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Microalgae-Based Wastewater Treatment as a Circular Solution for Sustainable Resource Recovery

Aziza Lamchaimech [1], *Khadija* El-Moustaqim [2*] [0009-0007-9193-6638], *Ahmed* Abarkan [3], *Dalal Boudoudou* [4] , *Mounir* Boutarbouch [1], *Ayoub* Ghailane [1], *Chaimae* Lamiri, *Abderrazzak* Ihouaten[1], and *Jamal* Mabrouki[1] [0000-0002-3841-7755]

[1]Laboratory of Spectroscopy, Molecular Modelling, Materials, Nanomaterials, Water and Environment, CERN2D, Mohammed V University in Rabat, Faculty of Science, AV Ibn Battouta, Agdal, Rabat 10106, Morocco

[2]Improvement and Valuation of Plant Resources, Faculty of Sciences, Ibn Tofaïl University—KENITRA-University Campus, Kenitra 14000, Morocco

[3] Biotarde,31120 Toulouse, France
[4] Ibn Tofail University, Faculty of Sciences, Laboratory of Plant, Animal and Agro-Industrial Production, Kénitra, Morocco.

Abstract. The need for sustainable and circular wastewater management solutions has increased due to water scarcity and environmental degradation. A promising eco-biotechnological strategy that can lower carbon emissions, recover valuable resources, and purify wastewater is microalgae-based systems. Along with important operational parameters that control process efficiency, like light intensity, temperature, CO_2 availability, and hydraulic retention time, the metabolic ability of microalgae to absorb nitrogen, phosphorus, and organic matter is investigated. The energy consumption, carbon footprint, and effluent quality of various cultivation configurations—such as open ponds, photobioreactors, and hybrid systems—are contrasted with conventional wastewater treatment technologies. This chapter examines how microalgae contribute to biomass valorization, nutrient recycling, and pollution removal in order to demonstrate these processes as essential elements of a circular bioeconomy. The benefits of turning energy into biofuels and recovering resources by recycling nutrients into biofertilizers are also highlighted in the chapter. Furthermore, future possibilities for process automation, integration with smart cities, and adherence to international carbon neutrality targets are critically looked at, along with difficulties like biomass collection, contamination hazards, and large-scale feasibility.

1 Introduction

In addition to being a vital resource for industrial production, water is also necessary for human survival [1]. The world would produce an overwhelming amount of wastewater each year due to the rapid growth of urbanization, industrialization, and population. River discharges, wastewater, and wind processes continue to build up in coastal habitats as a result

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[*] Corresponding author: elmoustaqim.khadija@gmail.com

of the fast industrialization and economic expansion of these regions [2], [3]. As a result, it surely contributes to the significantly increased contamination of the natural environment*. Issues related to global warming are currently becoming worse at an alarming rate and are getting more interrelated [4], [5]. Climate change is increasing the frequency and severity of extreme weather events including heat waves, droughts, and floods, endangering human security [6], [7]. It should be mentioned that water scarcity is the result of an imbalance between supply and demand, which is naturally brought on by the fast urban population increase, the unequal distribution of water resources, periods of extreme drought, and pollution of the groundwater and surface water. Various nutrient elements found in wastewater, such as Nitrogen, phosphorus, organic compounds, and heavy metals, can lead to water eutrophication if they are discharged into natural water bodies untreated. Because of its numerous impurities, the direct disposal of the contaminated water released from these applications presents significant environmental dangers and is becoming a growing concern. Wastewater includes a range of materials, some of which include extremely damaging to living things. Even though microalgae hold great potential for a wide range of uses, their application is now restricted to lab conditions [8]. Applications at the industrial level have not advanced as much as they should for a number of reasons, the main one being the enormous financial expenses of large-scale implementations. Two obstacles to microalgae's ability to produce raw materials for a variety of uses are Artificial media's high cost and low biomass output. One of the best strategies to address this issue is to cultivate microalgae using effluents [9]. This is a practical technique to reduce process costs and provide microalgae biomass for a variety of uses. Numerous studies show that microalgae can produce biomass from a variety of wastewater types, including industrial, agro-industrial, domestic, and livestock wastewaters, by totally eliminating nitrogen, phosphorus, and harmful components. Nutrient recovery and recycling are crucial for preserving natural resources and reducing the harmful effects of human activity on the environment. However, major problems like soil contamination, greenhouse gas emissions, and water body eutrophication have been caused by unchecked resource exploitation and their release into the environment through industrial, agricultural, and urban effluents. Systems designed to effectively remove pollutants and generate biomass rich in proteins, lipids, carbohydrates, and other bioactive chemicals can be used to cultivate microalgae. Biofuels, nutritional supplements, and fertilizer can all be produced from this biomass.

Regarding the application of microalgae for resource recovery and wastewater treatment, this study offered a number of problems and potential solutions. It is hoped that the conversations and feedback will motivate researchers to find practical solutions to these challenging problems and steer clear of overly optimistic viewpoints regarding the useful application of microalgae in resource recovery and wastewater treatment.

2 Integrated wastewater-algae-biorefinery for the synthesis of valuable chemicals

2.1 Wastewater and microalgae

The amazing capacity to absorb nutrients, organic waste, and contaminants from wastewater is possessed by microalgae, which are small photosynthetic algae. The potential benefits of using microalgae may significantly aid in the production of sustainable goods such as food, feed, fertilizers, fuels, fodder, cosmetics, and other bioproducts. The use of wastewater instead of chemical fertilizers to supply nutrients for microalgae development has been thoroughly studied in the literature due to the possible financial and environmental savings. Additionally, microalgae can treat wastewater, which is comparable to secondary or tertiary treatment (**Fig. 1**). Wastewater's physicochemical properties differ based on the manufacturing technology and materials used. For instance, the majority of nitrogen in wastewater from the silk industry is found in organic molecules, whereas NH_4^+-N is found in swine dung. The physicochemical properties of wastewater collected from various silk industry processing units such as reeling wastewater, frigon wastewater, and boiling cocoon wastewater.

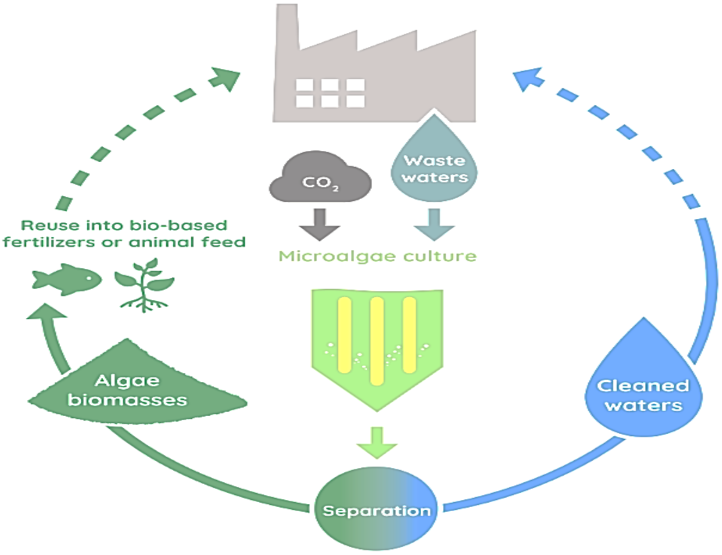

Fig. 1. Revolutionizing wastewater treatment with microalgae.

2.2 Hight-value compounds synthesis

The effectiveness of microalgae in extracting nitrogen and phosphorus compounds from urban and industrial effluents has made their application in nutrient recovery more popular. The usage of various microalgal strains, including *Chlorella vulgaris*, *Scenedesmus sp*., and *Anabaena sphaerica*, has been highlighted in recent studies. These strains have a high removal efficiency of over 90% for nitrogen and phosphate contained in effluents. The wastewater integrated algal-biorefinery has garnered a lot of attention lately due to its effectiveness as an algae biorefinery. Numerous earlier researches show that a variety of wastewaters, including those from homes, farms, and industries, are rich in the right nutrients. These wastewaters might be used as a low-cost alternative supply of raw nutrients to grow microalgae utilizing CO_2 from the atmosphere and flue gasses. Throughout human history, microalgae have been essential to human life as major providers of food, medicine, building materials, and energy. Their production capacity is comparable to that of a terrestrial plant. Various unicellular photosynthetic microalgae are becoming new renewable energy sources that can meet human activity demands [10]. As seen in **Fig. 2**, the leftover biomass, which is high in carbs, can be converted into bioethanol or biogas, while microalgae lipids can be used as a raw material for the synthesis of biodiesel.

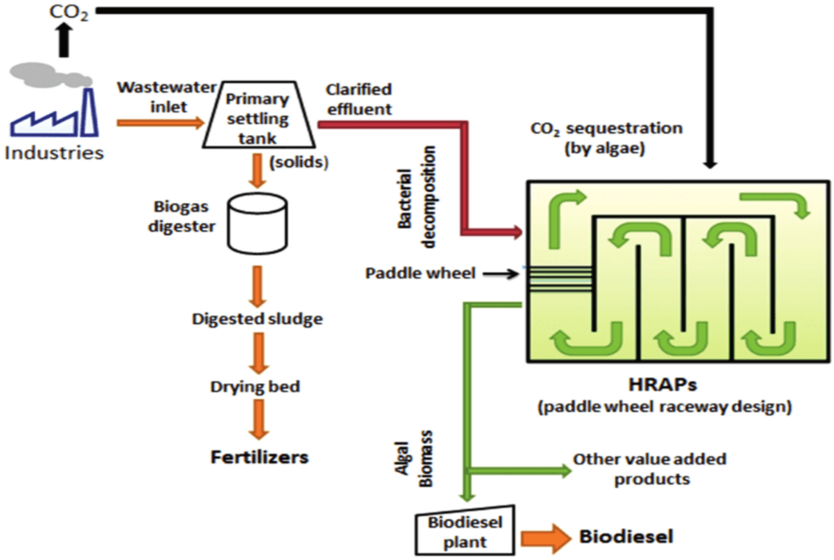

Fig. 2. Biorefinery approaches of wastewater management by microalgae.

High levels of proteins, lipids, carbohydrates, and amino acids found in microalgae make them potential feedstock for a variety of medicinal products. They are grown in PBRs or OPs that use focusing and mixing techniques. These procedures use a lot of energy, though. Thus, the key goal continues to be producing the most microalgae biomass with the least amount of energy. Microalgae biomasses cultivated in wastewater have the potential to be a substantial source of feedstock for the synthesis of biofuel and medicinal compounds. Their lipid concentrations vary, and fat removal technology is continuously being developed [11].

3 Role of Microalgae in Nutrient Recovery

As worries about the possible effects of Greenhouses Gas emissions from Fossil fuel combustion for energy have grown, it has become more and more crucial to find a trustworthy substitute for energy sources based on carbon. Algal-based biofuel has become one of the most well-known types of modern renewable energy sources in recent decades [12]. Similar to other plants, microalgae use photosynthetic processes to take in CO_2 from the atmosphere during the day and release it back into the atmosphere at night. **Fig. 3** shows the process of biologically fixing CO_2 to produce biofuels. When grown under closed cultivation circumstances, microalgae can sequester up to 90% of CO2, while when grown in raceway ponds, they can sequester between 25% and 50%.

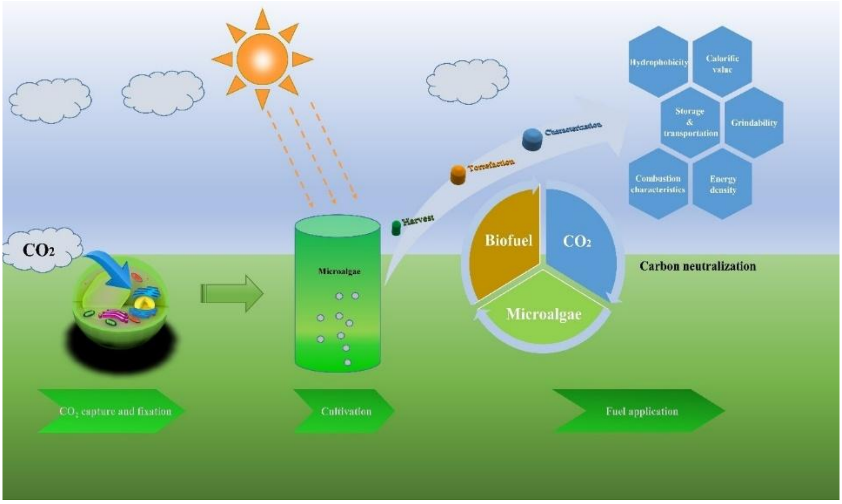

Fig. 3. Photosynthesis in microalgae and their potential contribution to future renewable energy generation through CO_2 sequestration.

3.1 Microalgae-based Wastewater Treatment for Nutrient Recovery

Many of the biomolecules that microalgae make have a wide variety of uses. There are several applications for a wide range of different kinds of molecules, from the use of pigments and sterols in medicinal and cosmetic applications to the use of lipids, proteins, and carbohydrates in food and nutraceutical applications. The remainder of biomass, which is high in carbs, can be converted into bioethanol or biogas, while may microalgae lipids used as a feedstock for biodiesel synthesis. Furthermore, the entire biomass can be converted directly into crude bio-oil using a variety of thermochemical conversion procedures. The transesterification process can be used successfully to produce biodiesel because microalgae can store a sizable amount of lipids even in the face of unfavorable environmental circumstances. The rapid development rates and productivity of algae, their ability to thrive on non-arable land using wastewater, their capacity to utilize water pollutants and CO_2, and their potential to generate various high-value biological compounds confer a competitive edge over first-generation biofuels sourced from sugar, starch, and plant-based oils. Microalgae contribute to alleviating the impacts of climate change by fixing carbon dioxide (CO_2) during photosynthesis in addition to removing nutrients. It is important to remember that the type of effluent and the intended product determine which reactor and microorganisms are used. Photosynthetic bioreactors, for instance, encourage high nutrient recovery for biofertilizers.

3.2 Membrane Photobioreactor as Emerging Technology

Recent developments and potential applications of some reactors, like membrane photobioreactors (MPBRs), for wastewater treatment and nutrient recovery include the creation of nanocomposite membranes, like graphene oxide/silver (Ag/GO), which have already demonstrated promising outcomes in terms of lowering membrane fouling and improving nutrient removal efficiency. The efficiency of these procedures has increased because to the creation of particular bioreactors for nutrient recovery. It is anticipated that the usage of reactors like MPBRs and the integration of Artificial Intelligence to optimize operating criteria would be a component of a larger circular economy in the future, encouraging not just the recuperation of water and nutrients but also carbon capture and energy recovery. Currently, the area of wastewater treatment using microalgae has directly replaced the commonly utilized microalgae cultivation facilities. Some open systems, like raceway reactors, waste stabilization ponds, and advanced high-rate algal ponds, have been used in this industry, for instance, because they are simple to scale up and reasonably priced to construct [13].

3.3 Biohydrogen and biogas

Anaerobic digestion is often accomplished in two ways: 1) simple sugar is fermented by fermentative bacteria and anaerobically digested to produce alcohols, and 2) metanogenic microorganisms consume these chemicals to produce biomethane. Microalgae are excellent biogas producers due to their elevated carbohydrate and lipid concentrations, lack of lignin, and low cellulose content. Furthermore, anaerobic digestion generates solid waste that can subsequently be utilized as a soil amendment [14]. The generation of biogas from microalgae possesses considerable untapped potential. Various microalgal species, such as *Scenedesmus*, *Spirulina*, and *Chlorella*, have been utilized in biogas production [15]. **Kinnunen and Rintala** demonstrated that the biomethane potential of *C. vulgaris* and a mixed culture of indigenous algal species, primarily *Scenedesmus sp.*, ranged from 154 to 252 L CH_4 kg−1 VS, contingent upon the culture media utilized, which included synthetic medium, wastewater (both sterilized and non-sterilized), and digestate from the anaerobic digestion of pulp and paper biosludge (also sterilized and non-sterilized) [16]. Although hydrogen is widely used in many industrial applications, the most common way to produce it is by burning fossil fuels or other conventional energy sources. Because of its clean oxidation properties and high calorific value, bio-hydrogen has garnered a lot of attention as a possible energy source [17]. Recently, the synthesis of bio-hydrogen from microalgae has become a promising substitute for the production of sustainable energy. Dark fermentation is an economical and environmentally sustainable process [18], [19], [20], [21]. Additionally, this produces easily marketable byproducts like lactic and acetic acids. This technology reduces additional expenses by doing away with the need for aeration or a light source.

4 Challenges and future perspective

The development of fully integrated and optimized systems that combine emerging biotechnologies with automation and supervisory systems for process monitoring and control is a step forward for nutrient recovery and recycling [22]. In addition to the development and application of cutting-edge technologies like membrane photobioreactors, the use of microbial consortia aims to improve nutrient recovery efficiency and selectivity. Fossil fuels and first-generation biofuels made from corn, soy, and sugarcane can be replaced by microalgae, a third-generation feedstock and potential precursor for bio-renewable production [23]. Nowadays, almost no environmental waste can be produced by combining microalgae with clean technologies like biorefineries and biofuel production. Furthermore, in order to advance large-scale production, some gaps must be recognized as environmental considerations. An inorganic fertilizer called ammonia (NH_3) is used to maximize the growth rates and productivity of algal biomass. Economically speaking, using a microalgae system to remove nitrogen, phosphorus, and dissolved organic carbon from different wastewaters is much more sustainable than using traditional systems because it can operate outside in the sun, which reduces costs [23]. The nutritional makeup of various urban wastewaters must be taken into account when treating microalgae, which presents another major challenge. In order to comply with effluent discharge regulations, different types of wastewaters must be combined to equilibrate the ratio and concentration of nutrients. Since even small changes in cultivation parameters can have a significant impact on product yields, future research on carbon sequestration via microalgae should focus on the factors influencing their growth, such as their broad tolerance and sensitivity to temperature, pH, irradiance, and nutritional conditions.

5 Conclusion

Addressing increased energy demand and reducing the harmful environmental effects of industrial waste are the main issues brought about by the world's industrial revolution and excessive reliance on fossil fuels. The main source of water contamination, along with agricultural waste, is industrial waste. Since pollution and water scarcity are major environmental problems, many people are looking for solutions. As fossil fuel supplies run out, there is a growing need for alternative energy sources. Compared to other physical-chemical treatment techniques, microalgae are the most suitable biological agents for wastewater treatment and solving the energy problem. Microalgae are therefore effective agents for treating wastewater and producing biofuel at the same time. The foremost problem linked with green technology is the identification of sustainable energy sources. However, despite the opportunities, significant obstacles still exist, especially with regard to economic viability and scalability. The search for integrated and creative solutions is driven by the growing demand for raw materials and the requirement to lessen environmental effects. As a result, it is expected that production techniques focused on nutrient recovery and recycling will become more established, promoting global environmental and economic sustainability.

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