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Microalgae: Harnessing Environmental and Nature Benefits – A Comprehensive Review

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ABSTRACT

Microalgae, as photosynthetic microorganisms, possess significant potential in addressing environmental challenges and promoting sustainable practices. This review explores the wide-ranging applications of microalgae, emphasizing their pivotal roles in bioremediation, biofuel production, bioethanol generation, and biofertilizer development. Microalgae's ability to thrive in various wastewater types, including municipal, agricultural, and industrial, signifies a sustainable approach to wastewater treatment. By efficiently removing nitrogen, phosphorus, carbon, and heavy metals, microalgae make substantial contributions to environmental sustainability. Furthermore, their integration into wastewater treatment processes not only reduces operational costs but also yields valuable biomass for various applications. Microalgae's capacity to sequester carbon dioxide, coupled with their role in enhancing soil fertility, renders them invaluable tools in mitigating climate change and promoting sustainable agriculture. This review underscores the importance of ongoing research to fully harness microalgae's potential, paving the way for a greener and more resilient future. It summarizes the effects of microalgae's potential on agricultural soil and wastewater treatments, among other areas, by examining relevant works related to the topic. To achieve this, databases such as Google Scholar, Frontier in Microbiology, Microbial Cell Factory (MCF), Scopus, Web of Science, ScienceDirect, and Directory of Open Access Journals (DOAJ) were explored to identify studies on microalgae's potential in various fields.

INTRODUCTION

Microalgae are photosynthetic prokaryotic or eukaryotic microorganisms that grow rapidly and have the ability to live in different environments due to their unicellular or simple multicellular structure and their simple growth needs (Christi, 2007). Microalgae are sunlight-driven cell factories that convert carbon dioxide to potential biofuels, foods, feeds, and high-value bioactive (Spolaore *et al.*, 2006). In addition, these photosynthetic microorganisms are useful in bioremediation applications (Munoz and Guieysse, 2006) and as nitrogen fixing biofertilizers (Vaishampayan *et al.*, 2001). Microalgae, as photosynthetic unicellular microorganisms, play a crucial role in enhancing the productivity, biodiversity, and functioning of aquatic ecosystems. Particularly, phytoplankton, a subgroup of microalgae adapted to living in suspension in water, account for a substantial portion of the global net primary production in marine and freshwater environments, contributing approximately 49% (Naselli-Flores and Padisák, 2023). The taxonomic diversity of microalgae is extensive, encompassing species that exhibit significant evolutionary divergence. Despite their small size, ranging from 0.2 to 200 μm , microalgae have a remarkable capacity to contribute to climate change mitigation through their ability to fix CO_2 (Vu *et al.*, 2018). This process of carbon fixation by microalgae holds great potential for sequestering CO_2 from the atmosphere, offering possibilities for sustainable utilization such as bioenergy production and the development of value-added products (Alami *et al.*, 2021). However, this review paper seeks to understand

microalgae contents and shed more insight on the role of microalgae in nature and environmental benefits. It seeks to emphasize the significance of microalgae in tackling climate change and the loss of biodiversity. It aims to reveal the immense possibilities for promoting environmental sustainability. The chapter provides a detailed examination of microalgae's potential in areas such as bioremediation, bioenergy, wastewater treatment, sustainable agriculture, and the creation of valuable products. This exploration underscores their role in addressing the biodiversity crisis.

LITERATURE REVIEW

Microalgae and their associated microbiota grow and survive in all climate zones and many species are well adapted to extreme temperatures and pH values. Since microalgae are photosynthetic active organisms, which can be grown under a wide variety of conditions, they are highly attractive for the biotechnological production of a wide range of different chemical compounds. They are particularly well known for their use in the production of advanced biofuels (e.g. drop-in biofuels and fourth-generation biofuels) (Onen *et al.*, 2020; Keasling *et al.*, 2021).

Algae Culturing

Microalgae can be cultured by different methods and under different conditions. They need light as an energy source to convert the absorbed water and CO_2 into biomass through photosynthesis (Ozkurt, 2009). Photosynthetic products accumulate in various forms,

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such as cell components or storage materials, and vary from 20 to 50% of total biomass (Chisti, 2007). Algae also need nitrogen and phosphorus as major nutrients, which account for 10–20% of algae biomass (Benemann & Oswald, 1996). Other requirements for growth are the macronutrients Na, Mg, Ca, and K; micronutrients, such as Mo, Mn, B, Co, Fe, and Zn; and other trace elements. Wastewater is a good source of the required nutrients for microalgae cultivation. Thus, application of organic effluents from the food and agriculture industries can nourish microalgae. During growth, the algae cells pass through different phases (e.g., lag, exponential, stationary, death). Different species of microalgae may vary in their need for growth media. However, the major requirements are the same for almost all species and include essential nutrients, an organic or inorganic carbon source, nitrogen, phosphorus, and iron (Grobbelaar, 2004). One of the most important parameters in algae culturing is the type of bioreactor used. This should be designed according to the species and the purpose of culture. On a large scale, algae can be cultured in open ponds (high-rate ponds). Open culture systems are comparatively inexpensive, but they become easily contaminated. Other bioreactors have continuous or batch culture facilities (Adey *et al.*, 1996; Craggs, 2000). Some species of algae grow very well in heterotrophic culture (Morales-Sanchez, 2017). For commercial cultivation it is feasible to grow microalgae in wastewater treatment plant to get dual advantages of water treatment and biomass production. See water is also a good alternative for commercial cultivation of microalgae. Using sea water instead of fresh water for microalgae culturing will reduce the cost of production. Marine water is a good media for microalgae culture avoiding nutrients cost and enhancing productivity of lipids and other useful products in microalgae biomass (Park *et al.*, 2018). Most recently ocean cultivation system has attracted attention for commercial scale production of algae due the advantages like mixing of the culture by ocean waves, utilizing dissolve nutrients large area availability, etc. which result in the reduction of culturing and maintenance cost (Kim *et al.*, 2016; Novoveska *et al.*, 2016; Park *et al.*, 2018).

To make the algae biotechnology sustainable, feasible and economically viable it is necessary to develop successful culturing technologies for targeted production of biomass. For a feasible algal culture, the biomass output should be > 30 g/m²-day (US Department of Energy, 2014). Approximately 40,000 different species of microalgae have been reported. Microalgae culture depends on the species and is affected by factors such as nutrient availability (N, P, K, etc.), temperature, pH, salinity, inorganic carbon, oxygen, light intensity, and CO₂ (Mata *et al.*, 2010; Fuentes-Grunewald, 2012). Other important factors that determine the success of culture include stirring and mixing, width and depth of the bioreactor, harvest frequency, and dilution rate. Following are the important parameters of culture which has great influence and impact on the overall yield of biomass and bioproducts in microalgae.

Nutrients

Different microalgae species may vary in their nutritional needs; however, the basic requirements are same for all species. Nitrogen, phosphorus, and carbon form the backbone of microalgae (CH_{1.7} O_{0.4} N_{0.15} P_{0.0094}) (Juneja *et al.*, 2013), and are classified as macronutrients required for algal growth. Some marine microalgae species also require silicon as a macronutrient. Microalgae absorb O₂ and H₂ from water. The quantities of macronutrients such as nitrogen and phosphorus may vary for different species of microalgae. It has been reported the growth of chlorella declined when the concentrations of nitrogen and phosphorus reduced from 31.5 and 10.5 mg/l respectively (Aslan & Kapdan, 2006). Quantities of the available nitrogen in the culture directly alter cell growth. Nitrogen limitation in the microalgae culture, can reduce growth and biomass productivity although they increase production of carbohydrates and lipids. 0.5 g/l nitrogen has been proved to be optimum concentration for *Chlorella vulgaris* at which it produces 3.43 g/l biomass (Daliry *et al.*, 2017).

The micronutrients Mo, K, Co, Fe, Mg, Mn, B, and Zn are only required in trace amounts but have a strong impact on microalgae growth, as they influence many enzymatic activities in algal cells (Hu *et al.*, 2006; Gardner-Dale, *et al.*, 2017). Usually, inorganic nitrogen and phosphorus are absorbed as nitrates and phosphates. Urea is also a suitable source and a cost-effective alternative to other inorganic nitrogen sources. Carbon can be added to the algae culture in organic forms, such as glycerol or acetates, or as CO₂. However, for large-scale cultivation of microalgae, environmental CO₂ must be used as a carbon source, which is not only low cost but adds the benefit of CO₂ mitigation. P, N, and C are the primary inorganic nutrients that are essential for microalgal growth (Bold & Wynne, 1978). Nutrient deficiency greatly affects the microalgae growth rate and results in low biomass (Hu *et al.*, 2008; Devi and Mohan, 2012; Ito *et al.*, 2012). The nutrient supply strongly affects the synthesis and accumulation of carbohydrates and lipids in microalgae (Devi & Mohan, 2012). For commercial production of microalgae biomass, the culture must be grown rapidly; thus, providing the proper nutrients is very important to speed algal growth. Some strongly limiting substances can be used as growth enhancers for microalgae. In addition, certain bacteria can enhance the growth rates of microalgae by supplying important nutrients. These bacteria degrade nutrients into forms that can be readily assimilated by microalgae, such as ammonia or nitrate (Zhu *et al.*, 2011).

METHODOLOGY

A literature review was carried out to identify the relevant articles published. The earliest research publication concerning the review was found in 1981. Google Scholar, Microbial Cell Factories (MCF), Frontier in Microbiology, Scopus, Web of Science, Science Direct and Directory of Open Access Journals (DOAJ) databases were explored to identify studies on microalgae potential

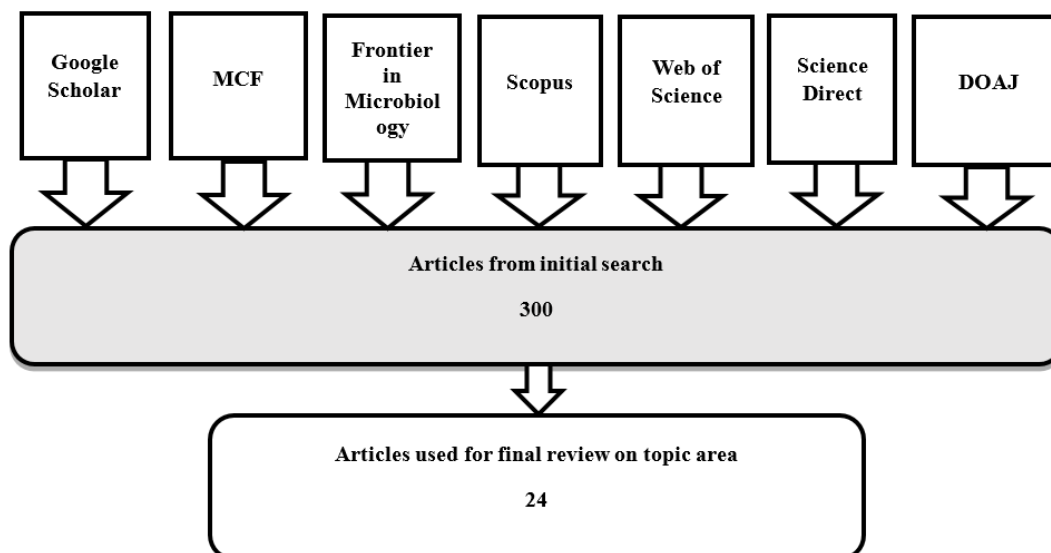


Figure 1: Flow chart showing methodology of review of discussion

using the following keywords in English; ‘microalgae role in agriculture’, ‘microalgae in wastewater treatments’, ‘microalgae as biofuels and biofertilizers.’ A total of 300 articles were identified in the initial review but 24 articles were selected to be a good match for the review study based on the objective of the study. Figure 1 below shows the system search method.

DISCUSSION

Roles of Microalgae-Based Systems for Biofuel, Biodiesel, Bioethanol and Bioremediation Process

Microalgae possess a productivity comparable to that of land plants, a quality crucial for human survival throughout history, providing significant sources of food, medicine, construction materials, and energy. These diverse single-celled photosynthetic microorganisms are emerging as innovative renewable energy sources capable of meeting human demands. Microalgae lipids serve as raw material

for biodiesel production, while the remaining biomass, rich in carbohydrates, can be used to generate bioethanol or biogas. Additionally, various thermochemical processes can convert the entire biomass directly into crude bio-oil (Wang *et al.*, 2022). Typically, microalgae accumulate lipids ranging from 20% to 50% of their dry weight, with certain species reaching as high as 80% under specific conditions (Chisti, 2007). These neutral lipids, primarily in the form of triacylglycerols (TAGs) constituting up to 90-95%, can be converted into fatty acid methyl esters (FAMES) and then into biodiesel (MacDougall *et al.*, 2011). Algae have distinct advantages over first-generation biofuels derived from sugar, starch, and vegetable oil due to their rapid growth rates, ability to thrive on non-arable land using wastewater, capacity to utilize water pollutants and CO₂, and capability to produce a variety of valuable biological compounds (Cheng and Luo, 2022).

Extensive research has been conducted on algal species

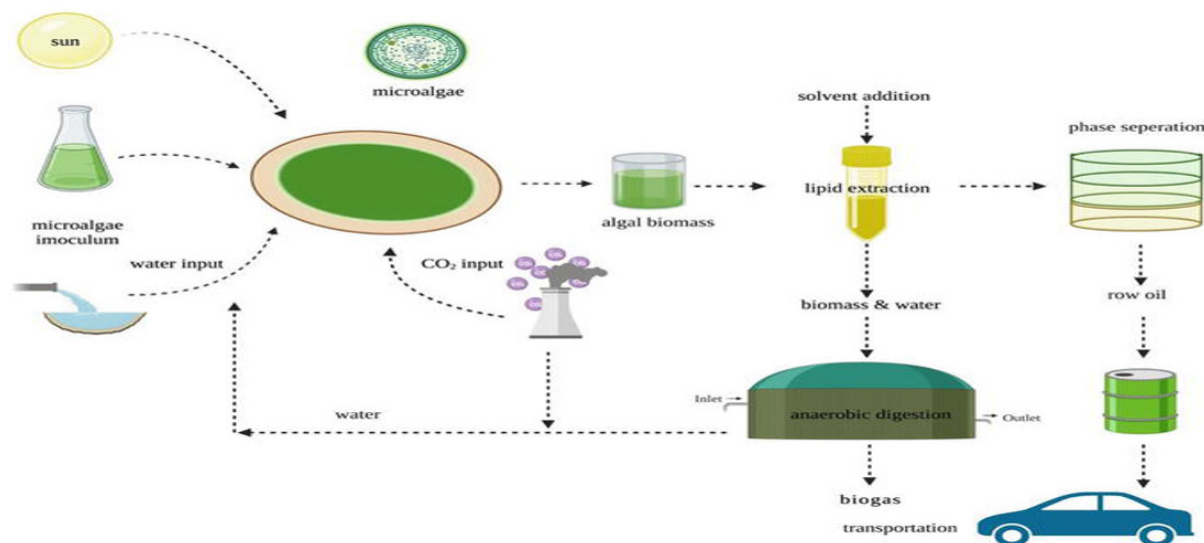


Figure 2: Biofuel production and process from microalgae
Source: adopted from Subeda (2023)

known for their high oil content, particularly in relation to biofuel production. Among these species, several have gained recognition for their remarkable oil accumulation capabilities. One such species is *Dunaliella tertiolecta*, which boasts an impressive oil content ranging from 60% to 67%. Another noteworthy species is *Botryococcus braunii*, known for its substantial oil content of approximately 43.06%. *Chlorococcus* spp. has been identified as possessing an oil content of about 38%. *Scenedesmus obliquus* is also worthy of mention, as it demonstrates oil content within the range of 35% to 55%. In addition, *Arthrospira platensis*, a species widely recognized for its valuable properties, exhibits an oil content of approximately 35.31% (Gouveia & Oliveira, 2009; Pradana *et al.*, 2017). The production of biodiesel from microalgae involves two distinct stages: firstly, extracting lipids from microalgal cells, and secondly, trans-esterifying these lipids using alcohol and a catalyst (Mondal *et al.*, 2017). In an initial investigation of biomass production and ammonium removal conducted on *Synechococcus* sp. VDW (accession number MH393765) isolated from natural seawater in Thailand (Tinpranee *et al.*, 2018), we found that under optimal conditions (initial pH 7.4, inoculum size of 0.17 (OD730), and ammonium concentration of 10.5 mg L⁻¹), the strain exhibited impressive ammonium removal (95%) and biomass productivity (34 mg L⁻¹d⁻¹). Moreover, analysis of fatty acid methyl esters (FAME) indicated that the predominant fatty acids, including palmitic acid (C16:0), linoleic acid (C18:2 n6 cis), palmitoleic acid (C16:1), and oleic acid (C18:1 n9 cis), constituted over 80% of total fatty acids. This composition highlights the strain's potential for simultaneous water treatment and biomass production for biofuel feedstock (Srimongkol *et al.*, 2019b). A review by Pancha *et al.* (2019) demonstrated that various microalgae cultivated in different wastewaters had lipid contents ranging from 18% to 79% w/w of biomass. Additionally, Chinnasamy *et al.* (2010) found that native algal isolates removed >96% of nutrients from treated wastewater, which contained 85–90% carpet industry effluents and 10–15% municipal sewage. These isolates had a biomass production potential of ~9.2–17.8 tons ha⁻¹ year⁻¹ and a lipid content of 6.82%. Furthermore, approximately 63.9% of algal oil could be converted into biodiesel. Zhu *et al.* (2013) reported that the FAME yield of *C. zoofingiensis* in piggyery wastewater, used for outdoor simultaneous wastewater treatment, was 9.19% of dry weight. Doma *et al.* (2016) demonstrated that the oil content of biomass collected from High-Rate Algal Pond (HRAP) constructed for municipal wastewater treatment was 5%, and the biodiesel yield reached 70.9%. Microalgae have the capability to generate and store significant quantities of carbohydrates, which are valuable for bioethanol production (Maia *et al.*, 2020). Typically, microalgae cultivated in wastewater need preprocessing to break down complex sugars into simpler forms, easily metabolized by fermentative microorganisms (Pancha *et al.*, 2019). In a study by Ellis *et al.* (2012), *Clostridium* spp.

produced 9.74 g L⁻¹ of acetone-butanol-ethanol (ABE) using wastewater algae biomass as a carbon source. Onay (2018) demonstrated that varying concentrations of municipal wastewaters (0%, 30%, 60%, and 100%) resulted in bioethanol yields for *Nannochloropsis gaditana* ranging from 70.3 ± 2.4 mg g biomass⁻¹ to 94.3 ± 5.5 mg g biomass⁻¹, with the highest yield (94.3 ± 5.5 mg g⁻¹ biomass) observed at 30% wastewater concentration. In a recent study, Bhuyar *et al.* (2021) illustrated that cultivating *C. vulgaris* in wastewater effluent from a tilapia culture pond produced biomass at a concentration of 0.376 ± 94.21 mg L⁻¹ after cultivation. Furthermore, this process resulted in the highest ethanol concentration of 33.213 g L⁻¹ after 96 hours of fermentation.

A study conducted by Arora *et al.* (2017) explored a synergistic method that combined arsenic bioremediation with efficient biodiesel production. The study focused on specific microalgae strains, particularly *Chlorella minutissima* and *Scenedesmus* spp., which effectively removed arsenic species (III, V) from synthetic soft water, regardless of their forms. Additionally, these microalgae strains showed a notable increase in lipid production, forming large lipid droplets. The biodiesel derived from these microalgae exhibited favorable characteristics and comparability to methyl esters from plant oils, indicating its suitability as a fuel source. The findings suggest that this approach offers dual advantages: the efficient removal of carcinogenic arsenic from drinking water sources and a high yield of lipid production.

Roles of Microalgae-Based Wastewater Treatment and Bioproducts Recovery

The use of microalgae in biological wastewater treatment (WWT) has emerged as a highly promising technology for the advanced treatment and reclamation of nutrients from wastewater. This method has gained increasing attention in recent years due to its ability to provide a reliable solution for managing liquid or solid waste produced by conventional methods. Additionally, it transforms these wastes into valuable products, offering added benefits. Microalgae, akin to plants, are oxygen-producing photosynthetic microorganisms that are commonly found in various water environments, including freshwater, marine water, and different types of wastewaters. Extensive research has demonstrated that microalgae can effectively absorb nutrients and thrive in wastewaters. Their capability arises from their substantial need for nitrogen and phosphorus, as well as solar energy and either CO₂ or organic substances as sources of carbon. These essential elements are vital for microalgae to synthesize important components like proteins, nucleic acids, and phospholipids, while simultaneously reducing the concentration of these substances in the water (Pires *et al.*, 2013).

Originally, microalgae were introduced in wastewater treatment (WWT) to tackle excessive nutrient levels in secondary effluent and reduce the risk of eutrophication in natural water bodies. However, it's important to recognize

the significant additional value associated with microalgae biomass production during wastewater treatment. The harvested algal biomass can serve as valuable raw material in biorefinery processes and other applications, offering potential economic and environmental advantages (Zhou *et al.*, 2012). Moreover, the symbiotic relationship between microalgae and bacteria involves resource utilization and the exchange of byproducts. Microalgae perform photosynthesis, using CO₂ to produce O₂. Heterotrophic bacteria benefit from the generated oxygen, which they use to assimilate and break down organic carbon, nitrogen, and phosphorus compounds. In return, the aerobic metabolism of bacteria releases CO₂, inorganic nitrogen, and phosphorus, serving as nutrients for microalgae and facilitating their continued photosynthetic activity. Microalgae-bacteria consortia not only efficiently remove contaminants and nutrients but also generate valuable biomass usable in diverse applications. For instance, microalgae cultivated using cattle dairy wastewater have proven beneficial for fertilizing pasture. This application has resulted in increased levels of essential minerals like phosphorus, calcium, magnesium, and manganese, along with higher dry matter content (Lorentz *et al.*, 2020).

Recent research has shown that algae can effectively assist in removing nutrients from wastewater. For example, Cai *et al.* (2019) demonstrated that using algae granules in synthetic wastewater resulted in efficient removal of phosphorus and its subsequent recovery and reuse from the phosphorus-rich algae biomass. Besides their ability to capture CO₂ and eliminate nutrients from wastewater, microalgae have shown potential as a viable energy source. Additionally, microalgae offer a promising method for removing and deactivating harmful microorganisms through various mechanisms, including pH elevation, production of microalgal toxins, and nutrient competition. The process of photosynthesis, vital for microalgal growth, raises pH levels and oxygen concentration in wastewater. Consequently, these changes in pH and dissolved oxygen levels effectively hinder the growth of pathogens in wastewater. In a study by Mezzari *et al.* (2017), it was observed that antibiotic-resistant *Salmonella typhimurium* was suppressed within 48 hours due to the favorable pH and dissolved oxygen levels created by the photosynthetic activity of microalgae.

Composition of Wastewater for Microalgae Cultivation

For over three decades, society, businesses, and governments have been deeply concerned about environmental issues related to biological and chemical water pollution (Crini & Lichtfouse, 2019). Enormous volumes of wastewater are generated, often containing harmful contaminants. This wastewater frequently contains significant amounts of organic and inorganic nutrients, leading to ecological imbalances due to their high biological oxygen demand (BOD) and chemical oxygen demand (COD). Excessive nutrients, especially nitrogen (N) and phosphorus (P), contribute to water eutrophication, a severe global environmental problem

(Yang *et al.*, 2008). Eutrophication leads to concerns such as solid waste and by-product generation, emission of undesirable products into the air, overgrowth of harmful microbes threatening aquatic life, and contamination of groundwater, resulting in widespread health issues in nearby areas where the discharge occurs (Amenorfenyo *et al.*, 2019). Treating wastewater is essential to reduce environmental contaminants (Rasoul-Amini *et al.*, 2014). Wastewater treatment is crucial for ensuring the sustainability of urban environments as it is a fundamental component of the global water cycle. The primary objective of wastewater treatment is the significant removal of contaminants like carbonaceous (organic, primarily measured as biological oxygen demand (BOD)) materials, nitrogen (N), and phosphorus (P) compounds before discharge into receiving systems (Grady *et al.*, 2011; Peter *et al.*, 2021).

The utilization of microalgae in wastewater treatment represents a sustainable approach that has been extensively studied for over 50 years. This method involves the production of valuable chemical compounds such as biofuels and wastewater treatment. Microalgae can efficiently convert carbon dioxide (CO₂) into biofuel products and chemical substances without causing pollution, thereby reducing greenhouse gas emissions. Moreover, these techniques surpass the drawbacks of conventional wastewater treatment, such as high operational costs and the generation of secondary waste from chemical processes (Rasoul-Amini *et al.*, 2014; Srimongkol *et al.*, 2019a; Aketo *et al.*, 2020; Chai *et al.*, 2021). It is crucial to treat various forms of wastewater to minimize environmental pollutants (Rasoul-Amini *et al.*, 2014). The composition of wastewater, influenced by different methods of generation and disposal systems, significantly affects the development of microalgae, the rate of pollutant removal, and the production of various intracellular compounds like carbohydrates, proteins, and lipids. Elements such as carbon source (organic or inorganic), macronutrients, nitrogen, phosphorus, micronutrients, vitamins, and trace elements present in wastewater impact the ability of microalgae to eliminate pollutants and thrive (Ahmad *et al.*, 2022; You *et al.*, 2022). The literature documents the widespread use of wastewater for microalgae production, categorized based on its source, including municipal, agricultural, and industrial wastewater (Chiu *et al.*, 2008; Liu & Hong, 2021).

Municipal Wastewater

Municipal wastewater, originating from homes and public facilities, contains lower levels of nitrogen (N), phosphorus (P), and chemical oxygen demand (COD) than other types of wastewater, making it suitable for microalgae-based processes (Li *et al.*, 2008). Different categories of municipal wastewater, such as raw sewage, primary sewage, secondary sewage, and centrate, have been utilized for microalgae cultivation (Li *et al.*, 2008; Liu and Hong, 2021; You *et al.*, 2022). Studies have explored the growth and purification abilities of microalgae like *C.*

vulgaris and *N. oleoabundans* in various types of municipal wastewater (Al-Momani and Örmeci, 2016). Additionally, *S. obliquus* demonstrated efficient removal of nitrogen and phosphorus from primary and secondary settling tank wastewater, indicating its potential in wastewater treatment (Han *et al.*, 2021). Enhancements in nutrient removal and microalgae growth have been achieved by introducing high concentrations of CO₂ (5-15%) into municipal wastewater (Li *et al.*, 2008; Lima *et al.*, 2020; Liu & Hong, 2021).

Agricultural Wastewater

Agricultural wastewater, arising from crop cultivation, livestock, and agricultural processing, offers a nutrient-rich medium for microalgae cultivation. Although animal manure wastewaters have high nutrient concentrations, they often require dilution to reduce turbidity and ammonia levels, which can inhibit microalgae growth (Chen *et al.*, 2020). Specific strains like *C. sorokiniana* have demonstrated effective removal of TN, TP, and COD in diluted swine wastewater (Chen *et al.*, 2020).

Industrial Wastewater

Industrial wastewater, originating from various sectors like palm oil, textile, and pharmaceutical industries, poses challenges due to diverse contaminants such as heavy metals, antibiotics, and chemicals (Udaiyappan *et al.*, 2017; Goswami *et al.*, 2021; Liu & Hong, 2021). Certain microalgae strains, including *Chlorella* and *Scenedesmus*, have shown promise in treating specific industrial wastewaters, such as those from pulp and paper mills and textile industries (Tao *et al.*, 2017; Wu *et al.*, 2017). Heavy metals, common in industrial wastewater, can be efficiently absorbed by microalgae through processes like biosorption and bioaccumulation, making microalgae a viable solution for heavy metal removal (Kumar *et al.*, 2015; Salam, 2019). Operational factors, including pH, temperature, and initial metal concentrations, influence

the biosorption process (Ayele & Godeto, 2021). However, challenges remain, including the small size and low mechanical strength of microalgae, hindering their separation from the effluent (Salam, 2019).

Roles of Microalgae-Derived Biofertilizer in Sustainable Agriculture

The high demand for food resources has significantly stressed soil, leading to its degradation. This degradation, intensified by climate change impacts like altered precipitation patterns and extreme weather events, results in loss of biodiversity and ecosystem services. Soil degradation involves adverse changes such as reduced fertility, diminished organic matter, and impaired water retention (Gibbs & Salmon, 2015). To counter this, fertilizers play a vital role in agriculture, replenishing depleted nutrients in the soil due to intensive farming. By supplementing essential elements, fertilizers boost crop yields, enhance agricultural productivity, and address the growing global food demand, ensuring food security (Nosheen *et al.* 2021). One of the ways to achieve sustainable agriculture is by the use of microalgae-derive biofertilizer in agricultural production.

Microalgae, encompassing both cyanobacteria and eukaryotic organisms, offer unique advantages in agriculture. They have the potential to enhance soil fertility, promote plant growth, and reduce reliance on chemical fertilizers and pesticides. Utilizing microalgal biomass as biofertilizer enhances soil nutrient cycling, making essential nutrients readily available to plants (see Figure 2 below). When in contact with soil and influenced by factors like moisture, pH, and light, viable microalgae cells become active, capturing atmospheric N₂ and providing crucial macronutrients and micronutrients for plants. Microalgae also produce bioactive compounds such as phytohormones that enhance plant growth and offer protection against pests. Additionally, they contribute to carbon sequestration by capturing CO₂ through photosynthesis. Certain

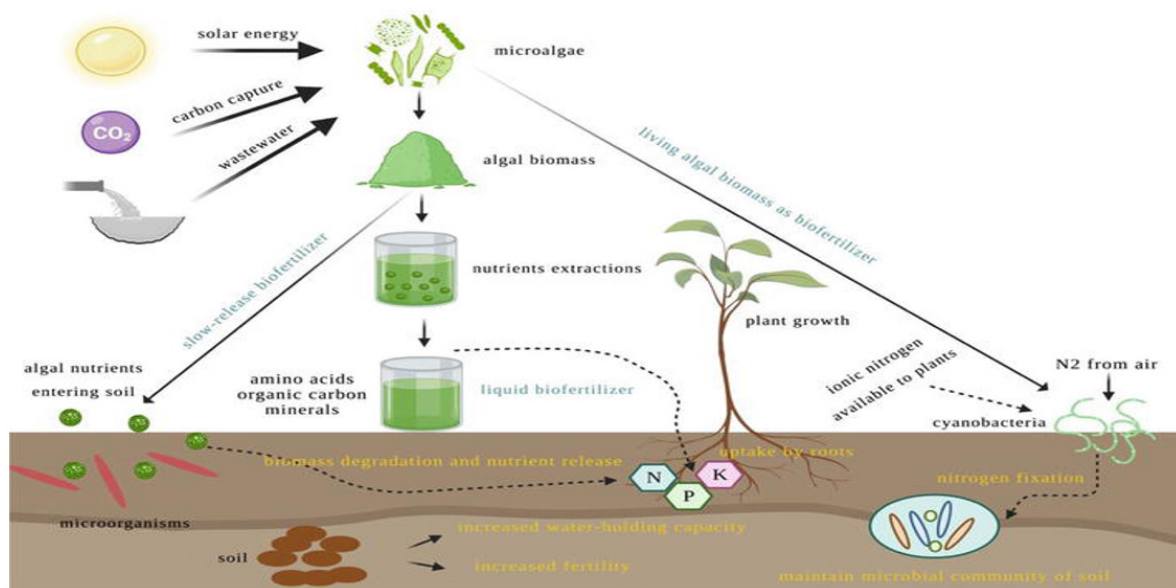


Figure 3: Microalgae-derived biofertilizers on soil and crop growth

Source: adopted from Subeda (2023)

microalgae species produce exopolysaccharides (EPS) that enhance soil structure, improving water retention and aeration (Alvarez *et al.*, 2021).

More so, microalgae can establish an endosymbiotic relationship with plant roots and other existing soil microorganisms. Extensive research on the symbiotic relationship between microalgae and plants was demonstrated in a study using a hydroponic system with *Chlorella vulgaris* and *Mentha spicata*. It was observed that the co-cultivation of microalgae and plants, coupled with aeration, had the most significant influence on the increment in plant weight. This effect was primarily attributed to the improvement of novel shoot and leaf (Özer & Mısmı, 2022). Utilizing microalgae as fertilizer involves direct application of microalgal extracts to soil or through foliar spray, with the latter method demonstrating promising outcomes. Dineshkumar *et al.* (2018) enhanced rice yield by 20.9% using *Spirulina platensis* and *Chlorella vulgaris* biofertilizers. These biofertilizers positively impacted plant height, leaf area, fresh weight, and dry weight, indicating improved crop performance. Although further research is needed, the foliar spray method is gaining popularity due to its efficient nutrient delivery to plants, despite variables like temperature and light. Garcia-Gonzalez and Sommerfeld (2016) used *Acutodesmus dimorphus* microalgal extract as a foliar spray, resulting in increased tomato plant growth, height, and flowering after treatment. Mahmoud *et al.* (2019) investigated the effects of *Chlorella vulgaris* and *Anabaena cylindrica* microalgae strains on *Spinacia oleracea* (spinach plant) growth and their ability to reduce heavy metal accumulation. Microalgae suspensions (1% and 2% dry weight) were applied to soil or as a foliar spray on plants grown in heavy metal-contaminated soil. Microalgae significantly enhanced spinach growth by 21% to 29%, with the most effective treatment being 2% *C. vulgaris* applied to soil. Both microalgae strains increased plant macronutrient uptake, with *A. cylindrica* (1% foliar spray) performing better than *C. vulgaris*. Regardless of strain or application method, microalgae reduced cadmium, lead, and copper accumulation in plants, preventing these contaminants from soil uptake. Additionally, Renuka *et al.* (2016) demonstrated the potential of microalgae cultivated in wastewater as biofertilizer for wheat plants, although not as effectively as commercial microalgal cultures.

One notable benefit of the application of microalgal biofertilizers is the enhancement of physical properties such as soil structure and water retention. This is because, Carillo *et al.* (2020) observed that the utilization of microalgal biofertilizer led to augmented agglomeration of soil particles and increased water-holding capacity. Studies concerning cyanobacteria have highlighted the positive impact of biofertilizer application on both soil structure maintenance and fertility enhancement and subsequent improvements in crop yields (Alvarez *et al.*, 2021).

CONCLUSION

This review paper explores the applications of microalgae and their potential in addressing nature and environmental

issues through reviewing different journal publications. Microalgae are photosynthetic microorganisms that play a vital role in the bioremediation of several types of wastewaters, including removal of N, P, and C, the reduction of BOD, as well as heavy metal removal. They have shown promise in producing biofuels, bioethanol, bioremediation, biofertilizers for agricultural production, and essential molecules like proteins. The integration of microalgae into several types of wastewaters can decrease the cost of wastewater treatment, obtain a lower footprint in terms of energy consumption, and provide environmental sustainability compared to existing conventional wastewater treatment processes. Additionally, microalgae-derived methods can reduce greenhouse gas emissions, alleviating climate-related impacts on biodiversity. It is highly vital to evaluate the environmental effects of large-scale use of microalgae bioenergy if it is to be developed into an alternative energy to reduce fossil fuel consumption. Ongoing research is vital to unleash the full potential of microalgae for a greener and more resilient future.

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