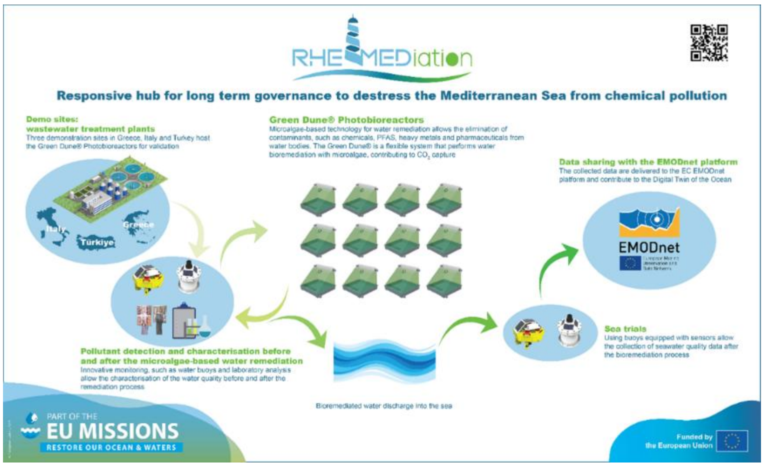
Benefits of microalgae-based wastewater treatment



Climate change, water scarcity, and environmental pollution are pressing global challenges. With projected increases in food, water, and energy demands by 60%, 80%, and 50% respectively between 2000 and 2050 [1], integrating wastewater treatment (WWT) with algal cultivation presents a sustainable solution. Both sectors operate at similar scales and share infrastructure, making microalgae an effective and eco-friendly tool for WWT [2]. Microalgae naturally disinfect water and remove nutrients more efficiently than conventional chemical or bacteria-based treatments, which often carry high costs and secondary pollution [3]. Their high surface-to-volume ratios and biosorption capacities enable them to absorb a wide range of pollutants. Additionally, microalgae adapt to various growth modes, such as photoautotrophic, mixotrophic, and heterotrophic, allowing them to thrive in different wastewater conditions, even when pollutant levels are low [4].

Microalgae eliminate contaminants through bioconversion (the breakdown of complex pollutants into harmless substances like CO_2 and H_2O through enzymatic reactions), bioadsorption (the passive binding of pollutants to the microalgae's cell walls, involving living or dead biomass, a process that relies on mechanisms like precipitation, ion exchange, and electrostatic attraction, and for which microalgae's large surface areas and rough cell textures is a clear advantage), and bioaccumulation (an active process in which pollutants such as nitrates, phosphates, heavy metals, and pesticides are absorbed into the cells, usually through passive diffusion) [5] [6] [7].

Additionally, microalgae contribute to carbon sequestration by absorbing CO_2 from the atmosphere or industrial emissions. Wastewater provides an ideal aquatic environment for algal growth. In tandem with bacteria, microalgae enhance nutrient removal, increase dissolved oxygen through photosynthesis, and support aerobic bacterial degradation of organic pollutants. This synergy reduces the energy costs of WWT, particularly in aeration, which alone accounts for over 50% of energy use in treatment plants [8].

Several factors affect the efficiency of microalgae in wastewater treatment. Temperature plays a vital role, as most microalgae thrive between 15 and 28 °C, making them adaptable to a variety of climates. pH is also critical; levels above 9 hinder photosynthesis by reducing carbon dioxide absorption, ultimately slowing algal growth [9,10]. The hydraulic retention time (HRT), which determines how long wastewater remains in the treatment system, impacts pollutant removal effectiveness. Short HRTs can lead to insufficient treatment or loss of algal biomass, while longer retention times paired with higher algal concentrations enhance removal efficiency [11]. Environmental processes like photolysis and hydrolysis assist in degrading pollutants; sunlight exposure and water-mediated chemical reactions reduce the persistence and toxicity of contaminants [12]. Biological and nutrient-related factors further affect treatment outcomes. Different algal species vary in their capabilities for pollutant absorption and degradation. The growth phase of algae influences its effectiveness, and interactions with bacteria or fungi can either enhance or inhibit

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bioremediation. Sufficient availability of essential nutrients such as nitrogen, phosphorus, and trace elements is necessary for optimal performance. Conversely, nutrient deficiencies or high salinity levels can suppress algal activity and reduce treatment efficiency [5,13].

Depending on the type of wastewater being treated, microalgae-based wastewater systems will produce a microalgal enriched sludge with high valorization potential ranging from the production of biofuels, as biogas or biodiesel, to the production of biofertilizers or even to the extraction of fine chemicals as the carotenoid pigments; the value of the biomass being defined by its degree of contamination, which, in turn depends on the contamination of the wastewater being treated. Such valorization is a concern and a priority of the EU in wastewater treatment and can strongly help to minimize the costs associated with the process.

In summary, microalgae can provide an environmental and energy sustainable solution for wastewater treatment, as well as contribute for the mitigation of climate change.

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