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Investigating the removal of pollutants from wastewater using microalgae

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ABSTRACT

The application of microalgae in the treatment of wastewater has attracted considerable scholarly interest as a viable and environmentally sustainable alternative. In recent years, numerous combinations of microalgae and bacterial consortia have been investigated to evaluate their efficacy in the remediation of wastewater originating from various sources. The essential criteria for assessing their performance encompass their capacity to eliminate nutrients such as nitrogen and phosphorus, in addition to heavy metals including arsenic, lead, and copper. This study examines the efficiency of microalgae-based systems in treating wastewater, comparing them with traditional treatment methods. It also delves into the characteristics of wastewater, conventional treatment techniques, and the mechanisms used for nutrient and heavy metal removal. Microalgae have demonstrated remarkable potential, achieving removal rates of up to 99.6% for nitrogen, 100% for phosphorus, and 13–100% for heavy metals across various wastewater types. Despite these advantages, microalgae-based treatment systems face certain challenges. Their performance is influenced by factors such as temperature, biomass productivity, osmotic pressure, pH, and oxygen concentration.

1. Introduction

Humanity faces an escalating threat from water-related challenges, driven by population growth, rapid urban development, and the intensifying impacts of climate change [1]. Among these challenges, the proper management of wastewater, generated through agricultural, domestic, and industrial activities, is critical. This wastewater contains a mix of man-made pollutants as well as organic and inorganic chemicals that, if left untreated, can severely damage ecosystems and pose significant health risks to humans [2-4]. Consequently, effective wastewater management has become a global priority to protect water quality and ensure accessibility [5].

Many countries have directed their efforts toward advancing wastewater treatment methods, with a focus on reducing nutrient pollutants such as phosphorus and nitrogen from effluents [6]. Wastewater is rich in organic substances such as fats, proteins, carbohydrates, and amino acids and inorganic materials, including metals and salts like sulfur, chlorine, sodium, and magnesium [7]. It also harbors diverse microbial populations, some of which are non-pathogenic and beneficial for biological treatment. However, pathogenic microorganisms in untreated wastewater can lead to severe waterborne illnesses such as typhoid, cholera, and hepatitis [8]. Discharging untreated wastewater into natural water bodies exacerbates these risks, particularly due to the combination of microbial contaminants, toxic chemicals, and high biochemical oxygen demand [9].

Wastewater treatment plants (WWTPs) play an essential role in mitigating these threats by employing physical, biological, and chemical processes to remove pollutants and reduce pathogen loads. These treatment processes are categorized into primary, secondary, tertiary, and advanced stages, each designed to address specific contaminants [10]. Traditional methods often rely on aerobic and anaerobic systems to neutralize pollutants. However, these approaches are highly energy-intensive and contribute to greenhouse gas emissions, accounting for about 3% of global emissions [11]. They also generate significant quantities of sludge, which must be carefully managed to prevent secondary environmental contamination [12]. Additionally, conventional WWTPs have limited efficacy in removing emerging pollutants like pharmaceuticals, personal care products, and heavy

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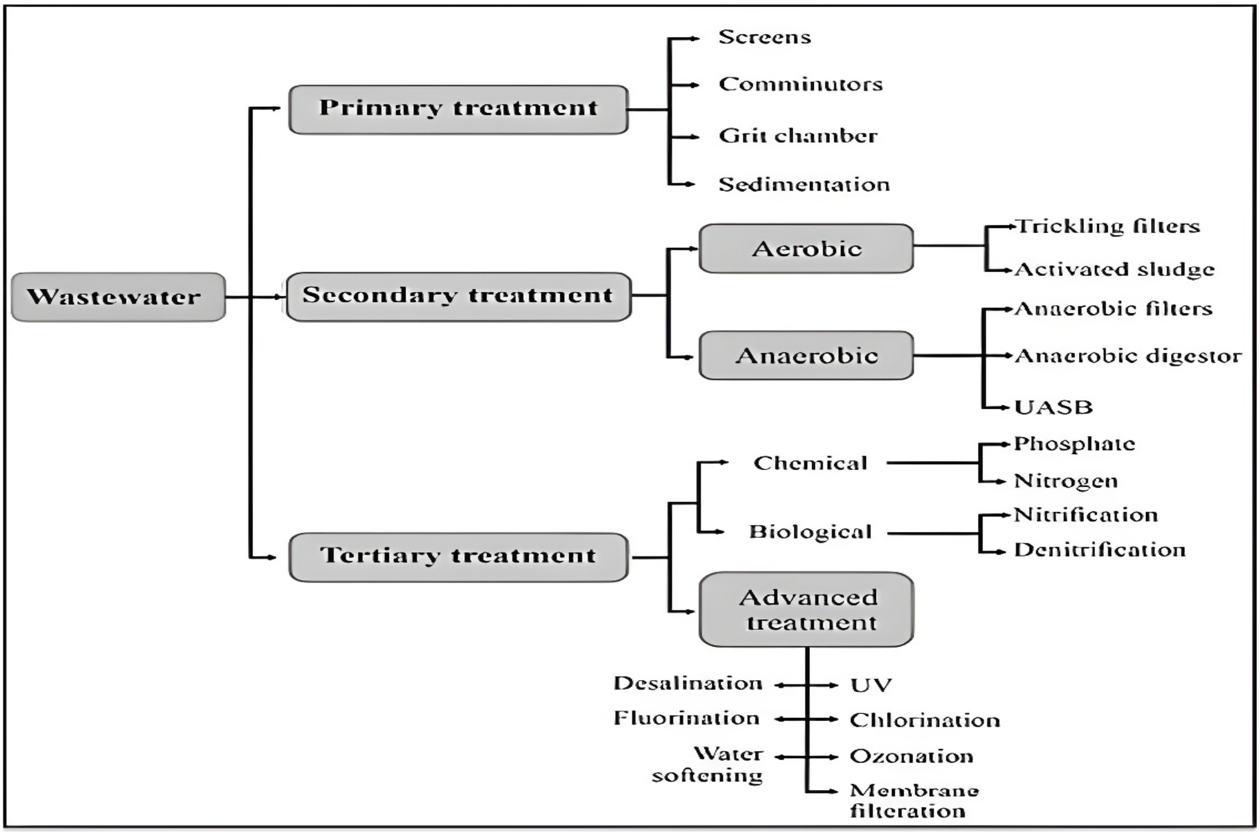

Fig. 1. Various methodologies for the treatment of wastewater [28].

Table 1. Principal attributes of wastewater originating from various sources [5].

Source	BOD mg/L	COD mg/L	pH	TS mg/L	TSS mg/L	VS mg/L	TN mg/L	TP mg/L	EC
heese industry	2.42	2.42	12.08	–	5.07	–	–	–	–
Dairy industry	27.36	50–70	6.0–6.5	55–65	10–15	–	–	–	–
	442	8,960	7.10	797.2	253.6	–	120.1	–	1,082.2
	650–6,250	400–15,200	–	250–2,750	–	–	10–90	–	–
	800–1,000	1,400–2,500	–	1,100–1,600	–	–	–	–	–
	170	1,007.3	4.53	–	299.67	–	–	–	1,091.67
	4,840.6	10,251.2	8.34	–	5,802.6	–	663	153.6	–
Ice cream industry	0.104	0.183	6.23	0.101	–	–	–	–	–
	523.5	11,900	6.25	664.2	264.8	–	88.51	–	794.4
Residential	2.45	5.2	5.2	3.9	3.1	2.6	–	–	–
	250	500	–	700	220	150	40	12	–

metals, further highlighting the need for alternative solutions [13]. One promising alternative is microalgae-based wastewater treatment, which offers a low-cost and environmentally-friendly approach. Microalgae can utilize the organic and inorganic nutrients in wastewater such as nitrogen, phosphorus, and carbon as growth substrates, effectively reducing pollutant levels [14]. This process also facilitates oxygen generation through photosynthesis, which supports the biodegradation of organic materials by bacteria. Unlike conventional methods, microalgae-based systems do not require transitioning between anaerobic, anoxic, and aerobic conditions, significantly simplifying the treatment process and reducing energy consumption [15]. Moreover, microalgae can capture carbon dioxide, recover nutrients, and remove emerging contaminants like heavy metals and pharmaceuticals, making them a versatile and sustainable choice [16,17].

Extensive research has demonstrated the potential of microalgae to treat wastewater effectively under various conditions. Research has demonstrated that green microalgae are capable of eliminating 30% to 70% of pharmaceutical contaminants present in domestic wastewater [18]. This method offers a significant advantage over conventional treatment approaches, primarily due to its reduced energy consumption and lower operational expenses [19]. Despite these advantages, microalgae-based systems face challenges such as scalability, process optimization, and integration into existing wastewater treatment infrastructure. In conclusion, while microalgae-based wastewater treatment offers numerous benefits, including sustainability, cost-effectiveness, and environmental compatibility, further research is needed to optimize these systems and address their limitations.

This study incorporates several innovations that significantly enhance the application of microalgae in wastewater treatment. One of the key innovations is the simultaneous utilization of the biological and physical properties of microalgae to remove nutrients and various pollutants, particularly heavy metals. The research also highlights that microalgae can not only purify wastewater but also produce valuable byproducts such as biomass for biofuels, bioplastics, and other bioproducts. Another innovative aspect is the proposed use of advanced technologies like genetic engineering to enhance the resilience of microalgae to harsh environmental conditions and improve their efficiency in treatment systems. Optimizing photobioreactor designs to maximize light utilization and reduce operational costs represents another novel contribution of this study, facilitating the broader adoption of these technologies on an industrial scale. Finally, emphasizing lifecycle assessment to analyze the environmental and economic impacts of these systems is a key innovation that underscores the environmental sustainability and economic feasibility of microalgae-based technologies.

The selection of literature for this study followed a systematic and structured approach to ensure the inclusion of comprehensive and relevant information.

The primary databases accessed included PubMed, ScienceDirect, Scopus, and Web of Science, chosen for their extensive coverage of peer-reviewed articles in environmental sciences and wastewater treatment. Keywords utilized in the search process included "microalgae biosorption," "heavy metal removal," "wastewater treatment," "nutrient recovery," "bioaccumulation," and "decentralized water treatment systems." Boolean operators (AND, OR) were employed to refine the search and ensure the retrieval of pertinent studies. Titles, abstracts, and keywords were screened initially, followed by detailed reviews of full-text articles to identify those that aligned with the research objectives. This systematic approach facilitated a robust and transparent review process, laying a strong foundation for the study's findings.

2. Characteristics of Wastewater

Wastewater is produced in large quantities daily due to urban expansion, agricultural irrigation, and industrial activities. If left untreated, it poses significant environmental risks. This is primarily caused by the accumulation of excessive pollutants, including emerging contaminants (ECs), nutrients such as nitrogen, phosphorus, and carbon, as well as heavy metals [20,21]. The exact composition of wastewater depends largely on its source, whether agricultural, industrial, or urban, and on local environmental factors such as climate, geographical location, and socio-economic conditions [22-24]. Wastewater typically contains a mix of organic and inorganic materials, chemical substances, suspended solids, and a variety of microorganisms [25]. It also includes essential nutrients like nitrogen, phosphorus, carbon, micronutrients, vitamins, and heavy metals that are vital for microalgal growth [26]. However, certain toxic substances, such as heavy metals and ECs, can inhibit the growth and survival of microalgae [27-29]. In the past, the detailed examination of wastewater composition was often overlooked during the design of treatment systems, largely due to the complexity and challenges associated with the required experimental procedures. Nevertheless, research has identified suspended solids as a crucial factor significantly affecting the performance of treatment processes [30]. The fundamental objective of wastewater treatment facilities (WWTPs) is to strengthen water's innate ability to purify itself by lowering pollutant levels to sustainable thresholds [31]. As illustrated in Figure 1, various wastewater treatment methods, including primary, secondary, and tertiary stages, are comprehensively depicted in a schematic framework. These stages address the removal of suspended solids, reduction of biochemical oxygen demand (BOD), and elimination of specific contaminants such as heavy metals and emerging pollutants. The primary treatment focuses on removing coarse particles and suspended solids, while secondary treatment employs biological processes to reduce organic load and pollution levels [32]. Tertiary treatment enhances the quality of treated water by removing excess nutrients and specific pollutants, making it suitable for discharge or reuse. This figure offers a precise and systematic overview of the processes involved, highlighting their roles in effective wastewater management.

Table 1 provides a summary of the primary characteristics of wastewater from various sources. It compares parameters such as BOD, COD, pH, and nutrient concentrations (e.g., nitrogen and phosphorus) to highlight compositional differences across industrial, municipal, and residential wastewater. For instance, industrial wastewater typically contains higher concentrations of pollutants and nutrients, whereas municipal wastewater exhibits greater compositional variability. The data in Table 1 emphasizes the importance of thorough wastewater analysis to design treatment systems that are optimally suited to specific types of wastewater.

3. Advanced Wastewater Treatment Using Microalgae

The utilization of microalgae for biological treatment (refer to Fig. 2) has garnered heightened scholarly attention as a sustainable and economically viable strategy for addressing the complexities associated with wastewater management [32]. This methodology confers dual advantages: it not only facilitates the treatment of wastewater but also functions as a renewable biomass resource while promoting the bio-fixation of carbon dioxide. Microalgae assimilate both organic and inorganic carbon, as well as nitrogen and phosphorus contained within wastewater, thereby effectively mitigating these pollutants within the effluent. A prominent benefit of incorporating microalgae into wastewater treatment processes is their capacity for photosynthetic oxygen production, which enhances the degradation of organic carbon by heterotrophic bacteria. Furthermore, microalgae possess the aptitude for carbon sequestration and the utilization of nutrients present in wastewater effluents to generate value-added product, such as xenobiotics and nutrients from wastewater, is referred to as phytoremediation [37,38]. Investigative studies have identified numerous microalgal species that exhibit efficacy in this domain, including *Chlorella sorokiniana, Scenedesmus obliquus, Chlorella vulgaris, Chlorella pyrenoidosa*, and *Scenedesmus abundans* [39]. The efficacy of this approach is contingent upon a comprehensive analysis of organic carbon concentrations, particulate solids, nutrient levels, and the physical characteristics of wastewater. Organic compounds are quantified through biochemical oxygen demand, chemical oxygen demand (COD), and total organic carbon (TOC), while particulate solids are assessed via total suspended solids (TSS), total dissolved solids (TDS), and other pertinent metrics. Additionally, nitrogen and phosphorus concentrations, which are primary contributors to eutrophication, are systematically monitored alongside pertinent physical parameters such as pH, temperature, and turbidity.

Mechanisms of Contaminant Removal

Understanding the interaction between microalgae and bacteria is critical for developing microbial consortia that efficiently degrade pollutants. Enhanced wastewater treatment can be achieved by leveraging the synergistic effects of microalgae-bacteria consortia [40]. Microalgae utilize nutrients like nitrogen and phosphorus to produce biomass [41], while simultaneously providing dissolved oxygen that supports bacterial processes, reducing costs and mitigating environmental risks [42]. Conversely, bacteria supply inorganic carbon and secondary metabolites that promote algal growth, further enhancing the treatment process. Various nitrogenous compounds influence microbial diversity and interaction dynamics within algal-bacterial systems, depending on whether wastewater is treated under oxidative or reductive conditions [43]. Nitrogen and phosphorus species in wastewater are categorized as ammonium, nitrate, and phosphate, each requiring tailored treatment approaches. Traditional tertiary treatment methods for urban wastewater include disinfection, reverse osmosis, and electrodialysis [44]. However, pollutant removal efficiency varies with the microalgae strain and wastewater composition. Microalgae, as photosynthetic organisms, convert light and carbon dioxide into biomass. They can grow in open or closed systems, with controlled cultivation environments designed to maximize nutrient removal and biomass production [45]. Microalgae can be cultivated through three primary modes (Fig. 3):

- Photoautotrophic, where they rely on light, water, and inorganic carbon for growth.
- Heterotrophic, which does not require light but utilizes organic carbon sources like glucose.

Mixotrophic, combining organic and inorganic carbon sources in the presence of light [46].

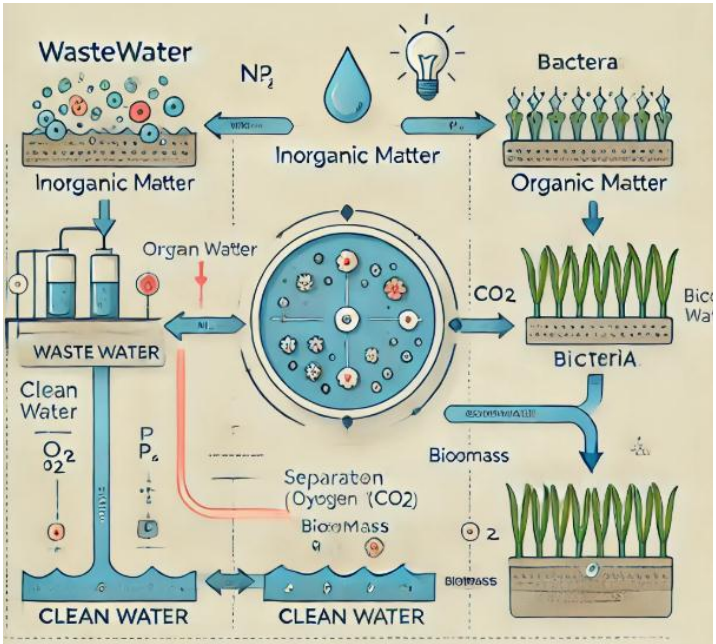

Fig. 2. Schematic representation of the operational workflow regarding the application of microalgae in the remediation of wastewater.

Microalgae-based wastewater treatment relies on a variety of metabolic processes that are integral to the removal of contaminants, particularly nitrogen, phosphorus, and organic carbon. The key metabolic pathways that facilitate pollutant removal in these systems are tied directly to the cultivation mode and environmental conditions. These processes are fundamental to understanding the efficacy of microalgae in wastewater treatment and their potential to contribute to sustainable environmental management [48].

Photosynthesis is the primary metabolic reaction in photoautotrophic microalgae cultivation. During this process, microalgae use light energy to convert inorganic carbon, typically in the form of CO_2, into organic biomass. The reaction also generates oxygen as a by-product, which is essential for aerobic microbial processes, particularly nitrification [49]. The assimilation of CO_2 by microalgae not only reduces carbon dioxide levels in wastewater but also plays a crucial role in nutrient uptake, particularly nitrogen and phosphorus, by algae. This makes photosynthesis a

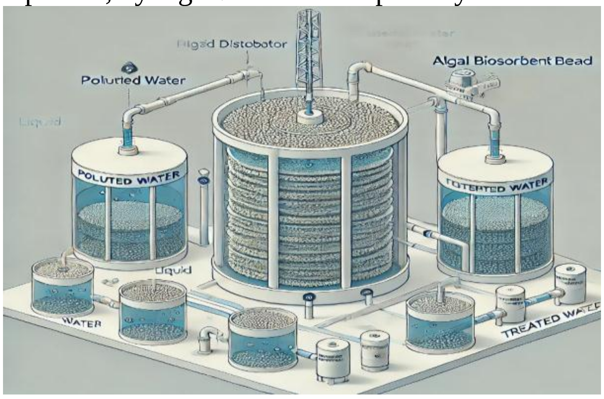

Fig. 3. Utilization of microalgae for the removal of heavy metals from wastewater

central metabolic reaction in the removal of both nitrogen and phosphorus from the water [50]. Nitrogen removal in microalgae systems occurs primarily through two interlinked processes: nitrification and denitrification. In nitrification, ammonium (NH_4^+) is oxidized to nitrite (NO_2^-) and then further to nitrate (NO_3^-) by nitrifying bacteria. The oxygen required for nitrification is provided by microalgae through photosynthesis [51]. This oxygen facilitates the conversion of ammonium to nitrate in aerobic conditions. In the second stage, denitrification occurs in anoxic environments, where denitrifying bacteria reduce nitrate to nitrogen gas (N_2), which is then released into the atmosphere [52]. Microalgae support denitrification by assimilating nitrogen in the form of nitrate, thereby lowering its concentration in the system and assisting the bacteria in the denitrification process. Thus, microalgae play a critical role in both the uptake and reduction of nitrogen compounds [53]. For phosphorus removal, microalgae predominantly absorb phosphate (PO_4^{3-}) from the wastewater. This process occurs when microalgae take up inorganic orthophosphate, which is stored in their cells as polyphosphate. If orthophosphate is not available, microalgae can also utilize organic phosphorus, converting it into the inorganic form for uptake. The ability of microalgae to remove phosphorus from the water by incorporating it into their biomass is significant in preventing eutrophication, which is a major environmental concern in water bodies receiving nutrient-rich effluent [54].

Organic carbon degradation is another vital process in microalgae metabolism, particularly in heterotrophic cultivation. In this mode, microalgae utilize organic carbon sources such as glucose and acetate in the absence of light [55]. The degradation of organic matter helps lower biochemical oxygen demand in the wastewater, improving water quality. This mode is particularly useful in scenarios where light is limited, and organic carbon is available in the wastewater. Heterotrophic cultivation thus provides a complementary metabolic pathway for microalgae to remove pollutants, especially organic contaminants.

Microalgae also engage in carbon fixation, where they absorb CO_2 and convert it into organic molecules, such as sugars and proteins, through photosynthesis [56]. This process reduces CO_2 concentrations in the wastewater, thereby helping in the overall mitigation of carbon emissions. Moreover, carbon fixation supports the uptake of other nutrients like nitrogen and phosphorus, further enhancing nutrient removal from the treated water. This makes the ability of microalgae to fix carbon a crucial aspect of their role in wastewater treatment [57].

In conclusion, the mechanisms involved in microalgae-based wastewater treatment are highly complex and depend on the synergy between algae and bacteria. The interaction between these microorganisms contributes to the effective removal of nutrients and contaminants, transforming the treatment process into a more efficient and sustainable approach. Proper management of growth conditions and understanding the metabolic capabilities of different algae strains are essential for optimizing the treatment efficiency in various wastewater scenarios.

Nutrient Removal by Microalgae

Microalgae efficiently remove nutrients like nitrogen and phosphorus from wastewater, incorporating these compounds into biomass and valuable bio-products. Nitrogen and phosphorus are metabolized into molecules essential for energy storage (e.g., ADP, ATP), amino acids, and genetic materials (DNA, RNA) [60,61]. Photoautotrophic microalgae predominantly utilize dissolved inorganic carbon (CO_2) from bicarbonate-carbonate systems as their carbon source [62,63]. Under heterotrophic conditions, organic carbon sources such as glucose and acetate are metabolized more frequently [64]. In photoautotrophic growth, the Calvin-Benson-Bassham (CBB) cycle is activated, with Rubisco facilitating CO_2 fixation [65,66]. Conversely, in heterotrophic growth, glucose metabolism begins with the phosphorylation of hexose sugars, resulting in glucose-6-phosphate, followed by either the Embden-Meyerhof (EMP) pathway or the Pentose Phosphate (PP) pathway, depending on light availability [67]. The assimilation of acetate involves its conversion to acetyl-CoA through acetylation, with subsequent oxidation occurring via the tricarboxylic acid (TCA) or glyoxylate cycles [68]. Mixed microalgae-bacteria cultures have demonstrated remarkable efficiency in nutrient removal. For example, studies revealed that raising the temperature from 15°C to 25°C increased phosphate and nitrogen removal rates from 72% to 83% and 100%, respectively [67]. Interestingly, organic carbon supplementation was deemed unnecessary for such processes, highlighting the feasibility of secondary effluent treatment using these mixed cultures. Nitrogen removal primarily involves nitrification and denitrification. Ammonia-oxidizing and nitrite-oxidizing bacteria facilitate nitrification under aerobic conditions, converting ammonia to nitrate. Denitrification occurs under anoxic conditions, reducing nitrate to nitrogen gas [68]. Incorporating microalgae into these systems reduces aeration requirements by providing oxygen for nitrification, thereby improving overall energy efficiency.

Heavy Metal Removal Using Microalgae

Microalgae are also capable of binding and removing heavy metals from wastewater, attributed to the strong affinity of their cell walls for metal ions. Typical heavy metals found in wastewater include zinc, nickel, arsenic, mercury, copper, cadmium, lead, chromium, and manganese [69]. However, exposure to these metals triggers the generation of reactive oxygen species (ROS), leading to oxidative stress that negatively impacts cellular function and results in the depletion of photosynthetic pigments [70]. Microalgal heavy metal remediation occurs via mechanisms such as biosorption (non-metabolic binding of metals by dead biomass) and bioaccumulation (metabolic uptake by living cells) [55]. Biosorption involves physical adsorption, ion exchange, and complexation, while bioaccumulation depends on active transport processes. Various environmental factors, including pH, temperature, and metal concentration, influence the efficiency of these processes [70]. Additionally, biosorption and bioaccumulation rely on the functional groups present on algal cell walls, such as carboxyl and phosphate groups, which interact with metal ions. Precipitation of insoluble metals and intracellular accumulation further aid in detoxification. Research has shown that species like *Chlorella vulgaris* and *Chlorella salina* effectively reduce heavy metal concentrations and other pollutants, achieving removal efficiencies of 13.61–100% under optimized conditions [24]. To maximize heavy metal removal, factors such as algal species, functional group modifications, and environmental parameters must be carefully optimized. The integration of microalgae into wastewater treatment systems not only enhances heavy metal removal but also contributes to nutrient recovery and biomass production, aligning with sustainable waste management practices.

Efficiency of Contaminant Removal from Wastewater

The efficiency of microalgae in removing contaminants from wastewater depends on a variety of environmental, biological, and operational factors. Extensive research has been conducted to optimize these factors and develop advanced wastewater treatment technologies. One notable study investigated the potential of using a combination of microalgae and bacteria to reduce excess nutrients and organic matter in sewage-polluted lake water. This research compared the performance of a symbiotic co-culture of bacteria and microalgae with that of traditional activated sludge cultures. The results revealed that the co-culture system achieved higher removal rates for nutrients and organic matter. Specifically, the system demonstrated nitrate and phosphate removal efficiencies of 93% and 99%, respectively, along with a chemical oxygen demand removal rate of 73%. Additionally, this setup produced the highest biomass yield of 7.8 g/L [71]. Further evidence of the efficacy of microalgae-bacteria symbiosis was provided by a study involving *Pseudomonas putida* and *Chlorella vulgaris*. This research demonstrated that the mixed culture could achieve 80% removal efficiency for ammonium and COD within just four days. The mutualistic interaction between bacterial oxidative degradation and microalgae photosynthesis played a critical role in these results, emphasizing the advantages of integrating these two systems [72]. A comparative study of *Chlorella vulgaris* and *Chlorella salina* highlighted the differences in their wastewater treatment capabilities. Over ten days, both species effectively reduced levels of biochemical oxygen demand, total dissolved solids, COD, pH, ammonia, phosphate, nitrate, heavy metals, and coliform bacteria. However, *C. vulgaris*, a freshwater species, demonstrated higher efficiency in most parameters, achieving heavy metal removal rates ranging from 13.61% to 100%, depending on the type of metal [73]. Another study explored the role of nutrient availability in the removal of nitrogen and phosphorus from wastewater. *Chlorella vulgaris* exhibited the ability to absorb either nitrogen or phosphorus even under conditions of nutrient limitation. However, native microorganisms in wastewater and pH variations significantly influenced nutrient removal efficiency. For instance, when isolated, *C. vulgaris* cultures increased the pH of the growth medium, which, while promoting nutrient precipitation, could hinder algal growth and nutrient uptake efficiency [77].

Carbon dioxide addition is another factor influencing the efficiency of microalgae-based wastewater treatment. A study investigating *Spirulina platensis* and mixed algal cultures demonstrated that adding CO_2 not only optimized pH levels but also enhanced nitrate and phosphate removal efficiencies to 99.6% and 99.41%, respectively. These results underscore the potential of integrating carbon capture with wastewater treatment [78]. The design of photobioreactors (PBRs) plays a crucial role in optimizing the performance of microalgae. One experiment used a PBR inoculated with a mixed microalgae consortium dominated by cyanobacteria, achieving sustained nutrient removal for over 200 days. Cyanobacteria's dominance facilitated efficient nutrient uptake and biomass production under controlled conditions [79]. Seasonal factors and operational parameters, such as high-rate algal pond (HRAP) depth, have also been shown to influence treatment efficiency. Increasing pond depth improved areal productivity and nutrient removal during certain seasons but also reduced nitrogen and phosphorus removal during extended dark cycles, emphasizing the need for season-specific operational strategies [80,81]. As highlighted in Table 2, the table presents a collection of pivotal studies focusing on the removal of contaminants from wastewater using microalgae. These studies evaluate the efficiency of various microalgal species and their cultivation methods across diverse environmental contexts. The primary objective of these investigations is to determine the removal rates of specific contaminants such as nitrate (NO_3), ammonia (NH_3), phosphate (PO_4), and heavy metals.

Conducted in different aqueous matrices, including domestic, industrial, and surface wastewater, these studies employ diverse techniques to enhance removal efficiency. For instance, utilizing species like *Chlorella vulgaris* and *Scenedesmus obliquus* under laboratory conditions mimicking natural environments has led to significant reductions in nutrients and heavy metals. Furthermore, some studies have optimized performance using methodologies such as central composite design (CCD) and response surface methodology (RSM).

Noteworthy findings include the high efficacy of bacterial-algal symbiosis systems, demonstrating that combining these organisms can achieve superior removal of both organic and inorganic pollutants. Additionally, mixed cultures, such as *Chlorella vulgaris* and *Chlorella salina*, have shown varying results depending on the type of contaminant, underscoring the necessity for detailed analyses to determine optimal methods.

These findings not only emphasize the potential of microalgae in wastewater management but also highlight the need for broader and more precise research to refine technologies and industrial applications.

4. Challenges in Using Microalgae for Wastewater Treatment

Despite its promising potential, microalgae-based wastewater treatment faces several challenges that hinder its large-scale implementation. These challenges are categorized into economic, biological, and operational aspects.

Economic Challenges

One of the primary barriers to widespread adoption is the high operational cost associated with microalgae cultivation. Energy-intensive processes, such as aeration, CO_2 injection, and harvesting, contribute to the financial burden. For example, energy consumption in microalgae-based treatment systems can reach up to 323 kWh per kilogram of treated biomass, which is significantly higher than conventional methods. Cost-reduction strategies, such as optimizing aeration rates and exploring alternative energy sources, are critical to enhancing feasibility [80,81]. The land requirement for constructing HRAPs further adds to the capital costs. Land scarcity and the environmental impacts of land-use changes, such as soil depletion and greenhouse gas emissions, must be carefully managed to ensure sustainability. Advanced life-cycle assessment studies have highlighted these concerns and proposed mitigation strategies [82].

Harvesting microalgae poses another economic challenge due to the small size and low sedimentation rates of algal cells. Conventional harvesting methods, including centrifugation and filtration, are energy-intensive. Emerging techniques like bio-flocculation and magnetic separation have shown the potential to reduce costs but require further optimization for large-scale applications [83,84].

Biological Challenges

Biological constraints, such as the composition of wastewater, can significantly affect the efficiency of microalgae. High levels of COD, toxic substances, or extreme pH conditions can inhibit algal growth. Additionally, turbidity in wastewater reduces light penetration, limiting photosynthesis and biomass productivity. Pre-treatment processes, such as filtration and flocculation, are often necessary to enhance microalgae performance [85]. Genetic engineering offers a potential solution to overcome these biological limitations. Genetically modified microalgae have been developed to tolerate harsh conditions, including high salinity, heavy metal concentrations, and low light availability. However, concerns regarding biosafety and regulatory approval remain significant obstacles to their deployment [86,87]. Moreover, the complex interactions between microalgae and native microbial communities in wastewater can lead to unpredictable outcomes. Understanding these interactions through advanced modeling and real-time monitoring systems is critical for improving process stability and efficiency.

Table 2. Main surveyed studies were conducted for removing contaminants from wastewater using microalgae.

Water type	Main tasks	Algae	Methods	Target contaminants	Efficiency of removal			Outcomes	Ref.
					N	P	Heavy metals		
Sewage contaminated lake	Minimize surplus nutrients and high organic content from polluted lake water with sewage using bacteria and microalgae in activated sludge form.	*Symbiotic co-culture of microalgae*	Central composite design (CCD) using response surface methodology (RSM); plate streak method	NO_3 and PO_4	93 %	99 %	–	Co-culture of bacteria and microalgae were more effective in removing organic and nutrient substances.	[74]
Sewage water, seawater, and freshwater	Reduce toxic contaminants from different water using freshwater and marine algae.	*Chlorella vulgaris* *Chlorella salina*	Inoculation with algae cell culture; artificial illumination; aeration; culture flask; MPN method; SPSS	NO_3, NH_3, PO_4, Zn, Cu, Mn, Ni, Co, Fe, Cr	59.99–75.00% 62.00–73.03%	87.14–90.08 and 76.97–82.48%	13.61–100%	Phycoremediation can be used to recycle and reuse different mixtures of water samples. Under the given parameters, C. vulgaris had higher removal efficiency than C. salina.	[75]
Greywater	An assessment was performed on a modified algal biofilm reactor (ABR) for high production of biomass and its ability to treat wastewater using wastewater samples of variable strength followed by a build-up of specialized bio-products.	*Consortia of Chlorella and Phormidium sp.*	Algal biofilm reactor, fixed natural sunlight	NO_3 and PO_4	94 %	90 %	–	The ABR, in comparison to the suspended culture system, showed a higher nutrients removal rate and higher biomass production under undiluted high strength wastewater.	[52]
Synthetic wastewater	Find out nutrient availability's influence on C. vulgaris' potential in removing phosphorus and nitrogen from wastewater and the possibility of using it as a biofuel feedstock.	*Chlorella vulgaris*	Agar slants; Bristol media; artificial illumination; standard method of TSS	NO_3 and PO_4	81%	–	–	C. vulgaris has the capacity to persist in a varying range of conditions that are nutrient-limiting.	[12]
Synthetic municipal wastewater	Investigating the combination of P. putida and C. vulgaris as a possible candidate of symbiotic mixed culture in removing nutrients and organic pollutants at the same time.	*Chlorella vulgaris and Pseudomonas putida co-culture system*	Bubble- column photobioreactor; single reactor system; continuous illumination with the fluorescent lamp; no aeration; Neubauer hemocytometer counting	NO_3 and PO_4	80 %	60 %	–	Co-culture system that constitutes P. putida and C. vulgaris has the potential of being a mixed culture scheme for cleaning wastewater of organic carbon and nutrients in wastewater treatment with the use of a single reactor. An important element for maintaining the activity of nutrient removal is alkalinity.	[37]
Municipal wastewater	An assessment was performed on the effect of temperature and photoperiod on biomass productivity and nitrogen and phosphorus removal.	*Native microalgae-bacteria consortium*	Batch culture; continuous illumination with fluorescent lamps; Bristol medium	NO_3 and PO_4	72%–83 %	100 %	–	The depletion rates of nitrogen and phosphate were high. An organic carbon supply was not required by the system for this process.	[41]
Water from WTTP	Using S. platensis and a	*Spirulina platensis*	Culture system; daylight	NO_3 and PO_4	99.6 %	99.41 %	–	Mixed algae have a higher	[66]

	dioxide and treating wastewater.							and organic matter, and have a higher rate of bio-fixation compared to *Spirulina platensis.*	
Sewage treatment plant wastewater; slaughterhouse wastewater; dairy processing industry	Exploring the phycoremediation potential of eleven cultures of algae in different types of wastewater.	*Chlorella vulgaris* *C. pyrenoidosa* *C. minutissima* *Spirulinasp.*	Procured and isolated culture; blooming process; BG11 media (HIMEDIA); shaking condition	NO_3 , NH_3 and PO_4	32.1 %, 88.5 %, 95.0 %	100 %, 84.8 %,99.3	–	For effective wastewater treatment, it is indispensable to have the presence of specific solutions. It is important to use native microalgal community over microalgal species that are axenic.	[76]
Pond	Find out the relationship between depth and microalgal performance in wastewater treatment HRAPs.	*Mucidosphaerium pulchellum*	HRAP; supplementary carbon; aeration	NH_3 and PO_4	63.6 %	33.8 %	–	As the depth increased, the overall areal productivity increased, thus forming a directly proportional relationship between these two figures.	[19]
Municipal wastewater	Find out if a settable algal-bacterial culture that is cultivated from wastewater can be utilized in treating municipal wastewater.	*Algal-bacteria consortium*	Stirred tank photobioreactor	NO_3 and PO_4	88.3 %	64.8 %	–	The algal-bacterial culture was successful in treating wastewater and showed good settle ability. Blue-green algae that is filamentous was the main algae species in the bioreactor.	[41]
Freshwater	Investigate the joint impacts of Cu(II) and 17β-estradiol (E2) on the growth of microalgae and biological and chemical characteristics.	*Scenedesmus dimorphus*	Green algae are exposed to various Cu(II) and E2 concentrations; fluorescence; high-performance liquid chromatography (HPLC)	Cu (II)	–	–	76.6 %	*S. dimorphus* has the potential to effectively remove Cu(II).	[28]
Municipal wastewater	Find out the influence of photoperiod on a consortium of bacteria and algae to minimize the organic nutrients in municipal wastewater using a lab-scale bioreactor.	*Algal-bacterium consortium*	Photobioreactors; batch process; plate-count method; aeration; artificial illumination	NO_3 and PO_4	35–88 %	43–89 %	–	Photoperiod condition has a significant effect on the production of microbial biomass, adjusting nutrient removal, and fluctuating algal-bacterial population dynamics.	[70]

Operational Challenges

Operational factors, including photobioreactor design, mixing strategies, and CO_2 delivery, also influence the overall efficiency of microalgae systems. Poorly designed systems can result in inadequate light distribution, CO_2 losses, and inefficient nutrient uptake. Recent advancements in PBR technology, such as vertical column reactors and flat-panel systems, have improved light utilization and mass transfer rates, but further research is needed to optimize these designs for large-scale operations [88]. Addressing these challenges through innovative research and sustainable practices is essential for realizing the full potential of microalgae-based wastewater treatment technologies.

5. Conclusion and Future Directions

This study has clearly demonstrated that integrating microalgae into wastewater treatment systems offers significant potential for pollution reduction and the generation of valuable biomass. The findings reveal that microalgae are highly effective in removing nitrogen and phosphorus from wastewater while simultaneously producing biomass that can be utilized for various biological applications. This dual functionality positions microalgae as a promising alternative to traditional, cost-intensive wastewater treatment methods. However, the results also indicate that to fully exploit this technology, optimizing system conditions and designing scalable solutions for industrial applications remain critical challenges. Based on the findings of this study, the following recommendations are proposed to enhance the performance of microalgae-based systems and guide future research:

- **Wastewater Composition:** A comprehensive analysis of wastewater composition before designing and implementing treatment systems is essential. Tailored solutions can significantly improve nutrient removal efficiency.
- **Pre-Treatment Methods:** Implementing advanced pre-treatment techniques, such as UV radiation, filtration, and autoclaving, can improve microalgae cultivation in wastewater environments.
- **Genetic Engineering:** Genetic modifications to enhance microalgae's tolerance to harsh environmental conditions should be explored. Understanding algal physiology through transgenesis could improve bioremediation systems and increase the efficiency of wastewater treatment.
- **Pilot Studies:** Conducting pilot-scale experiments under real-world conditions can effectively address complexities such as nutrient fluctuations, light limitations, and microalgae-bacteria interactions.
- **Reactor Design Optimization:** Improving photobioreactor designs to optimize light utilization, mixing efficiency, and CO_2 delivery while reducing costs is crucial.
- **Microalgae-Bacteria Consortia:** Investigating the interactions between microalgae and bacteria in hybrid cultivation systems can improve nutrient removal, enhance biomass yield, and provide insights into microbial interactions.
- **Lifecycle Assessment (LCA):** Performing LCAs is necessary to assess the environmental impacts and sustainability of microalgae-based wastewater treatment systems. These evaluations will provide critical data for comparing energy consumption, economic viability, and environmental benefits.
- **Heavy Metal and Contaminant Removal:** Research should focus on the removal efficiency of specific contaminants, including heavy metals, at various stages of microalgae-based wastewater treatment. Identifying potential toxic by-products for improved safety and efficiency is essential.
- **Economic Viability:** Developing innovative biomass technologies for generating energy or high-value products, such as biofuels and bioplastics, could enhance the economic sustainability of the system.
- **Policy Support:** Advocating for policy-driven initiatives to strengthen collaborations between research institutions and industries can accelerate the development and deployment of innovative wastewater treatment solutions.

In conclusion, while the potential of microalgae in wastewater treatment is considerable, achieving industrial-scale implementation requires overcoming both technical and economic challenges. By integrating advanced research, innovative technologies, and supportive policies, this approach can significantly contribute to global efforts for sustainable water management and environmental conservation.

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