Harnessing the Power of Green Cells: A Fresh Outlook on Microalgae-Based Wastewater Treatment

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Abstract: ***Rapid population growth, urbanization, and industrial expansion have intensified the discharge of organic and inorganic pollutants into aquatic environments, leading to significant water quality deterioration. With the global population projected to reach nine billion by 2050, the need for efficient and scalable wastewater treatment technologies is increasingly urgent. Microalgae-based systems have emerged as a cost-effective and sustainable approach for wastewater remediation Rapid increase in human population, urbanization and industrialization, have resulted in rampant discharge of organic and inorganic pollutants from different sources directly into the surrounding water bodies resulting in their degeneration. This has resulted in people lacking serviceable water which has, for long, served and still is the lifeline of any thriving civilization. By 2050, human population is estimated to increase to nine billion people and in order to provide serviceable water to this number of people, we need to ramp up our remediation efforts in treating wastewater before discharging them in to the water bodies. Among all the processes, algae have stood out and have served as one of the most cost-effective tools in remediating waste water. This review summarizes the capacity of microalgae to remove key contaminants-including nutrients, heavy metals, and coliform bacteria—and highlights their potential as an integral component of future wastewater treatment strategies.***

Keywords: Waste water, Microalgae, Pollutants, Urbanization, Remediation

1. Introduction

Wastewater is defined as water whose quality has been degraded by agricultural, domestic, and industrial activities, as well as surface runoff and sewer inflow (Hammouda et al., 1994). The combined effects of population growth, urbanization, and industrialization continue to generate large volumes of such water, constituting a significant source of environmental pollution (Mouchet, 1986; Lim et al., 2010). Typical municipal wastewater contains organic matter and ammoniacal nitrogen in the range of 25–45 mg/L, along with phosphorus in the order of 4–16 mg/L (Tchobanoglous et al., 2003). The discharge of inadequately treated domestic and municipal wastewater into natural water bodies poses acute ecological and public health risks (Abdel-Raouf et al., 2012).

Consequently, there is growing recognition of the need for robust strategies for wastewater remediation. Despite increasing regulation and improved environmental governance, water resource authorities continue to struggle with both **quantity** and **quality** challenges in fresh water supply (Abdel-Raouf et al., 2012). In this context, microalgal systems have gained renewed attention. Recent studies demonstrate that microalgae can effectively remove excess nitrogen and phosphorus, while simultaneously reducing chemical oxygen demand (COD) and recovering valuable biomass (Sharma et al., 2024)

Different constituents of waste water

There are multiple sources of wastewater, and its strength and volume can differ substantially depending on its origin (Gray, 1989). The chemical makeup of wastewater also reflects the activities in its surrounding environment. It contains a complex mixture of organic compounds — such as carbohydrates, lipids, and proteins — as well as numerous inorganic constituents, including sodium, calcium, potassium, magnesium, chloride, sulfate, phosphate, bicarbonate, ammonium salts, and trace heavy metals (Tebbutt, 1983; Horan, 1990; Lim et al., 2010).

Common sources of wastewater include domestic effluents, industrial discharge, and agricultural runoff (Horan, 1990). As wastewater generation intensifies, freshwater scarcity is becoming a more severe global threat. This growing scarcity underscores the critical importance of treating and recycling wastewater at regular intervals to conserve water resources (De la Nouë & De Pauw, 1988).

In fact, recent literature emphasizes wastewater reuse as a key strategy in sustainable water management. For example, a systematic review by Silva (2023) demonstrates that expanding wastewater reclamation and reuse offers a viable solution for urban water stress by supplementing traditional water supplies (Silva, 2023). Similarly, innovative treatment technologies — such as advanced oxidation, membrane bioreactors, and resource-recovery systems — are being developed to make reuse more efficient and environmentally friendly (Shamshad & Rehman, 2025). Moreover, the circular-economy potential of reclaimed water is explored under new regulatory frameworks, especially in regions striving to balance public health and environmental protection (Berbel, Mesa-Pérez & Simón, 2023).

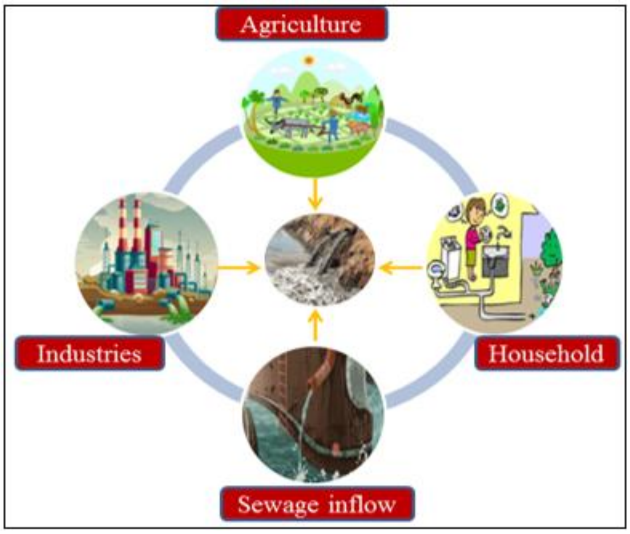

Figure 1: Important contaminants of waste water (After Davies, 2005)The Imperative of Wastewater Remediation

Wastewater requires consistent and adequate treatment, as untreated effluents containing toxic metals, pathogenic microorganisms, and persistent organic pollutants pose serious risks to human and animal health (Akpor et al., 2014). Exposure to such contaminants can result in gastrointestinal infections, dermatological irritations, and long-term health complications due to bioaccumulation of heavy metals. In addition to direct health effects, the discharge of nutrient-rich wastewater into natural water bodies accelerates eutrophication—a process driven by excess nitrogen and phosphorus that promotes uncontrolled algal proliferation (Akpor & Muchie, 2011). This phenomenon leads to oxygen depletion, fish mortality, toxin release, and progressive ecological destabilization.

As noted by Davies (2005), many waterborne diseases of public-health significance can be mitigated through proper wastewater treatment. Modern wastewater treatment aims not only to remove conventional pollutants but also to safeguard ecosystems and enable water reuse. Over the years, physical, chemical, and biological treatment approaches have been developed, including coagulation–flocculation, advanced oxidation, membrane filtration, phytoremediation, and microbial remediation strategies (Rubalcaba, 2007).

Recent advances in wastewater research emphasize sustainable and low-energy processes, particularly in the context of global water scarcity. Biological treatment systems have gained substantial attention, with microalgae emerging as one of the most promising options. Microalgal systems efficiently assimilate nutrients, capture carbon dioxide, degrade organic pollutants, and simultaneously generate biomass that can be used for bioenergy or value-added products. Contemporary studies highlight their superior nutrient removal efficiency compared to many conventional processes (Kumar et al., 2021; Li et al., 2023). Moreover, integrated microalgae-bacteria consortia and photobioreactor-based technologies have demonstrated improved resilience, reduced operational cost, and enhanced contaminant removal under real wastewater conditions (Zhang & Hu, 2022; Patel et al., 2024).

With increasing pressure on freshwater resources and heightened regulatory demands, microalgae-based treatment systems are now regarded as an environmentally sustainable and economically viable alternative for municipal and industrial wastewater management. Their multifunctional potential positions them as a key component of next-generation wastewater treatment technologies.

Micro algae as a tool of remediation

Micro-algae are non-vascular, microscopic, plant-like organisms containing chlorophyll. It includes green algae, brown algae, red algae of eukaryotes along with cyanobacteria of prokaryotes (Richmond, 1986). Microalgae have abundant usefulness in the field of biotechnology, such as, they are used as source of protein and carbohydrate, as aquatic feed, as bio fuel, as biofertilizer, as antioxidants and also in production of medicines etc.(Muhammad, 2019); an environmental biotechnologist uses microalgae in sewage plants to recover nitrogen and phosphorous and reintroduce them through organic fertilizers into nutrient cycle (Borowitzk,1991).

The idea of using microalgae in removing heavy metal from waste water was given by Oswald and Gotaas of U.S. (1957) and since then, many countries have been using it in waste water treatment plants (Goldman, 1979; Shelef and Soeder, 1980; De Pauw and Van Vaerenbergh, 1983). Waste water treatment by algae is called phycoremediation. Microalge have been successfully used in remediation of human sewage (Shelef*et al.*, 1980; Mohamed, 1994; Ibraheem, 1998), livestock wastes (Lin-coln and Hill, 1980), agricultural wastes (Phang and Ong, 1988), industrial wastes (Kaplan *et al.*, 1988) and treatment of agro- industrial wastes (Zaid-iso, 1990; Ma et al., 1990).

Dubey et al. (2011) reported that poultry wastewater can be treated with Oscillatoria and Nostoc sp. A viable treatment solution for oil drilling effluent using microalgae was also envisaged (*Sivasubramanian and Muthukumaran, 2012*). Microalgae-based wastewater treatment technologies are now widely regarded as sustainable and highly efficient because they can target multiple classes of pollutants at once, including nutrients, heavy metals, organic load, and microbial

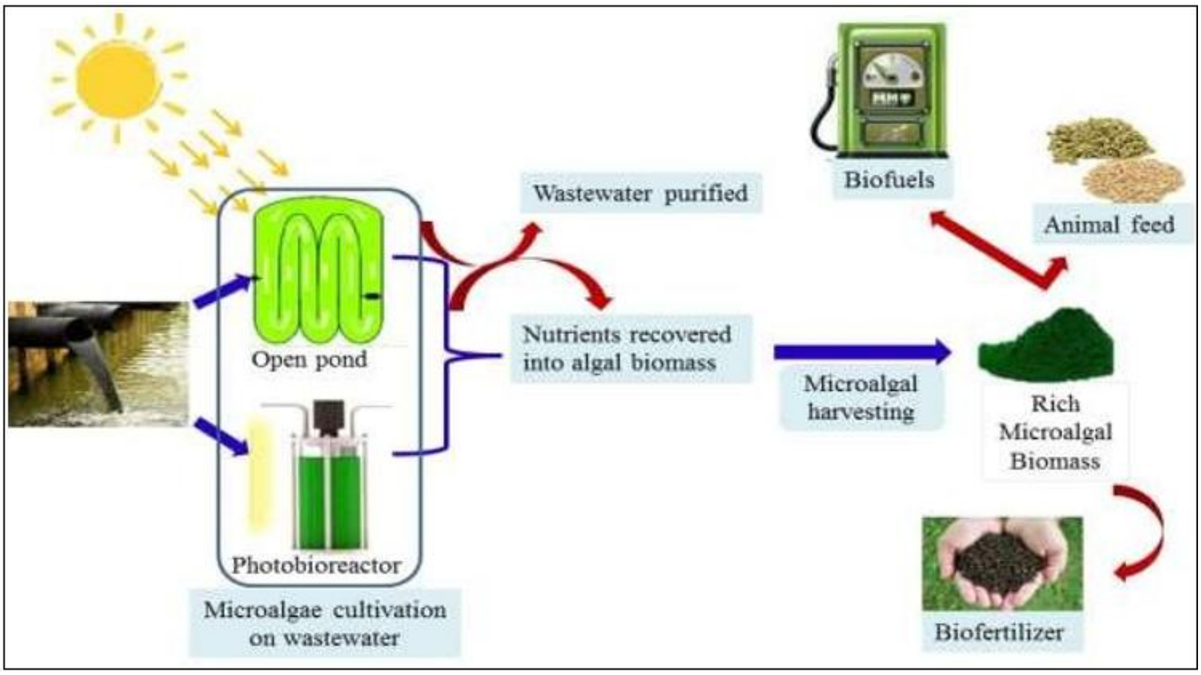

Figure 2: Algae from sewage for different applications

contaminants. Recent research demonstrates that genera such as *Chlorella* and *Scenedesmus* are capable of removing 80–99% of nitrogen and phosphorus when grown under favorable conditions (Rehman et al., 2024; Abdullah et al., 2025).

These microalgae also contribute to substantial decreases in COD and BOD by taking up organic compounds and working in cooperation with bacterial communities (Khan et al., 2023). In addition, their ability to bind and accumulate metals enables significant reductions of contaminants such as Cu, Zn, Cd, Pb, and Cr across various wastewater sources (Singh et al., 2023; Lopez-Serna et al., 2024). Studies further indicate that microalgal systems can eliminate more than 95–99% of coliforms and *E. coli*, largely due to enhanced oxygen production, rises in pH, and secretion of antimicrobial substances (Hernández-Pérez et al., 2024). Another advantage is the generation of microalgal biomass, which can be processed into biofertilizers, biopolymers, and biofuels, supporting circular and sustainable resource-use models (Zhang et al., 2024). Altogether, recent findings highlight microalgae as versatile and eco-friendly agents capable of addressing multiple challenges in modern wastewater treatment.

Microalgae in removing nutrients from waste water

Microalgae are considered as an efficient tool in removing nutrients like nitrogen and phosphorous from waste water. It has been considered as one of the most cost effective method in removing nutrients from waste water (Barrington *et al.*, 2009; Chopin *et al.*, 2012; Bolton *et al.*, 2009; Ridler *et al.*, 2007; Neori *et al.*, 2004). Studies on *Spirulina* by Kosaric *et al*, 1974; *Chlorella* and *Scenedesmus* by Tam and Wong,1989*,* reported that algae are efficient absorbers of phosphorous, nitrogen and heavy metals from wastewater effluents. The organic nitrogen, ammonia and total phosphorous were removed by 90.2%, 84.1% and 85.5 % from distillery waste water with microalgal treatment (Hodaifa*et al.,* 2008). Chen *et al*. (2003) investigated nutrient removal by the integrated use of high rate algal ponds and macrophyte systems in China and found it especially efficient in removing ammonia from waste water. A study by Wang *et al* (2010) showed that green algae *Chlorella* sp. can remove nitrate by 74-82 % and phosphorus by 83- 90%. Dalrymple *et al*. (2013) showed that there are important benefits to be derived from integrating algal production systems with nutrient-rich waste streams. Chlorella vulgaris is reported of removing 95.3% nitrogen and 96% phosphorous from a 25% secondarily treated waste water (Kim *et al*., 1998). Kim *et al.* (2014) demonstrated high removal efficiencies fortotal nitrogen (93%) and total phosphorus (83%) from untreated municipal wastewater in an algae dominated consortium in a High Rate Algal Ponds (HRAP). Rafiq *et al.* (2016) successfully reduced phosphate and total phosphorus (100%), inorganic carbon (99%), total carbon (42%), nitrate (10%), heavy metal Aluminium (41%) of domestic waster using freshwatergreen microalgae *Botryococcus* sp. Some of the most widely used algae in removing nutrients from waste water are *Chlorella* (Gonzales *et al*., 1997), *Scenedesmus* (Martinez *et al*., 2000) and *Spirulina* (Olguın *et al*., 2003).

Microalgae have shown strong potential for nutrient recovery from wastewater, with *Chlorella* species achieving near-complete nitrogen and phosphorus uptake under controlled growth conditions (Liu et al., 2025). Studies using mixed microalgae–bacteria cultures also report high reductions of total nitrogen and phosphate in municipal effluents (Ortega-Blas et al., 2025). Similarly, *Chlorella vulgaris* cultivated in agro-industrial wastewater demonstrated efficient nutrient removal while simultaneously fixing CO_2 (Pattanaik et al., 2024). Together, these findings confirm microalgae as a reliable and sustainable option for nutrient removal in modern wastewater treatment system.

Microalgae in removing heavy metals from waste water

Heavy metal contamination is a serious threat as it affects the existing flora and flora in the environment. As heavy metals are not biodegradable they tend to accumulate in living organisms. So, in order to get rid of heavy metals, there is a need of an unconventional method which is effective and also economical at the same time. The efficiency of microalgae in absorbing algae has been recognized by many workers. They have the ability to absorb heavy metal from their surrounding environment (Megharaja *et al*., 2003). The lead (Pb) absorbing capacity of *Spirulina* is estimated to be 0.62mg Lead per 10^5 alga cells (Prabha *et al*., 2016). Gupta and Rastogi (2008) reported Spirogyra to be very effective in removal of lead (II) from waste water. Gupta *et al.* (2001) and Gupta *et al.* (2006) performed an experiment regarding the chromium (VI) and copper(II) absorbing capacity of *Spirogyra* from wastewater and observed that the maximum chromium absorbing capacity of *Spirogyra* is 14.7 mg kg^{-1} and the maximum copper absorbing capacity of *Spirogyra* is 133.3 mg g^{-1} of dry at an optimum pH 5 in 120 min. Overall, microalgae is considered as a promising candidate in absorbing heavy metals and in degrading xenobiotics (Suresh and Ravishankar 2004) as it has no secondary pollution and has high adsorbing capacity (Dwivedi, 2012).

Microalgae in removing COD and BOD from waste water

Pollution in waste water may contain organic or inorganic compounds along with different microorganisms. The organic compounds contain carbon which gets oxidized both biologically and chemically to release carbon dioxide (Abdel-Raouf *et al*., 2012). When biological oxidation test is used, it is called BOD and when chemical oxidation test is used, it is called as COD. With increase in BOD, the dissolved oxygen content in the water body decreases resulting in death of the aquatic fauna and anaerobiosis (Abdel-Raouf *et al*., 2012). Hence in waste water treatment process, removal of BOD serves the primary purpose. In a domestic waste water treatment using algae, resulted in elimination of BOD by 68.4% and BOD by 67.2% (Colak and Kaya,1988). Mahapatra *et al.* (2013) investigated the treatment efficiencies of the Algae based sewagetreatment plant located in Mysore. The study showed moderate treatment levels with 60% total COD removal, 50 % of filterable COD removal, 82% of total BOD removal, and 70% of filterable BOD removal. Kim *et al.* (2014) demonstrated high removal efficiencies for COD (86%) from untreated municipal wastewater in an algae dominated consortium in a HRAP.

Microalgae in removing coli-forms from waste water

Disinfection of any sewage ponds are generally rated based on the estimation of total numberof coliforms removed from it (Sebastian and Nair, 1984). The coliform removal capacity of 88.8% was achived by Malinaand Yousef (1964) in a stabilization pond. In another report, a removal of 99.6% of coliform was observed (Meron *et al*., 1965).It has been marked that, the growth of coliform is less in an algal growth system (Moawad, 1968) compared to others. Algae increase the pH and dissolved oxygen concentration in high rate algal ponds making the aquatic environment favourable to growth even in presence of Faecal Coliforms (FC) (Ansa *et al.,* 2012).Algae are reported of producing different substances which inactivates the growth of faecal coliforms (Ansa *et al.,* 2012). *Rhizocloniumimplexum*, a fresh water algal species could be considered as effective tool in remediating sewage effluents as it can remove the total coliform and faecal coliform from sewage (Ahmad *et al*., 2014).

2. Conclusion

Overall, traditional wastewater treatment systems that rely on physical and chemical processes contribute noticeably to greenhouse gas emissions, particularly carbon dioxide. In contrast, microalgal treatment systems present a far more sustainable option. Although these systems also release some CO_2, the rapid growth of microalgae allows them to capture and use even greater amounts of carbon dioxide, making the overall process carbon-negative. The success of pollutant removal, however, is closely tied to both the specific algal species employed and the characteristics of the wastewater being treated. With increasing pollution from industrial, agricultural, and domestic sources, there is an urgent need for countries worldwide to invest in microalgal wastewater treatment technologies. This environmentally friendly approach not only reduces contamination but also supports global efforts to lower carbon emissions.

Conflict of Interest: The authors declare no conflict of interest.

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