

Research article

Opportunities for Microalgae-Bacteria Consortium Application to the Treatment of Effluents Generated in Fiber-Waste-Based Recycling Processes

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Abstract.

Technologies based on microalgae-bacteria seem to be sustainable options for wastewater treatment and reuse, with lower costs than conventional biological treatment technologies. Furthermore, they can generate added-value products produced from algae biomass. Among other advantages, the consortium bacteria-algae produce photosynthetic oxygen through the microalgae, which can be used by aerobic bacteria for oxidizing organic matter and nitrogen, thus reducing the need for introducing artificial oxygen. In this review paper, the main systems that use microalgae-bacteria consortium are discussed. Microalgae-bacteria present advantages in the removal of organics, nitrogen and phosphorus, when compared with conventional biological treatment systems (e.g., activated sludge, percolating filters and ponds), and are able to produce final effluents for reuse (e.g., in agricultural irrigation, industry or aquifer recharge) and excess of microalgae that can be converted to added-value products such as biogas and biofuels. Attention is given to the innovative aspects of applying photobioreactors to the treatment and reuse of pulp and paper effluents and fiber-waste-based recycling wastewaters, which seems to open a new opportunity for the pulp, paper and recycling paper industries.

Keywords: fiber-waste-based industry, microalgae-bacteria consortium, removal of nutrients, wastewater treatment

1. Introduction

Anthropic activities and water pollution have intensified, due to population growth and the increase in the industrial process in the last decades. Water pollution has been thus caused by inadequate domestic, industrial and agricultural effluent discharge, which provides increases concentrations of nutrients in the environment [1], [2]. The application of biological processes is widely used in the world scenario for the treatment of domestic and industrial wastewater aiming at reducing the generated impacts [3]. However, conventional wastewater treatment plants face technical limitations, with

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Published 10 August 2022

Publishing services provided by Knowledge E

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Selection and Peer-review under the responsibility of the FibEnTech21 Conference Committee.

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a high operational cost to obtain nutrient removals [4]. Besides being sustainable, systems that use microalgae-bacteria aggregate and promote more efficient and less costly techniques for the effluents treatment [5]. The great advantage of this system is the production of photosynthetic oxygen, which is used by aerobic bacteria to oxidize organic matter, reducing the need for introducing artificial oxygen into the system. According Ashrafi et al. (2015) [6], wastewater generated in the processes of the paper and cellulose industry is a result of the processes of debarking wood, paper manufacturing, fiber recycling, pulp manufacturing, among others. In general, the operational processes present in this type of industry are chemical, mechanical, thermo- mechanical and chemical-mechanical, so these processes generate a large volume of effluents with a range of pollutants. It seems that the use of microalgae-bacteria consortium (MABA) for wastewater treatment would lead less costly operation with greater efficiency in removal of nutrients. Therefore, the main objective of this article is to analyse the opportunity in using the consortium microalgae-bacteria for wastewater treatment from paper pulp and used paper recycling.

2. Use of microalgae-bacteria consortium in wastewater treatment

Microalgae and bacterial aggregate systems constitute a symbiotic form of the consortium of these elements and can be applied to wastewater treatment [7]. Such systems do not require the addition of artificial oxygen, in contrast to activated sludge or aerobic granular sludge systems, which demand high energy costs, due to the insertion of artificial oxygen and because they are operationally complex processes [8]. In general, the aerobic systems commonly used for wastewater treatment are aerated lagoons, biological filters and activated sludge [9]. However, closed photobioreactors stand out for their better control of operation, as well as in the supply of CO₂, temperature, lighting, crop density, pH levels and mixing rates [10]. These photobioreactors are characterized by aerobic decomposition commonly known as fermentation and respiration, biosynthesis and endogenous respiration; and their main feature is the conversion of organic compounds into biomass and CO₂ [11]. The operation of photobioreactors can occur in two ways: in sequential batches [12]–[14] and in continuous flow [15]–[17], with anaerobic and anoxic zones [18]. Table 1 presents the characteristics of several photobioreactors in sequential batches (PBSB). It can be seen that the behaviour of the aggregate depends on the species of microalgae attached to the biomass. According to Zhao et al. (2018) [19] and Liu et al. (2018) [20] applied variations of aeration and lighting in the PBSB

and thus found granules with a great abundance of microalgae from the seventh day of operation and particle size larger than 2.5 mm. [14], using synthetic wastewater, obtained removals of 99% of COD and 96% of N-ammonia, due to the good stability and content of extracellular polymeric substances (EPS) found in the MABAs.

Table 2 presents the characteristics of several continuous flow photobioreactors (PBCF), which present low installation and operation costs, when compared to the batch system, and a simpler operation [15]. However, when applied in systems with microalgae-bacteria aggregate, there is greater concern and caution with food control, to ensure the structural integrity of the biomass in its stratified form [21]. Ansari et al. (2017) [22] compared two ways of operating the PBCF with the microalgae-bacteria aggregate and with recirculation. The results showed better performance in the microalgae reactor, reaching 100%, 98% and 64% COD, TN and TP removals, respectively. In addition, the PBCF system showed greater energy efficiency when compared to PBSB with microalgae-bacteria consortium of [23]. Hydraulic retention time (HRT) in the order of 24 hours results in higher operational costs. According to Ahmad et al. (2017) [15] were able to establish MABAs in PBCF with 6-hour HRT, treating effluent with COD: 300mg/L; NH₄-N: 100mg/L; PO₄-P: 10mg/L). Some studies indicate the need for an internal sedimentation zone in PBCF in order to avoid washing the biomass, and the applied pressure must be associated with the particle sedimentation velocity. There are still few investigations on the behaviour of these aggregates, considering that the use of the microalgae-bacteria consortium for wastewater treatment arises with the objective of filling the gap of costly systems for treatment, thus allowing for a reduction energy consumption, as well as promoting biomass harvesting with greater sedimentability [24], [25]. Biomass generated by the consortium has a high molecular weight, high lipid content and, due to this, has a high potential to produce methane and biofuels [26], [27].

3. Application of microalgae-bacteria consortium fibers-waste-based recycling effluents

Despite the wide applicability for domestic wastewater treatment, in general, the use of microalgae- bacteria consortium can be applied to industrial effluents (Table 3), as an alternative technology for producing final effluents for discharge in watercourses or for reuse (e.g. in agricultural irrigation, industry or aquifer recharge). Satisfactory results from aerobic treatment systems were found in the use of high rate activated sludge (pilot scale) treating effluents from pulp and paper industries [9], [29]. These

TABLE 1: Studies that applied the microalgae-bacteria consortium in photobioreactors operated in sequential batches (PBSB).

Type of treatment concentration (mg/L)	Reactor dimensions and operating conditions	Treatment performance	Biomass Characteristics	Microalgae species present	Remarks	References
Synthetic sewage (50% glucose and 50% sodium acetate) COD = 200 mg/L; NH ₄ ⁺ -N = 20 mg/L; PO ₄ ³⁻ -P = 5 mg/L;	Volume = 3.6L; Natural lighting; HRT = 12h. 300 mL/min flow rate	-	Dark green granules were observed on day 7 of operation	<i>Diatomea</i> , <i>Chloro-phyceae</i> , <i>Chryso-phyceae</i> and <i>Tre-bouxioplyceae</i> (naturally growing algae)	The symbiosis decreased the average size and sedimentation capacity of the granule, but stimulated bioactivity	[12]
Synthetic sewage (sodium acetate) COD = 50-400 mg/L; NH ₄ ⁺ -N = 50 mg/L; PO ₄ ³⁻ -P = 10 mg/L;	Volume = 0.92 L; Light intensity 7200 lux (12 h light phase and 12 h dark phase; TDH = 7.5 hours; 0.55 cm/s air flow rate through an air pump at the bottom of the reactor	Best performance COD/N = 8 for nutrient and organic matter removal. 96% COD removal; 100% nitrification efficiency;	MLVSS = 3.21 g/L. Well-formed dark green granules, with an average diameter of 2.5 mm.	-	Satisfactory results with COD/N = 1	[19]
Synthetic sewage (glucose) COD = 300 mg/L; NH ₄ ⁺ -N = 35 mg/L; PO ₄ ³⁻ -P = 10 mg/L;	Volume = 2 L; Light intensity 200-6000 lux (12 h light phase and 12 h dark phase; Introduction of air at the bottom of the reactor	98.4% NH ₄ ⁺ -N removal; 50.2%PO ₄ ³⁻ -P removal;	MLVSS = 28.9 mg/L; IVL5 = 24 ml/g;	<i>Chlorella sp.</i> and <i>Scenedesmus sp.</i> (Targeted algae)	Directed algae maintain dominance during the experiment. The inter-cropping showed better performance in nutrient removal efficiency.	[20]

processes are also efficient in the removal of pharmaceutical compounds, being applied under ideal operating parameters for the removal of antibiotics, antihypertensives and psychiatric drugs [2], [30]. Additionally, during system operation, the process of gas transfer is also evident, in which the photosynthetic oxygen produced is used by aerobic bacteria to oxidize organic matter, reducing the need for introducing artificial oxygen into the system. On the other hand, bacteria, through the action of the enzyme carbonic

TABLE 2: Studies that applied the microalgae-bacteria consortium in continuous flow photobioreactors (PBCF).

Type of treatment concentration (mg/L)	Reactor dimensions and operating conditions	Treatment performance	Biomass Characteristics	Microalgae species present	Remarks	References
Synthetic sewage (50% glucose and 50% sodium acetate) R1:COD=300-600 mg/L; NH ₄ ⁺ -N =200 mg/L; PO ₄ ³⁻ -P = 20 mg/L; R2: COD = 300 mg/L; NH ₄ ⁺ -N = 100 mg/L; PO ₄ ³⁻ -P = 10 mg/L;	HRT = 6 hours; 60 min of aeration and 30 min without aeration. DO=7-8 mg/L Intensity of illumination 900-1100; TRS = 30-70 days. R1 = 1L; H=31cm; D = 6.5 cm R2-1 and R2-2 in series: 1L; H = 23 cm; D = 5.3 cm	R1:(96% COD removal; 94%NH ₄ ⁺ -N removal; 46% of phosphorus); R2:(95% COD removal; 99%NH ₄ ⁺ -N removal; 50% phosphorus	R1 : Average diameter 1.0 – 1.5mm; MLVSS = 4.8 g/L; IVL = 44 mL/g R2 : Average diameter 1.0 – 1.5mm; MLVSS = 4.3 g/L; IVL = 49 mL/g	<i>Phormidium sp.</i> (Algae that grow naturally)	Formation of alga- bacteria granules Internal separator made hydraulic selection easier	[22]
Synthetic sewage (sodium acetate) COD = 300 mg/L; NH ₄ ⁺ -N = 152 mg/L; PO ₄ ³⁻ -P = 47 mg/L;	Volume = 2L; Light intensity on the surface 200 μmol/(m ² -s); HRT = 24 h; No oxygen supply; Use of magnetic mixer;	90% COD removal; 94.5%NH ₄ ⁺ -N removal; 9% phosphorus removal;	MLVSS = 4g/L	<i>Scenedesmus sp.</i> ; <i>Closterium sp.</i> ; <i>Chlorella sp.</i> ; <i>Diatoms</i> ; <i>Oscillatoria Sp.</i> ; <i>Chroococcus sp</i>	Heterotrophic, autotrophic, algae and PAO bacteria coexisted and functioned in the reactor. Stable reactor performance.	[16]
Wastewater with dyes COD = 600-750 mg/L; NH ₄ ⁺ -N = 20-30 mg/L; PO ₄ ³⁻ -P = 5-6 mg/L;	Volume = 5L; Rectangular with three phases and sedimentation zone HRT = 16; TRS = 15 days; DO = 2.8 mg/L	78-85% COD removal; 88.6% removal of NH ₄ ⁺ -N; 36.6% removal of phosphorus;	MLVSS = 3,4 g/L; IVL = 135 mL/g	<i>Chlorella</i> ; <i>Filamentous algae</i> ; <i>Selenastrum bibraianum</i>	Color reduced 60- 80 times compared to the TEE under study. Best performance with TDH=16h; DO=0.45 mg/L	[17]

anhydrase (CA), release CO₂ from the breathing process, in which they are assimilated in the form of HCO₃⁻ by microalgae [31]. The great challenge for application in industrial effluents - such as the pulp and paper industry, is related to the composition of the effluent generated, in particular chemical products and heavy metals, which can be toxic and cause negative environmental impacts in aquatic bodies [32]. The effluents produced in industries of pulp and paper and fibers-waste-based recycling processes

are important sources of heavy metals [33] and, therefore, innovative solutions should be looked in order to improve recycling and reuse of wastes.

During paper production, several fibers are produced including wastepaper, and cellulose fibers from plants and trees, which are mixed in aqueous cellulosic suspension through filters or other shear device [34]. The main characteristics of these wastewater may include strong color, due to organic and extractive compounds, tannin resins, synthetic dyes, lignin and the degradation products formed by the action of chlorine on the lignin during the bleaching process [35]. Some researchers have used microalgae for removing high content of nitrogen and phosphorus in pulp and paper effluents [36]. Additively, microalgal species such as *Microcystis*, *Chlorella*, *Chlamydomonas*, in good lighting conditions, can remove up to 80% of the color. Table 3 shows some data collected in research works that have used microalgae for treating wastewater from the pulp and paper industry, showing an average total nitrogen removal of 80% and an average total phosphorus removal of around 70% [37], [38]. The most applied microalgae species in the works was *Chlorella vulgaris* and *Scenedesmus sp.* The works indicate good conditions of the algae biomass production, with high protein and lipid content, which could be used for bioenergy and biofuel production [39], [40], such as biodiesel and bioethanol, but also for energy, animal feed, and fertilizers production. In this context, in addition to economic aspects and nutrient removal, the application of microalgae-bacteria consortium to pulp and paper mills and fibers-waste-based recycling effluents shows potential for resource recovery, contributing for the circular economy [41]. Subashchandraboise *et al.*, (2011) [42] indicated that the consortium algae-bacteria can reach high efficiencies in removing heavy metals, organics, nitrate and phosphate.

4. Conclusion

This work has shown that photobioreactors are a viable technology for industrial wastewater treatment and reuse. The consortium microalgae-bacteria may bring several advantages for the treatment of pulp and paper mills and fibers-waste-based recycling effluents, when compared to conventional wastewater treatment technologies. This technology allows producing oxygen, carbon sequestering, removal of water pollutants such as biodegradable organics, refractory organics, nutrients and heavy metals by the industry, and the production of added-value products, which are advantages for the pulp, paper and recycling paper industries.

TABLE 3: Studies that applied microalgae-bacteria consortium to wastewater treatment in the paper industry.

Type of treatment concentration (mg/L)	Reactor dimensions and operating conditions	Treatment performance	Microalgae species present	Remarks	References
Wastewater paper industry $\text{NH}_4^+\text{-N} = 22,35 \text{ mg/L}$ $\text{PO}_4^{3-}\text{-P} = 10,1 \text{ mg/L}$	Radiation (PAR) = $130,0 \mu\text{mol.m}^{-2}\text{s}^{-1}$ Air Pump = 50 L/h Volume = 500mL	96% ammonia removal 91% phosphate removal	<i>Scenedesmus dimorphus</i> <i>Selenastrum minutum</i>	Biomass generated with high lipid content.	[40]
Wastewater paper industry $\text{NO}_3\text{-N} = 2,24 \text{ mg/L}$ $\text{PO}_4^{3-}\text{-P} = 9,86 \text{ mg/L}$	Outdoor open circular tanks (1m x 1,5m) Volume = 30 L	65% nitrogen removal 71% phosphorus removal	<i>Scenedesmus</i> sp.	Obtainment of protein-rich biomass with significant production of linolenic acid.	[43]
Wastewater paper industry COD = 296 mg/L $\text{NO}_3\text{-N} = 8,73 \text{ mg/L}$ $\text{NO}_2\text{-N} = 3,42 \text{ mg/L}$ $\text{PO}_4^{3-}\text{-P} = 12,3 \text{ mg/L}$	Volume = 950 mL Air Pump = 90 L/h	80% removal of nitrogen (nitrite + nitrate) 54% phosphorus removal	<i>Chlorella vulgaris</i>	The microalgae species used showed good adaptation for phosphorus removal.	[37]
Wastewater pulp and paper industry COD = 266 mg/L TN = 3,6 mg/L TP = 3,72 mg/L	Volume = 1 L Variation in effluent concentration 20%, 40%, 60%, 80% and 100%. Radiation = $202,9 \mu\text{mol.m}^{-2}\text{s}^{-1}$	82% average nitrogen removal 87% average removal of total phosphorus	<i>Chlorella vulgaris</i>	Treatment was sustainable based on microalgae, with potential for generating bioenergy.	[38]

5. Acknowledgments

The authors are grateful to the Foundation for Science and Technology (FCT, Portugal) for financial support by national funds through the projects UIDB/00195/2020 (FibEnTech) and UIDB/04035/2020 (GeoBioTec).

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