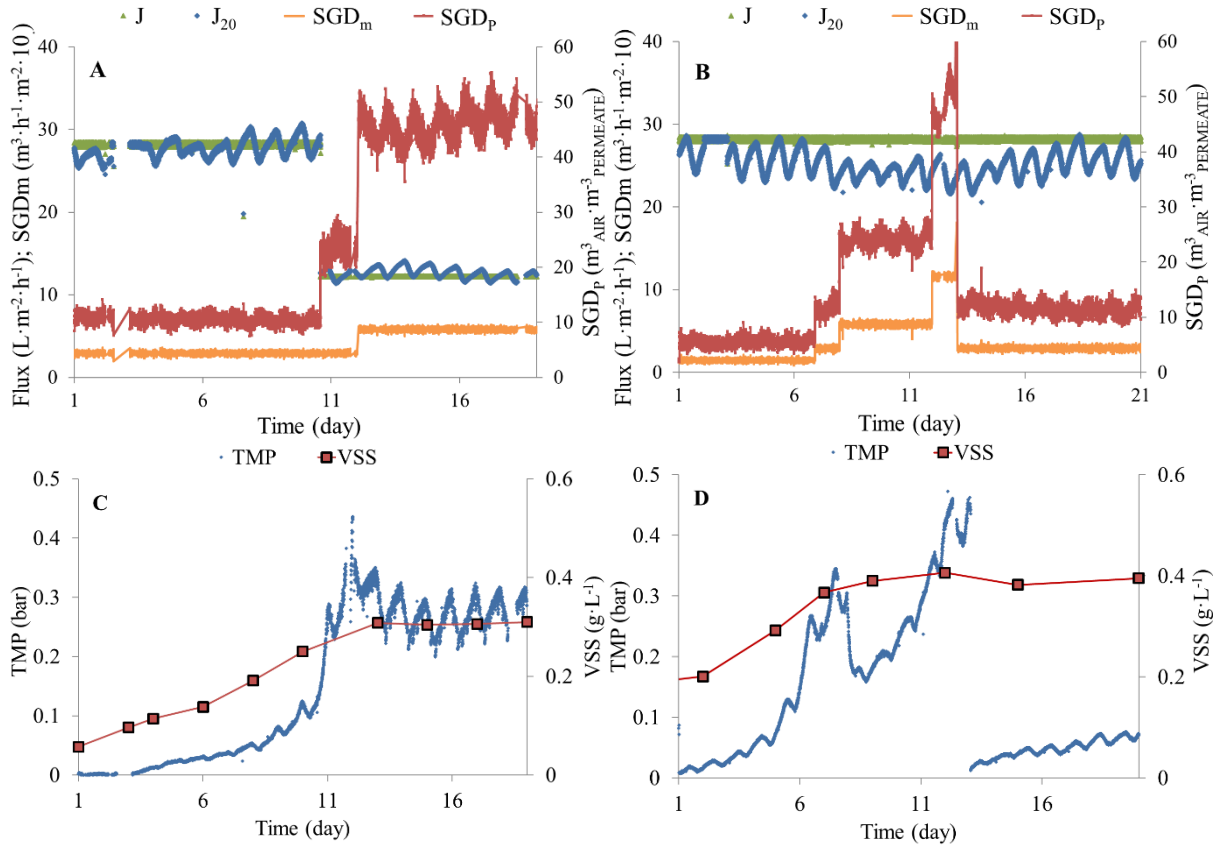
Low  $\text{SAD}_m$  values were maintained at the beginning of run II ( $0.3 \text{ Nm}^3\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ ), aiming at keeping low energy requirements. However, the increasing VSS concentrations and membrane fouling led to a TMP peak around day 10. To keep the TMP below 0.4-0.5 bar and avoid membrane damage,  $J$  was lowered and the  $\text{SAD}_m$  was increased to  $0.6 \text{ Nm}^3\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ , which led to stable TMP values, but increasing the  $\text{SAD}_p$  due to the reduced  $J$  up to unsustainable values (see Figure 4A and Figure 4C). The relatively small reduction in the



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TMP after increasing the  $SAD_m$  suggests that the membrane fouling responsible for the TMP peak was not caused by the formation of an easily-removable cake layer. Observations of the membrane showed that, although reversible, the fouling layer consisted of a remnant viscous layer, covering the surface of the membrane. This also suggests that further increasing the  $SAD_m$  would not improve the membrane performance and that back-flushing was more effective to clean the membrane than relaxation with air. Despite this issue, the last days of operation during this run period show that the membrane can be efficiently operated at relatively low  $SAD_m$  values, keeping the TMP within acceptable limits.

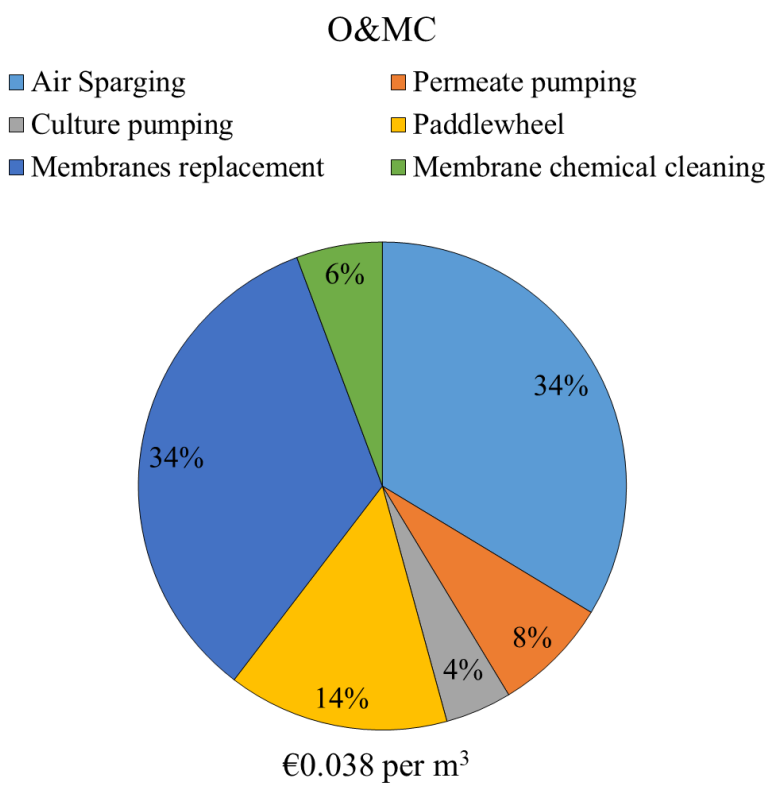
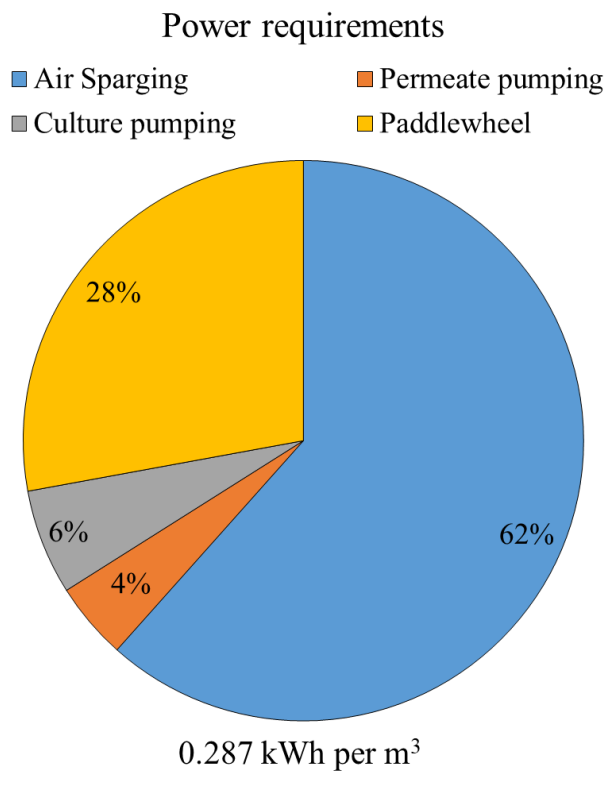
The same issue was observed during run III (Figure 4B and Figure 4D). The higher VSS concentrations led to a TMP peak earlier (days 6-9), which was corrected by further increasing the  $SAD_m$ , keeping the same  $J$ . Nevertheless, after a momentary drop, the TMP continued to increase, even when the  $SAD_m$  was raised up to unsuitable values of around  $1.2 \text{ Nm}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ , confirming that increasing the  $SAD_m$  above  $0.5 \text{ Nm}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$  did not improve the filtration performance. Because of this continuous TMP raise, the membrane was manually washed with water (no chemical regeneration occurred) on day 13. The instantaneous TMP drop confirmed the reversible nature of the fouling layer. After membrane cleaning, it was possible to keep the TMP below 0.1 bar with a  $SAD_m$  of  $0.25 \text{ Nm}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ . This operation was maintained for over a week, without significant TMP increases. This suggests that it is possible to operate the system with low  $SAD_m$  without applying any chemical recovery to the membranes, simply by sporadically cleaning them with water.



**Figure 4.** Evolution of  $J$ ,  $J_{20}$ ,  $SAD_m$  and  $SAD_p$  during (A) run II and (B) run III. The TMP and the VSS concentration (C) run II and (D) run III are also presented

As representative example, the values of  $J_{20}$  ( $28 L \cdot m^{-3} \cdot h^{-1}$ ) and  $SAD_m$  ( $0.25 m^3 \cdot m^{-2} \cdot h^{-1}$ ) achieved during the last section of run III were used to calculate the power requirements and the operational and maintenance costs of the M-HRAP. The results are presented in Figure 5.

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**Figure 5.** (A) Power requirements and (B) operational and maintenance costs (O&MC) for a full-scale plant design with a treatment capacity of 1,000 m<sup>3</sup>·d<sup>-1</sup>.  $J_{20} = 28 \text{ L} \cdot \text{m}^{-3} \cdot \text{h}^{-1}$ ;  $\text{SAD}_m = 0.25 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$

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2 The low  $SAD_m$  resulted in energy requirements for the M-HRAP of around 0.29 kWh per  $m^3$   
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4 of treated water. These values are lower than those achievable for other wastewater treatment  
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6 methods, such as conventional activated sludge systems (0.25-0.6 kWh per  $m^3$  or aerobic  
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8 membrane bioreactors (0.50-2.5 kWh per  $m^3$ ), pointing out the energetic feasibility of  
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10 proposed M-HRAP system (Lazarova et al., 2012). Despite the low  $SAD_m$  applied, air  
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12 sparging still accounted for almost 62% of the total energy requirements of the system,  
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14 indicating that there is a clear room of improvement to further reduce this cost. Control  
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16 strategies aimed at optimising the working conditions for given situations (*i.e.* HRTs, T and  
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18 light intensity) have a great potential for further improving the energetic costs of these  
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20 systems.  
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29 The operational and maintenance costs (O&MCs) further reinforce the importance of reducing  
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31 the air sparging frequency, representing 34% of the total O&MCs. The results of the  
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33 economic analysis also point out that, together with air sparging, the membrane replacement  
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35 and its chemical cleaning account for most of the O&MC, representing 34% and 6% of the  
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37 total, respectively. The frequency of membrane replacement and chemical cleaning depend  
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39 greatly on how the plant is operated (*e.g.* the working TMP, the applied J, the VSS  
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41 concentrations and the BRT). Therefore, control strategies optimising the working conditions  
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43 can also help to reduce these costs. In addition, water could be effectively used for cleaning  
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45 the membranes, applying an expert control system to optimise the back-flushing effect.  
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53 Finally, it is worth to point out that the water produced in the the M-HRAP was free of  
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55 pathogens and could be directly used for reusing purposes (*i.e.* irrigation or fertirrigation).  
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57 Therefore, the disinfecting cost needed for ad equating the effluent from other systems (*e.g.*  
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conventional activated sludge systems) is avoided.

#### 4. Conclusions

Decoupling BRT and HRT enhanced biomass productivities (BPs), NRR and PRR. BP increased from 30 to 95  $\text{g}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$  when lowering the HRTs from 6 to 2.5 days (at 6 days of BRT). NRR and PPR also increased from 4 to 11  $\text{g N}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$  and 0.5 to 1.6  $\text{g P}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ , respectively. The system kept high BPs, NRR and PRR at lower temperatures and solar irradiances. The membrane was efficiently operated at low  $\text{SAD}_m$  (around  $0.25 \text{ m}^3\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ), resulting in adequate energy requirements ( $0.287 \text{ kWh}\cdot\text{m}^{-3}$ ) and treatment costs ( $0.04 \text{ €}\cdot\text{m}^{-3}$ ). The produced water could be directly used for reusing purposes (*i.e.* irrigation).

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#### References

- APHA, 2005. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington, DC.
- Arbib, Z., de Godos, I., Ruiz, J., Perales, J.A., 2017. Optimization of pilot high rate algal ponds for simultaneous nutrient removal and lipids production. *Sci. Total Environ.* 589, 66–72. <https://doi.org/10.1016/j.scitotenv.2017.02.206>

- 1 Bhave, R., Kuritz, T., Powell, L., Adcock, D., 2012. Membrane-based energy efficient  
2 dewatering of microalgae in biofuels production and recovery of value added co-  
3 products. *Environ. Sci. Technol.* 46, 5599–5606. <https://doi.org/10.1021/es204107d>
- 4 Bilad, M.R., Arafat, H.A., Vankelecom, I.F.J., 2014a. Membrane technology in microalgae  
5 cultivation and harvesting: A review. *Biotechnol. Adv.* 32, 1283–1300.  
6 <https://doi.org/10.1016/j.biotechadv.2014.07.008>
- 7  
8 Bilad, M.R., Discart, V., Vandamme, D., Foubert, I., Muylaert, K., Vankelecom, I.F.J.,  
9 2014b. Coupled cultivation and pre-harvesting of microalgae in a membrane  
10 photobioreactor (MPBR). *Bioresour. Technol.* 155, 410–417.  
11 <https://doi.org/10.1016/j.biortech.2013.05.026>
- 12  
13 Bilad, M.R., Vandamme, D., Foubert, I., Muylaert, K., Vankelecom, I.F.J., 2012. Harvesting  
14 microalgal biomass using submerged microfiltration membranes. *Bioresour. Technol.*  
15 111, 343–352. <https://doi.org/10.1016/j.biortech.2012.02.009>
- 16  
17 Boelee, N.C., Temmink, H., Janssen, M., Buisman, C.J.N., Wijffels, R.H., 2011. Nitrogen and  
18 phosphorus removal from municipal wastewater effluent using microalgal biofilms.  
19 *Water Res.* 45, 5925–5933. <https://doi.org/10.1016/j.watres.2011.08.044>
- 20  
21 Capson-Tojo, G., Rouez, M., Crest, M., Trably, E., Steyer, J., Bernet, N., Delgenes, J.,  
22 Escudié, R., 2017. Kinetic study of dry anaerobic co-digestion of food waste and  
23 cardboard for methane production. *Waste Manag.* 69, 470–479.  
24 <https://doi.org/10.1016/j.wasman.2017.09.002>
- 25  
26  
27 Craggs, R.J., Heubeck, S., Lundquist, T.J., Benemann, J.R., 2011. Algal biofuels from  
28 wastewater treatment high rate algal ponds. *Water Sci. Technol.* 63, 660 LP – 665.
- 29  
30 Dalrymple, O.K., Halfhide, T., Udom, I., Gilles, B., Wolan, J., Zhang, Q., Ergas, S., 2013.  
31 Wastewater use in algae production for generation of renewable resources : a review and  
32 preliminary results. *Aquat. Biosyst.* 9, 1–11.
- 33  
34 Drexler, I.L.C., Yeh, D.H., 2014. Membrane applications for microalgae cultivation and  
35 harvesting: a review. *Rev. Environ. Sci. Biotechnol.* 13, 487–504.  
36 <https://doi.org/10.1007/s11157-014-9350-6>
- 37  
38 Fernández-Sevilla, J.M., Brindley, C., Jiménez-Ruíz, N., Acien, F.G., 2018. A simple  
39 equation to quantify the effect of frequency of light/dark cycles on the photosynthetic  
40 response of microalgae under intermittent light. *Algal Res.* 35, 479–487.  
41 <https://doi.org/10.1016/j.algal.2018.09.026>
- 42  
43  
44 Foladori, P., Petrini, S., Andreottola, G., 2018. Evolution of real municipal wastewater  
45 treatment in photobioreactors and microalgae-bacteria consortia using real-time  
46 parameters. *Chem. Eng. J.* 345, 507–516. <https://doi.org/10.1016/j.cej.2018.03.178>
- 47  
48 Galès, A., Bonnafous, A., Carré, C., Jauzein, V., Lanouguère, E., Le, E., Pinoit, J., Poullain,  
49 C., Roques, C., Sialve, B., Simier, M., Steyer, J., Fouilland, E., 2019. Importance of  
50 ecological interactions during wastewater treatment using High Rate Algal Ponds under  
51 different temperate climates. *Algal Res.* 40, 101508.  
52 <https://doi.org/10.1016/j.algal.2019.101508>
- 53  
54  
55 González-Camejo, J., Jiménez-Benítez, A., Ruano, M. V., Robles, A., Barat, R., Ferrer, J.,  
56 2019. Optimising an outdoor membrane photobioreactor for tertiary sewage treatment. *J.*  
57 *Environ. Manage.* 245, 76–85. <https://doi.org/10.1016/j.jenvman.2019.05.010>
- 58  
59  
60  
61  
62  
63  
64  
65

- 1 Honda, R., Boonnorat, J., Chiemchaisri, C., Chiemchaisri, W., Yamamoto, K., 2012. Carbon  
2 dioxide capture and nutrients removal utilizing treated sewage by concentrated  
3 microalgae cultivation in a membrane photobioreactor. *Bioresour. Technol.* 125, 59–64.  
4 <https://doi.org/10.1016/j.biortech.2012.08.138>
- 5 Kumar, K., Mishra, S.K., Shrivastav, A., Park, M.S., Yang, J.W., 2015. Recent trends in the  
6 mass cultivation of algae in raceway ponds. *Renew. Sustain. Energy Rev.* 51, 875–885.  
7 <https://doi.org/10.1016/j.rser.2015.06.033>
- 8  
9 Lazarova, V., Choo, K.-H., Cornel, P., 2012. Water-Energy Interactions in Water Reuse.  
10 <https://doi.org/10.2166/9781780400662>
- 11  
12 Liao, Y., Bokhary, A., Maleki, E., Liao, B., 2018. A review of membrane fouling and its  
13 control in algal-related membrane processes. *Bioresour. Technol.* 264, 343–358.  
14 <https://doi.org/10.1016/j.biortech.2018.06.102>
- 15  
16 Luo, Y., Le-Clech, P., Henderson, R.K., 2017. Simultaneous microalgae cultivation and  
17 wastewater treatment in submerged membrane photobioreactors: A review. *Algal Res.*  
18 24, 425–437. <https://doi.org/10.1016/J.ALGAL.2016.10.026>
- 19  
20 Marbelia, L., Bilad, M.R., Passaris, I., Discart, V., Vandamme, D., Beuckels, A., Muylaert,  
21 K., Vankelecom, I.F.J., 2014. Membrane photobioreactors for integrated microalgae  
22 cultivation and nutrient remediation of membrane bioreactors effluent. *Bioresour.*  
23 *Technol.* 163, 228–235. <https://doi.org/10.1016/j.biortech.2014.04.012>
- 24  
25 Mata, T.M., Martins, A.A., Caetano, N.S., 2010. Microalgae for biodiesel production and  
26 other applications: A review. *Renew. Sustain. Energy Rev.* 14, 217–232.  
27 <https://doi.org/10.1016/J.RSER.2009.07.020>
- 28  
29 Nopens, I., Capalozza, C., Vanrolleghem, P.A., 2001. Stability analysis of a synthetic  
30 municipal wastewater. *Gent.* <https://doi.org/10.1017/CBO9781107415324.004>
- 31  
32 Novoveská, L., Zapata, A.K.M., Zabolotney, J.B., Atwood, M.C., Sundstrom, E.R., 2016.  
33 Optimizing microalgae cultivation and wastewater treatment in large-scale offshore  
34 photobioreactors. *Algal Res.* 18, 86–94. <https://doi.org/10.1016/j.algal.2016.05.033>
- 35  
36 Perin, G., Cimetta, E., Monetti, F., Morosinotto, T., Bezzo, F., 2016. Novel micro-  
37 photobioreactor design and monitoring method for assessing microalgae response to light  
38 intensity. *Algal Res.* 19, 69–76. <https://doi.org/10.1016/j.algal.2016.07.015>
- 39  
40 Pretel, R., Robles, A., Ruano, M.V., Seco, A., Ferrer, J., 2016. A plant-wide energy model for  
41 wastewater treatment plants: application to anaerobic membrane bioreactor technology.  
42 *Environ. Technol. (United Kingdom)* 37.  
43 <https://doi.org/10.1080/09593330.2016.1148903>
- 44  
45 Ras, M., Steyer, J.P., Bernard, O., 2013. Temperature effect on microalgae: A crucial factor  
46 for outdoor production. *Rev. Environ. Sci. Biotechnol.* 12, 153–164.  
47 <https://doi.org/10.1007/s11157-013-9310-6>
- 48  
49 Robles, A., Capson-Tojo, G., Ruano, M. V., Seco, A., Ferrer, J., 2018. Real-time optimization  
50 of the key filtration parameters in an AnMBR: urban wastewater mono-digestion vs. co-  
51 digestion with domestic food waste. *Waste Manag.* 80, 299–309.  
52 <https://doi.org/10.1016/j.wasman.2018.09.031>
- 53  
54 Robles, A., Ruano, M. V., Ribes, J., Seco, A., Ferrer, J., 2014. Model-based automatic tuning  
55 of a filtration control system for submerged anaerobic membrane bioreactors (AnMBR).  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

J. Memb. Sci. 465, 14–26. <https://doi.org/10.1016/j.memsci.2014.04.012>

- 1 Salama, E.S., Kurade, M.B., Abou-Shanab, R.A.I., El-Dalatony, M.M., Yang, I.S., Min, B.,  
2 Jeon, B.H., 2017. Recent progress in microalgal biomass production coupled with  
3 wastewater treatment for biofuel generation. *Renew. Sustain. Energy Rev.* 79, 1189–  
4 1211. <https://doi.org/10.1016/j.rser.2017.05.091>
- 5  
6  
7 Seco, A., Aparicio, S., González-Camejo, J., Jiménez-Benítez, A., Mateo, O., Mora, J.F.,  
8 Noriega-Hevia, G., Sanchis-Perucho, P., Serna-García, R., Zamorano-López, N.,  
9 Giménez, J.B., Ruiz-Martínez, A., Aguado, D., Barat, R., Borrás, L., Bouzas, A., Martí,  
10 N., Pachés, M., Ribes, J., Robles, A., Ruano, M. V., Serralta, J., Ferrer, J., 2018.  
11 Resource recovery from sulphate-rich sewage through an innovative anaerobic-based  
12 water resource recovery facility (WRRF). *Water Sci. Technol.* 78, 1925–1936.  
13 <https://doi.org/10.2166/wst.2018.492>
- 14  
15  
16 Shoener, B.D., Schramm, S.M., Béline, F., Bernard, O., Martínez, C., Plósz, B.G., Snowling,  
17 S., Steyer, J.P., Valverde-Pérez, B., Wágner, D., Guest, J.S., 2019. Microalgae and  
18 cyanobacteria modeling in water resource recovery facilities: A critical review. *Water*  
19 *Res. X* 2. <https://doi.org/10.1016/j.wroa.2018.100024>
- 20  
21 Solimeno, A., García, J., 2017. Microalgae-bacteria models evolution: From microalgae  
22 steady-state to integrated microalgae-bacteria wastewater treatment models – A  
23 comparative review. *Sci. Total Environ.* <https://doi.org/10.1016/j.scitotenv.2017.07.114>
- 24  
25 Sun, X., Wang, C., Tong, Y., Wang, W., Wei, J., 2013. A comparative study of microfiltration  
26 and ultrafiltration for algae harvesting. *Algal Res.* 2, 437–444.  
27 <https://doi.org/10.1016/j.algal.2013.08.004>
- 28  
29 Viruela, A., Robles, Á., Durán, F., Ruano, M.V., Barat, R., Ferrer, J., Seco, A., 2018.  
30 Performance of an outdoor membrane photobioreactor for resource recovery from  
31 anaerobically treated sewage. *J. Clean. Prod.* 178, 665–674.  
32 <https://doi.org/10.1016/j.jclepro.2017.12.223>
- 33  
34  
35 Wang, Y., Guo, W., Yen, H.W., Ho, S.H., Lo, Y.C., Cheng, C.L., Ren, N., Chang, J.S., 2015.  
36 Cultivation of *Chlorella vulgaris* JSC-6 with swine wastewater for simultaneous  
37 nutrient/COD removal and carbohydrate production. *Bioresour. Technol.* 198, 619–625.  
38 <https://doi.org/10.1016/j.biortech.2015.09.067>
- 39  
40 Wang, Y., Ho, S.-H., Cheng, C.-L., Guo, W.-Q., Nagarajan, D., Ren, N.-Q., Lee, D.-J.,  
41 Chang, J.-S., 2016. Perspectives on the feasibility of using microalgae for industrial  
42 wastewater treatment. *Bioresour. Technol.* 222, 485–497.  
43 <https://doi.org/10.1016/J.BIORTECH.2016.09.106>
- 44  
45  
46 Wicaksana, F., Fane, A.G., Pongpaiboj, P., Field, R., 2012. Microfiltration of algae (*Chlorella*  
47 *sorokiniana*): Critical flux, fouling and transmission. *J. Memb. Sci.* 387–388, 83–92.  
48 <https://doi.org/10.1016/j.memsci.2011.10.013>
- 49  
50  
51  
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## 54 **Figure and table captions**

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57 **Figure 1.** Flow diagram of the membrane-coupled high-rate algal pond. Nomenclature: FT:  
58 feeding tank; HRAP: high-rate algal pond; MT: membrane tank; CIP: clean-in-place; P:



pump; and B: blower

**Figure 2.** M-HRAP performance when operating at a BRT of 6 days and HRTs of (A) 6, (B) 4, and (C) 2.5 days. The evolutions of the total and soluble chemical oxygen demand (CODT and CODS, respectively), and the measured volatile suspended solids (VSS) are presented, together with the optical density values used for VSS estimation

**Figure 3.** M-HRAP performance when operating at a BRT of 6 days and HRTs of (A) 6, (B) 4, and (C) 2.5 days. The evolutions of the concentrations of total nitrogen (NT) in the mixed liquor and the inorganic nutrients (NH<sub>4</sub>-N, PO<sub>4</sub>-P, NO<sub>3</sub>-N and NO<sub>2</sub>-N) in the effluent are given

**Figure 4.** Evolution of J, J<sub>20</sub>, SAD<sub>m</sub> and SADP during (A) run II and (B) run III. The TMP and the VSS concentration (C) run II and (D) run III are also presented

**Figure 5.** (A) Power requirements and (B) operational and maintenance costs (O&MC) for a full-scale plant design with a treatment capacity of 1,000 m<sup>3</sup>·d<sup>-1</sup>. J<sub>20</sub> = 28 L·m<sup>-3</sup>·h<sup>-1</sup>; SAD<sub>m</sub> = 0.25 m<sup>3</sup>·m<sup>-2</sup>·h<sup>-1</sup>

**Table 1.** Characteristics of the synthetic urban wastewater

**Table 2.** Average operating conditions and objectives of the different run periods

**Table 3.** Average results in runs I to III at pseudo-steady state for: nitrogen and phosphorous removal rates, biomass productivities, photosynthetic efficiency, and carbon dioxide biofixation

**Table 4.** Average nitrogen and phosphorous removal rates and biomass productivities in runs III and IV at pseudo-steady state

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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