Phycoremediation

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The microalgae-based wastewater treatment process is one of the most promising technologies for the treatment and nutrient recovery of wastewaters from various sources (industrial, municipal, and agricultural): microalgae could be adapted to a variety of water bodies, can be extensively used to treat effluents, and could provide a tertiary biotreatment coupled with the production of potentially valuable biomass.

wastewater phycoremediation microalgae

1. Chlorella sp.

Chlorella sp. is widely used for wastewater treatment, and has proven abilities of removing nitrogen, phosphorus, and COD, mixing with bacteria or not, which show their potentiality as tertiary biotreatment step (**Figure 1**) [1]. Microalgae of the genus *Chlorella* can be grown both in autotrophic and mixotrophic cultivation conditions, reaching high growth rates.

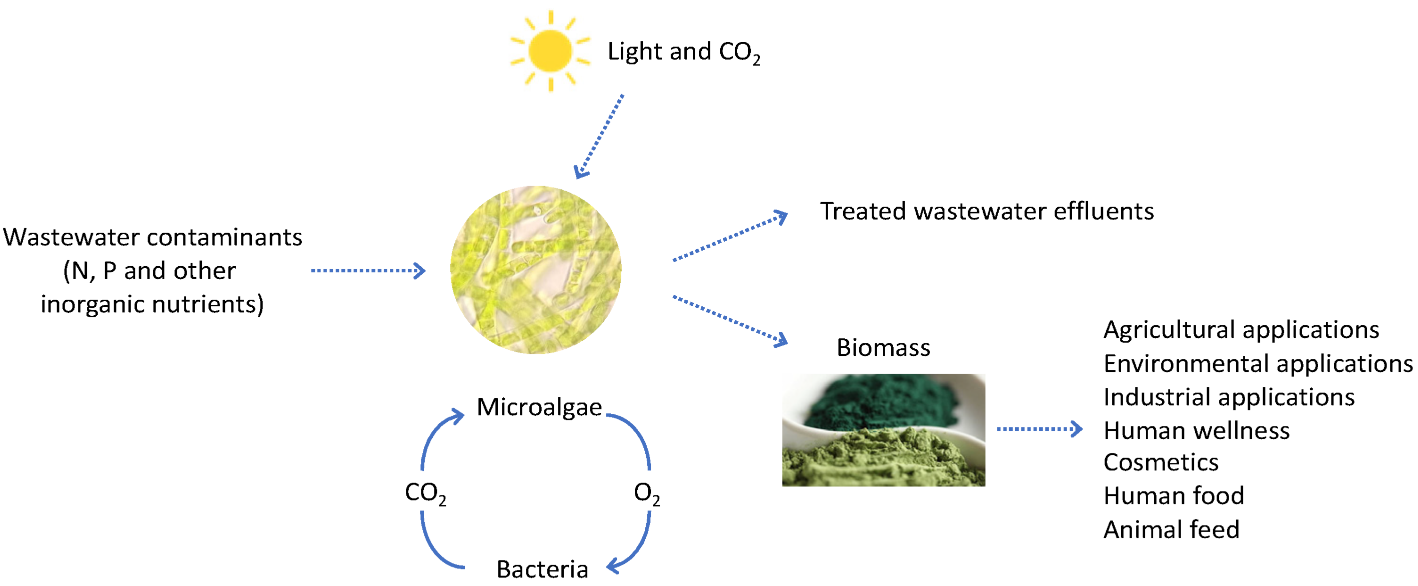

Figure 1. Uptake mechanism of nutrients and interactions among bacteria and microalgae.

Lau et al. [2] reported that *Chlorella vulgaris* can reduce 86% of the inorganic nitrogen and 78% of the inorganic phosphates in primary settled wastewater. Instead, Colak and Kaya [3] reported that *Chlorella* sp. can remove 50.2% and 85.7% of these two elements from industrial wastewater.

Wang et al. [1] evaluated the ability of *Chlorella* sp. to remove nitrogen, phosphorus, COD, and metals on wastewaters sampled from four different points of the treatment process flow of a local municipal wastewater treatment plant: wastewater before primary settling, wastewater after primary settling, wastewater after activated sludge tank, and wastewater generated in sludge centrifuge. The results, reported in **Table 1**, demonstrate the efficiency in nutrient removal of *Chlorella* sp.

Baglieri et al. [4] tested the ability of *C. vulgaris* to remove contaminants from agricultural wastewater, considering two case studies: (i) the first on the growth rate of the species in wastewater from a hydroponic greenhouse cultivation, in order to evaluate the degree of removal of the main inorganic compounds; (ii) the second on microalgae ability to degrade five different active ingredients commonly used in agricultural practices (pyrimethanil, metalaxyl, iprodione, fenhexamid, and triclopyr). *C. vulgaris* demonstrated a good aptitude for the decontamination, removing about 99% of nitric nitrogen, 83% of the ammonia nitrogen, and 88% of phosphates. A reduction in the contents of other elements, such as iron, potassium, and total organic carbon, was also observed. The microalgae also showed ability to grow in the presence of all five active ingredients used in the trials, although in some cases, signals of suffering from a slightly toxic effect were observed. The dissipation of metalaxyl and fenhexamid provided the most interesting results, occurring faster in the presence of microalgae [4]. With regard to iprodione and triclopyr, the dissipation was less evident. Pyrimethanil showed a different behavior with respect to the other pesticides, resulting in more resistance to dissipation, although in the presence of *C. vulgaris* [4].

Rasoul-Amini et al. [5] tested two strains of *Chlorella* sp. (YG01 and YG02) for removal of nitrogen and phosphorus from municipal wastewater. The experiment confirmed that *Chlorella* sp. (YG01) can be considered an efficient nutrient remover in wastewaters of different origin, while in the other strains, a minor efficiency in the purification process was shown. All this evidence is summarized in **Table 1**.

Table 1. Removal rates by microalgae of pollutants in wastewaters of different sources.

Microalgae Species	Wastewater Type	Treatment Efficiency (%)	Reference
Anabaena flos-aquae	Ammonium form nitrogen group	N: 94.9	[6]
		P: 96.8	
Anabaena flos-aquae	Orthophosphate form phosphorous group	P: 97.7	[6]
Ankistrodesmus falcatus	Aquaculture wastewater	NO_3^-: 80.85	[7]
		NO_2^-: 99.73	
		NH_4^+: 86.45	
		P: 98.52	

Microalgae Species	Wastewater Type	Treatment Efficiency (%)	Reference
		COD: 61	
Arthrospira platensis	Dairy farm wastewater	NO_{3-}–N: 99.6 NH_4–N: ~100 PO_4–P: 98.8 COD: 98.4	[8]
Calothrix sp.	Sewage water	N: 57 P: 74	[9]
Chlamydomonas sp. (YG04)	Municipal wastewater	N: 77.57 P: 100	[5]
Chlamydomonas sp. (YG05)	Municipal wastewater	N: 74.49 P: 100	[5]
Chlorella sp.	Domestic wastewater	N: 50.2 P: 85.7 BOD_5: 68.4 COD: 67.2	[3]
Chlorella sp.	Municipal wastewater before primary settling	NH_4–N: 82.4 P: 83.2 COD: 50.9	[1]
Chlorella sp.	Municipal wastewater after primary settling	NH_4–N: 74.7 P: 90.6 COD: 56.5	[1]
Chlorella sp.	Municipal wastewater after activated sludge tank	NH_4–N: 62.5 P: 4.7	[1]
Chlorella sp.	Municipal wastewater generated in sludge centrifuge	NH_4–N: 78.3	[1]

Microalgae Species	Wastewater Type	Treatment Efficiency (%)	Reference
		P: 85.6	
		COD: 83	
Chlorella sp.	Sewage water	N: 78 P: 45	[9]
Chlorella sp. (YG01)	Municipal wastewater	N: 84.11 P: 82.36	[5]
Chlorella sp. (YG02)	Municipal wastewater	N: 68.23 P: 99	[5]
Chlorella vulgaris	Wastewater from the Shatin sewage treat.	N: 86 P: 78	[2]
Chlorella vulgaris	Agricultural wastewater	NH_4–N: 99 NO_3–N:83 P: 88	[10]
Lyngbya sp.	Sewage water	N: 59 P: 92	[9]
Oocystis sp. (YG03)	Municipal wastewater	N: 83.32 P: 99.01	[5]
Scenedesmus obliquus	Secondary effluent—without stirring (20 °C)	N: 94 P: 97	[11]
Scenedesmus obliquus	Secondary effluent—without stirring (25 °C)	N: 99 P: 98	[11]
Scenedesmus obliquus	Secondary effluent—without stirring (30 °C)	N: 99 P: 94	[11]
Scenedesmus obliquus	Secondary effluent—without stirring (35 °C)	N: 79	[11]

Microalgae Species	Wastewater Type	Treatment Efficiency (%)	Reference
Scenedesmus obliquus	Secondary effluent—with stirring (20 °C)	P: 54 N: 80 P: 98	[11]
Scenedesmus obliquus	Secondary effluent—with stirring (25 °C)	N: 100 P: 98	[11]
Scenedesmus obliquus	Secondary effluent—with stirring (30 °C)	N: 99 P: 97	[11]
Scenedesmus obliquus	Secondary effluent—with stirring (35 °C)	N: 82 P: 62	[11]
Scenedesmus quadricauda	Agricultural wastewater	NH_4–N: 99 NO_3–N: 5 P: 94	[10]
Scenedesmus sp. LX1	Secondary effluent	N: 98 P: 98	[12]
Ulothrix sp.	Sewage water	N: 67 P: 85	[9]

due to its efficiency of nutrient removal, rapid growth rate, and high biomass productivity [11][14][15]. *Scenedesmus* sp. can be grown under autotrophic, heterotrophic, and mixotrophic cultivation conditions.

Xin et al. [12] studied the properties of lipid accumulation and nutrient removal of *Scenedesmus* sp. LX1 in secondary effluent. With regard to the total nitrogen and total phosphorus contents, the results showed a notable removal efficiency, for both nutrients, of over 98% (**Table 1**).

Martinez et al. [11] studied the kinetics of N and P elimination as well as simultaneous growth of *S. obliquus* in the effluent from a secondary-sewage-treatment facility, under different conditions of stirring and temperature. The researchers chose as experimental conditions 20, 25, 30, and 35 °C, representing the range of average temperatures of wastewater in different seasons of a warm climate, and two levels of mixing: maximum (magnetic stirring and air bubbling in the culture medium) and minimum (absence of magnetic stirring), as reported in **Table 1**.

Many works are also available in literature about the cultivation process of microalgae to promote the degradation of inorganic compounds and pesticides in water. Baglieri et al. [10], as above reported on *C. vulgaris* in the same case studies, also evaluated the *Scenedesmus quadricauda* removal efficiency, showing in the wastewater of hydroponic greenhouse cultivation a consumption of about 99% nitric nitrogen, but only 5% of the ammonia nitrogen, and a remotion of 94% phosphates. *S. quadricauda* also showed to be able to grow in the presence of all five active ingredients (pyrimethanil, metalaxyl, iprodione, fenhexamid, and triclopyr) used in the trials, determining a reduction in their contents, and providing similar results to those above reported for *C. vulgaris* [10]. Another study in which the removal ability of active ingredients from agricultural wastewater by microalgae was evaluated was conducted by Kurade et al. [16]. The researchers screened *S. obliquus* for the removal of diazinon, an organophosphorus insecticide. The removal efficiency was evaluated in Erlenmeyer flasks containing 100 mL of BBM added to 20 mg diazinon L^{-1}. However, *S. obliquus* did not show high removal capacity of diazinon.

Although microalgae-based wastewater treatment is oriented towards efficient removal of nitrogen and phosphorus, not all contaminants can be eradicated [17].

4. Other Species

In literature, other studies about microalgae species and cyanobacteria able to remove organic and inorganic compounds from wastewaters, of different origins, are reported. Rasoul-Amini et al. [5] evaluated the removal efficiency of nitrogen and phosphorus from municipal wastewater of the following species: two strains of *Chlamydomonas* sp. (YG04 and YG05), and one strain of *Oocystis* sp. (YG03). The results showed that *Chlamydomonas* sp. (YG04 and YG05) can act as efficient nutrient removers from wastewaters of different origin, while *Oocystis* sp. (YG03) showed a minor efficiency in the purification process, as reported in **Table 1**.

Zhu et al. [6] studied the nitrogen and phosphorus removal during the *Anabaena flos-aquae* biofilm growth, in two nutrient mediums, containing different nitrogen and phosphorus compounds. The results demonstrated that the nitrogen and phosphorus removal reached 94.9 and 96.8%, respectively, in the form of ammonium nitrogen, while 97.7% of phosphorus were removed in the form of orthophosphate phosphorous (**Table 1**).

Renuka et al. [9] tested the phycoremediation ability of four microalgae strains: *Calothrix* sp., *Lyngbya* sp., *Chlorella* sp., and *Ulothrix* sp. The researchers observed a different behavior of the strains, obtaining in all the cases a significant removal of NO_3–N (ranging from 57–78%) and PO_4–P (44–91%), as reported in detail in **Table 1**.

Hena et al. [8] evaluated the removal ability of *Arthrospira platensis* cultivated in dairy farm wastewater for biodiesel production. The results showed a good aptitude of *A. platensis* to remove the main pollutants.

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