Chemical Engineering Journal 313 (2017) 424–434

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Enhanced carbon, nitrogen and phosphorus removal from domestic wastewater in a novel anoxic-aerobic photobioreactor coupled with biogas upgrading

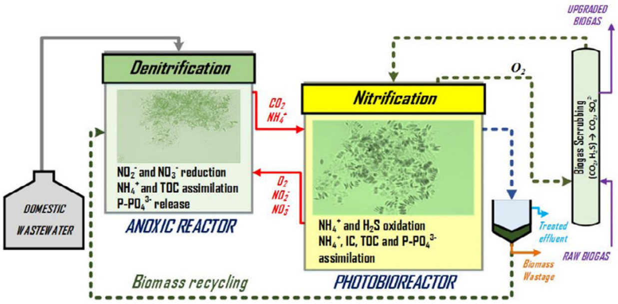
Dimas García [a], Cynthia Alcántara [a], Saúl Blanco [b], Rebeca Pérez [a], Silvia Bolado [a], Raúl Muñoz [a,*]

[a] Department of Chemical Engineering and Environmental Technology, Valladolid University, Dr. Mergelina, s/n, 47011 Valladolid, Spain
[b] The Institute of the Environment, La Serna 58, 24007 León, Spain

HIGHLIGHTS

- Biogas scrubbing enhanced TN and P-PO_4^{3-} recovery via biomass assimilation.
- Nitrification was limited by IC in the absence of biogas supply.
- Biogas scrubbing maintained pH below inhibitory levels during the light period.
- Biogas upgrading supported an efficient nitrification-denitrification process.
- Biomass recycling resulted in unialgal cultures with high settling rates.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form 2 December 2016
Accepted 13 December 2016
Available online 18 December 2016

Keywords:
Biogas upgrading
Biomass recycling
Inorganic carbon limitation
Microalgae
Nitrification-denitrification

ABSTRACT

This work evaluated the performance of an innovative anoxic-aerobic algal-bacterial photobioreactor coupled with biogas upgrading for the treatment of domestic wastewater via nitrification-denitrification. The process, which incorporated a biomass settling step followed by recycling to the anoxic tank, was operated at a hydraulic retention time of 2 days, a sludge retention time of ≈11 days under a 12 h/12 h light/dark irradiation cycle at 392 $\mu E\ m^{-2} * s^{-1}$. An increase in the removal efficiency of TN from 38% to 81%, NH_4^+ from 39% to 97%, and P-PO_4^{3-} from 59% to 64% were recorded when additional CO_2 was supplied to the photobioreactor via biogas scrubbing, which supported an almost complete nitrification of the NH_4^+ to NO_3^- and promoted microalgae growth (with the subsequent enhancement in N and P assimilation). TOC removal remained constant at 90 ± 2% regardless of the addition of CO_2, while the effluent biomass concentration averaged 26 ± 12 mg TSS/L. A DGGE-sequencing analysis of the bacterial community revealed the occurrence of 10 phyla, Proteobacteria being the dominant phylum. Finally, the morphological characterization of the microalgae population dynamics revealed a gradual dominance of the genus *Scenedesmus*, which accounted for 94–100% at the end of the experiment.

1. Introduction

The steady increase in human population [1] and industrial activity is generating large amounts of wastewaters and greenhouse gases [2], which represent two of the major environmental challenges to global sustainability nowadays. Domestic and industrial wastewaters and anaerobic digestion effluents are characterized by their high loads of carbon (C), nitrogen (N) and phosphorus (P), which must be treated before discharge into natural water bodies to avoid oxygen depletion, toxicity issues and eutrophication [3]. A wide range of biological and physical/chemical technologies is

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* Corresponding author.
E-mail address: mutora@iq.uva.es (R. Muñoz).

http://dx.doi.org/10.1016/j.cej.2016.12.054

currently available for carbon and nutrient removal in wastewater treatment plants (WWTPs). Unfortunately, these technologies often entail high investment and operating costs and do not allow for a cost-effective recovery of nutrients due to the low C/N and C/P ratios of most domestic and industrial wastewaters [4][5].

In this context, algal-bacterial processes can support both a low-cost process oxygenation and an enhanced nutrient recovery. The oxygen produced by microalgae during photosynthesis can support the oxidation of organic pollutants and ammonium by aerobic heterotrophs and nitrifiers, respectively, which thus reduces the operating costs and environmental impacts associated with conventional mechanical aeration in WWTPs [6]. On the other hand, the ability of algal-bacterial consortia to assimilate both organic carbon (inherently present in most wastewaters) and inorganic carbon (from the biological oxidation of organic carbon, alkalinity in wastewater or residual carbon dioxide (CO_2) externally supplied) result in larger biomass productivities and therefore enhanced nutrient recoveries[7]. However, despite the above-mentioned advantages, algal-bacterial processes devoted to wastewater treatment still present severe technical limitations that hinder the full-scale implementation of this technology, such as nutrient supply and recycling, gas transfer and exchange [8].

In this regard, although photoautotrophic algal metabolism can enhance N and P recovery in anoxic-aerobic algal-bacterial photobioreactor (AA-ABPh), the alkalinity present in raw wastewaters is low to support a complete nutrient recovery/removal and residual CO_2 sources (such as flue gas) are not always available on-site. In addition, the low hydraulic retention times (HRT) required in algal-bacterial processes to compete with activated sludge systems would limit the development of nitrifying bacterial communities that would eventually support nitrification-denitrification processes during the treatment of wastewaters with low C/N ratios. Finally, the poor sedimentation ability of the microalgae generated in the process often results in effluent total suspended solid concentrations (TSS) above the maximum European Union (EU) discharge limit (50 mg/L), which limits the scale-up of microalgae-based wastewater treatment [9]. In this context, AA-ABPh operated with autofloculated biomass settling and recycling constitutes an innovative technology capable of overcoming the above mentioned limitations. This technology was successfully evaluated for the treatment of synthetic wastewaters at moderate HRTs but experienced severe inorganic carbon limitations, which ultimately restricted the treatment potential of this innovative technique. Therefore, there is an urgent need to develop novel operating strategies to overcome the above mentioned inorganic carbon limitation and to evaluate the performance of this innovative technology using real domestic wastewater (RDWW) at low HRTs.

This work was devised to evaluate the treatment of RDWW in an innovative AA-ABPh configuration operated with biomass settling and recycling at a HRT of 2 days coupled to the simultaneous upgrading of synthetic biogas (in a separate and interconnected column). In this system, the supply of biogas (eventually available on-site from the anaerobic digestion of the algal-bacterial biomass produced in the process) will provide the additional inorganic C source required to boost nutrient removal by assimilation and bacterial nitrification to sustain an efficient nitrification-denitrification process [10][11]. The influence of photosynthetic biogas upgrading on the mechanisms underlying C, N and P removal in the anoxic tank and photobioreactor treating RDWW was assessed using a mass balance approach. A detailed characterization of the dynamics of microalgal and bacterial population structure was conducted using morphological and molecular identification tools.

2. Materials and methods

2.1. Microorganisms and culture conditions

The anoxic and aerobic tanks were inoculated with 3.2 g/L of total suspended solid (TSS) of an mixture of a microalgal-cyanobacterial consortium (from now on referred to as microalgae) from a high rate algal ponds (HRAP) treating diluted vinasse [12] and aerobic activated sludge from Valladolid WWTP (Spain). Domestic wastewater was collected from a nearby sewer located at Department of Chemical Engineering and Environmental Technology of Valladolid University. The average composition of the RDWW treated continuously was: 176 ± 26 mg/L of dissolved total organic carbon (TOC), 152 ± 34 mg/L of dissolved inorganic carbon (IC), 106 ± 9 mg/L of total nitrogen (TN), 93 ± 9 mg/L of N-ammonium ($N\text{-}NH_4^+$), 39 ± 12 mg/L of sulfate (SO_4^{2-}) and 33 ± 8 mg/L of P-phosphate ($P\text{-}PO_4^{3-}$) (Table 1).

Table 1
Operational conditions and physical/chemical characterization of the real wastewater and cultivation broth in the anoxic tank and photobioreactor.

Stage		Wastewater	SI		SII		SIII	
Parameter/Reactor			Anoxic	Aerobic	Anoxic	Aerobic	Anoxic	Aerobic
Operational period (days)		n.a	78		74		56	
HRT (days)		n.a	0.5	1.5	0.5	1.5	0,5	1.5
SRT (days)		n.a	12.5 ± 3.5		11 ± 0.9		10.5 ± 0.5	
Light (μmol/m^2.s)		n.a	n.a	367 ± 57	n.a	412 ± 15	n.a	395 ± 21
RWW feeding rate (L/d)		n.a	1.8		1.8		1.8	
Internal recycling rate (L/d)		n.a	2.8		2.8		3.6	
External recycling rate (L/d)		n.a	0.5		0.5		0.5	
pH (units)	*Light*	n.a	7.4 ± 0.3	8.6 ± 0.6	6.9 ± 0.1	8.0 ± 0.7	6.8 ± 0.2	8.9 ± 0.9
	Dark	n.a		7.1 ± 0.3		7 ± 0.2		7.0 ± 0.4
Dissolved oxygen (mg/L)	*Light*	n.a	0	23.3 ± 4.1	0	22.0 ± 2.0	0	23.0 ± 1.8
	Dark	n.a		6.0 ± 0.6		3.1 ± 1.2		3.9 ± 0.7
TOC (mg/L)		176 ± 26	26 ± 5	20 ± 4	30 ± 4	19 ± 1	23 ± 2	18 ± 2
IC (mg/L)		152 ± 34	48 ± 5	2 ± 1	56 ± 9	15 ± 5	47 ± 4	13 ± 4
TN (mg/L)		106 ± 9	74 ± 10	66 ± 8	32 ± 4	21 ± 3	28 ± 2	18 ± 4
$N\text{-}NH_4^+$ (mg/L)		93 ± 9	64 ± 4	54 ± 8	32 ± 5	3 ± 1	33 ± 2	3 ± 1
$N\text{-}NO_2^-$ (mg/L)		n.a	0.01 ± 0.01	5.6 ± 4.0	0.03 ± 0.05	3.1 ± 3.8	0.41 ± 0.68	1.1 ± 1.8
$N\text{-}NO_3^-$ (mg/L)		n.a	0.04 ± 0.03	0.9 ± 0.9	0.14 ± 0.15	8.9 ± 5.5	0.73 ± 1.25	13.0 ± 3.2
$P\text{-}PO_4^{3-}$ (mg/L)		33 ± 8	26 ± 5	16 ± 7	18 ± 3	9 ± 2	18 ± 1	11 ± 2
SO_4^{2-}		39 ± 12	29 ± 7	32 ± 6	51 ± 15	76 ± 11	47 ± 7	55 ± 4
TSS (mg/L)		n.a	1519 ± 252	1216 ± 260	3113 ± 361	2854 ± 324	2480 ± 309	2047 ± 186
SVI (mL/g)		n.a	95	161	128	169	80	97
Air flow (mL/min)		n.a	0	6	0	4	0	2
Biogas (L/day)		n.a	n.a			2.6		2.6

n.a: Not applicable.