

Overview of the Role of Microalgae in Wastewater Management: Challenges and Opportunities.

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ABSTRACT

Microalgae-based wastewater treatment has emerged as a sustainable approach to addressing global water pollution challenges while simultaneously producing valuable biomass. This method is based mainly on the natural nutrient uptake capabilities of microalgae to remove nitrogen, phosphorus, organic pollutants, and heavy metals from various wastewater sources, including municipal, industrial, and agricultural effluents. Scientific studies and successful implementations across different regions, such as High Rate Algal Ponds in New Zealand and microalgal systems in China and the United States, demonstrate high nutrient removal efficiencies, often exceeding 90%. The treated biomass can be used in diverse ways, including biofuel production, animal feed, and fertilizers. However, several challenges such as nutrient imbalances, variability in wastewater composition, light limitations, contamination risks, and high harvesting costs, hinder widespread adoption. Technological innovations such as advanced photobioreactors, integrated treatment systems, and genetic engineering are critical for overcoming these barriers and improving the system. Public awareness and policy support will essentially facilitate broader implementation of microalgae-based systems as well as continued innovation and collaborative efforts among researchers, industry, and policymakers. Microalgae wastewater treatment holds significant promise for advancing environmental sustainability, resource recovery, and rural development on a global scale. Future research priorities includes; optimizing operational parameters, developing cost-effective harvesting techniques and conducting comprehensive life cycle assessments to evaluate environmental and economic impacts.

Keywords: Microalgae, Wastewater treatment and water pollution.

INTRODUCTION

Water pollution caused by untreated or inadequately treated wastewater poses significant threat to environmental and public health worldwide. The rapid growth of urbanization, industrialization, and agricultural activities has escalated the volume and complexity of wastewater, increasing the load of nutrients, organic matter, pathogens, and emerging contaminants such as pharmaceuticals and personal care products in water bodies. Excess nitrogen (N) and phosphorus (P) from wastewater effluents contribute to eutrophication, resulting in harmful algal blooms, hypoxia, loss of aquatic biodiversity, and deterioration of water quality. Traditional wastewater treatment methods, primarily designed to reduce organic matter and suspended solids, face limitations in efficiently removing these nutrients and novel contaminants. The activated sludge process, a cornerstone of secondary treatment, although effective in biochemical oxygen demand (BOD) reduction, often requires high energy input for aeration and generates large volumes of sludge that demand further management. Moreover, emerging contaminants are typically not fully degraded by conventional processes, raising concerns over chronic environmental and health effects.

Given these challenges, there is an urgent need for sustainable, cost-effective, and environmentally friendly wastewater treatment technologies. Microalgae-based wastewater treatment systems have emerged as promising alternatives, leveraging the natural capacity of microalgae to assimilate nutrients directly from

wastewater streams while producing oxygen through photosynthesis. This approach not only offers enhanced nutrient removal efficiency but simultaneously generates valuable algal biomass that can be utilized for biofuel production, animal feed, and fertilizer, thus contributing to a circular economy. The integration of microalgal treatment with existing processes could potentially lower the carbon footprint of wastewater management and provide resilience against emerging contaminants. This paper presents a comprehensive review of microalgae's role in wastewater treatment, exploring biological mechanisms, synergistic microbial interactions, current implementations, challenges and future directions as a sustainable wastewater management strategy.

Conventional Wastewater Treatment Strategies

Wastewater treatment is a critical process in modern society, aimed at removing contaminants from water used in various domestic, industrial and agricultural applications. As urbanization and industrial activities increase, the volume and complexity of wastewater generated have also escalated, necessitating the development of effective treatment strategies.

Historically, wastewater treatment dates back to ancient civilizations, the Romans, Craggs, Heubeck, *et. al.*, (2011). However, modern wastewater treatment began to take shape during the 19th century due to the need to address public health crises caused by waterborne diseases. By the early 20th century, the activated sludge system was introduced which marked a significant advancement in wastewater treatment technology and laid the foundation for many traditional methods still in use today, Ferrero, Godos, *et. al.*, (2012).

Wastewater treatment is typically organized into four sequential stages; preliminary, primary, secondary, and tertiary treatments, each designed to remove different pollutant fractions and prepare the effluent for safe discharge or reuse.

Preliminary Treatment

This stage which is the first step in wastewater treatment process prevents damage to downstream equipment and reduces the load of suspended solids, with the aim of removing large solids and debris that could damage equipment or hinder subsequent treatment processes. The major advantage of the preliminary treatment is that it offers protection to the equipment and ensures efficiency of subsequent treatment stages. However, while its effective in removing large solids, this method does not address dissolved or colloidal contaminants, Hernández, Riaño, *et. al.*, (2013).

Primary Treatment

Primarily focuses on sedimentation and clarification to separate organic and inorganic solids that can settle down from wastewater. Large sedimentation tanks or primary clarifiers allow solids to settle, forming primary sludge, while lighter materials such as oil and grease float and are skimmed off. This stage can remove approximately 30–40% of suspended solids and biochemical oxygen demand (BOD). The major advantages of Primary treatment are its relative simplicity and cost-effectiveness. It performs a significant role in treatment of waste water by reducing the organic load and suspended solids, making it easier for subsequent treatment processes to function effectively, but only removes about 30-50% of the organic matter and does not effectively eliminate pathogens, dissolved pollutants or nutrients which can lead to environmental issues if discharged untreated, which is a major challenge of the system, Christenson and Sims, (2011).

Secondary Treatment

Secondary treatment employs biological processes to degrade dissolved and colloidal organic matter remaining after primary treatment. The activated sludge process is the most widespread technology, where microorganisms metabolize organic pollutants under aerobic conditions. This stage achieves significant reductions in BOD, suspended solids, and certain nutrients. Other biological methods include trickling filters, rotating biological contactors, and lagoons. The challenging issue with the trickling filter is that they may require larger land areas and can be less effective in removing nutrients compared to activated sludge processes, Craggs, *et. al.* (2011). However, standard secondary treatment is often insufficient for complete nitrogen and phosphorus removal, necessitating additional processes.

Tertiary Treatment

Tertiary treatment is an advanced stage of wastewater treatment that targets the removal of residual nutrients, pathogens, and emerging contaminants to meet stringent discharge or reuse standards. Techniques include chemical precipitation for phosphorus removal, nitrification-denitrification for nitrogen removal, filtration, disinfection (chlorination or UV irradiation), and adsorption or advanced oxidation processes for micro pollutants. Disinfection is crucial for ensuring that treated wastewater is safe for discharge or reuse and significantly improves water quality, making it suitable for discharge into sensitive environments or for reuse applications, however, it has the disadvantage of being costly and may require additional infrastructure and operational expertise, Kim, Ramanan, *et. al.*, (2014). Chlorination on the other hand can produce harmful disinfection by-products, while UV treatment requires energy and may not be effective against all pathogens, Ferrero, *et. al.* (2012). Although effective, tertiary treatments notably increase operational complexity and cost.

Conventional wastewater treatment methods offer several advantages such as; proven effectiveness, simplicity and scalability. Despite their proven performance, conventional treatment methods have limitations. High energy consumption, especially for aeration in secondary treatment, contributes to significant operational costs and greenhouse gas emissions. Additionally, sludge production requires environmentally sound disposal or further processing, adding to the overall treatment footprint. The incomplete removal of nutrients frequently results in eutrophication downstream, resulting in harmful algal blooms, oxygen depletion, and loss of aquatic biodiversity. The World Health Organization (WHO) emphasizes the importance of effective pathogen removal in wastewater treatment to protect human health and the environment (WHO, 2006), which is not properly achieved in conventional waste water treatment. Emerging contaminants, including pharmaceuticals, personal care products, and industrial chemicals, are increasingly detected in wastewater and pose challenges for conventional treatment methods. And are often resistant to standard treatment processes, Daughton and Ternes, (1999). The need for advanced treatment technologies capable of removing these substances is becoming increasingly urgent. All these underscore the need for integrated, sustainable solutions that can reduce pollutant loads.

As the demand for sustainable wastewater management practices continues to grow, there is a need to integrate traditional methods with innovative technologies and approaches, Woertz, Feffer, *et. al.*, (2009). Microalgae based treatment systems offer an alternative or complementary approach, capable of simultaneously removing nutrients while producing biomass, thus addressing several shortcomings of traditional approaches.

Current Wastewater Treatment Strategies

Current wastewater treatment strategies encompass a wide range of methods, from conventional processes to advanced technologies and emerging practices. Each approach has its advantages and challenges, and the choice of treatment strategy depends on various factors; characteristics of the wastewater, regulatory requirements, and economic considerations.

An overview of current wastewater treatment strategies, highlighting their effectiveness, challenges and future prospects are considered in tables 1 and 2.

Advanced Wastewater Treatment Technologies

Table1: Various advanced wastewater treatment technologies and their pros and cons.

Treatment Type	Pros	Cons
1. Membrane Bioreactors (MBRs)	MBRs utilize membranes to separate treated water from biomass, allowing higher concentrations of microorganisms and improved treatment efficiency (Hernández et al., 2013). They produce high-quality effluent with low Total Suspended Solids (TSS) and Biological Oxygen Demand (BOD), making them suitable for water reuse applications.	Expensive to operate and maintain (Woertz et al., 2009).
2. Constructed Wetlands	Engineered systems that mimic natural wetlands to treat wastewater using vegetation, soil, and microbial processes to remove contaminants. They are low-cost, environmentally friendly, and provide additional benefits such as habitat creation.	Require significant land area and may be less effective in cold climates.
3. Anaerobic	A biological process that breaks down organic matter in the	Requires careful

Digestion	absence of oxygen, producing biogas (methane) as a by-product. It reduces sludge volume and generates renewable energy.	management of temperature and retention time; quality of biogas can vary.
4. Advanced Oxidation Processes (AOPs)	AOPs involve the generation of highly reactive species (e.g., hydroxyl radicals) to degrade organic pollutants in wastewater. Common methods include ozonization, Fenton’s reagent, and photocatalysis (Kim et al., 2014). They effectively remove recalcitrant compounds and pathogens.	Energy-intensive and may require additional treatment steps to remove by-products.

Table2: Different types of emerging wastewater treatment practices and their pros and cons.

Treatment Type	Pros	Cons
1. Resource Recovery	Focuses on extracting valuable materials from wastewater such as nutrients, energy, and water. Uses technologies like struvite precipitation for phosphorus recovery and anaerobic digestion for biogas production. This approach promotes sustainability and reduces the environmental impact of wastewater treatment.	Implementing resource recovery technologies can be complex and may require changes to existing treatment processes.
2. Decentralized Treatment Systems	Small-scale wastewater treatment solutions such as composting toilets, constructed wetlands, and small-scale anaerobic digesters. These systems can be implemented at the point of generation, such as rural areas or individual households.	Can negatively impact the environment if not properly handled or professionally managed.
3. Smart Water Management	Involves the use of technology and data analytics to optimize wastewater treatment processes through real-time monitoring of water quality, automated control systems, and predictive modeling.	Requires investment in infrastructure and personnel training (Lee et al., 2013; Woertz et al., 2009).

As the demand for clean water continues to grow, the development and implementation of innovative wastewater treatment solutions will be essential for ensuring environmental sustainability and resource efficiency.

Microalgal biology and growth requirements

Microalgae employed in wastewater treatment systems belong to distinct taxonomic groups with diverse physiological traits that influence nutrient removal efficiency, environmental tolerance, and operational feasibility. The most relevant groups include cyanobacteria, green algae (Chlorophyta), diatoms (Bacillariophyta), and red algae (Rhodophyta).

Cyanobacteria are prokaryotic, photosynthetic microorganisms capable of rapid growth under alkaline and nutrient-rich conditions. Certain genera (e.g., *Anabaena*, *Spirulina*) possess nitrogen-fixing capability, enabling effective nitrogen removal even under nitrogen-limited conditions. Cyanobacteria generally tolerate high pH (8.5–11.0), light intensities of 100–300 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$, and temperatures between 25 and 40 °C, making them suitable for high-strength or alkaline wastewaters. However, the potential production of cyanotoxins and surface scum formation represents a significant operational and public health concern, limiting their application in municipal systems, Craggs, et al., (2013).

Green Algae (Chlorophyta) are the most extensively studied group for wastewater treatment applications. Species such as *Chlorella* and *Scenedesmus* demonstrate high assimilation rates for both nitrogen and phosphorus and maintain stable performance under fluctuating wastewater conditions. Optimal growth typically occurs at pH 6.5–8.5, light intensities of 80–250 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$, and temperatures of 20–35 °C. Their non-toxicity and high biomass productivity make them particularly attractive for integrated wastewater treatment and resource recovery systems. Nonetheless, small cell size can complicate biomass harvesting, and elevated free ammonia concentrations (>200 mg L⁻¹ NH₄⁺) may inhibit growth, Markou & Georgakakis (2011).

Diatoms (Bacillariophyta) are eukaryotic microalgae characterized by silica-based cell walls, which enhance settling properties and facilitate biomass separation. They are particularly effective in tertiary treatment or effluent polishing, showing strong uptake of phosphorus and moderate nitrogen removal. Diatoms perform optimally at pH 7.0–8.5, light intensities of 50–200 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$, and temperatures ranging from 15 to 30 °C. However, their reliance on dissolved silica (typically 5–30 mg L^{-1}) and relatively slower growth rates limit their suitability for untreated or high-strength wastewater streams.

Red Algae (Rhodophyta) are less commonly applied in wastewater treatment due to slow growth and limited nutrient removal capacity. Certain extremophilic species (e.g., *Galdieria sulphuraria*) exhibit tolerance to acidic environments (pH 2.0–6.5), low light intensities (30–150 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$), and temperatures up to 42 °C, enabling niche applications in acidic or industrial effluents. Their use is generally restricted to controlled photobioreactor systems, where high-value bioproduct recovery rather than bulk wastewater treatment is the primary objective, Park, et. al., (2011).

Overall, green algae remain the most suitable group for municipal wastewater treatment due to balanced nutrient removal, robustness, and safety. Cyanobacteria may be advantageous in alkaline or ammonia-rich systems but require careful management due to toxicity risks. Diatoms are best suited for polishing stages, while red algae are applicable only in specialized conditions. Selection of the appropriate algal group should consider wastewater characteristics, climatic conditions, and downstream biomass utilization strategies.

The Role of Microalgae in Wastewater Treatment

Some of the roles that microalgae can play in a wastewater treatment system includes;

1. Pathogen Reduction

Microalgal treatment systems promote pathogen removal through multiple mechanisms. The photosynthetic activity increases dissolved oxygen and raises pH to alkaline levels (>9), creating hostile conditions for pathogenic bacteria and viruses. Elevated oxygen concentrations produce oxidative stress detrimental to fecal coliforms and other pathogens. Microalgae also compete for nutrients, limiting pathogen proliferation, and some species produce antimicrobial compounds that inhibit microbial growth. Furthermore, suspended microalgal biomass facilitates adhesion and sedimentation of pathogens, physically removing them from the water column.

2. Removal of Emerging Contaminants

Recent research has highlighted the potential of microalgae to remove emerging contaminants from wastewater. Microalgae can absorb and metabolize various organic pollutants, including pharmaceuticals and personal care products, thereby reducing their concentrations in treated water (Khan, 2015). This capability positions microalgae as a viable option for addressing the challenges posed by emerging contaminants in wastewater treatment.

3. Sustainability and Cost-Effectiveness

Microalgae can grow in a variety of conditions, including wastewater with high nutrient loads, reducing the need for additional fertilizers (Zhang et al., 2010). Microalgae-mediated treatment is energy-efficient, relying primarily on sunlight and requiring minimal external inputs, contrasting sharply with energy-intensive aeration in conventional systems. This biology-driven approach reduces greenhouse gas emissions by fixing carbon dioxide during photosynthesis. When integrated with other treatment technologies such as anaerobic digestion, microalgal systems further enhance energy recovery and nutrient recycling. The potential for biomass recovery and conversion into valuable products also contributes to the economic viability of microalgal-based treatment systems.

4. Nutrient Removal and Recovery

Microalgae have a remarkable ability to assimilate nutrients from wastewater, particularly nitrogen and

phosphorus. Nitrogen is taken up mainly as ammonium (NH_4^+) or nitrate (NO_3^-) ions and incorporated into amino acids and proteins via enzymatic pathways. Phosphorus is absorbed as phosphate ions (PO_4^{3-}) and utilized in nucleic acids, ATP, and membrane phospholipids, (Gonzalez-Bashan et al., 2000). Additionally, microalgae can precipitate phosphorus chemically by altering pH, aiding removal via calcium phosphate formation. The growth of microalgae in nutrient-rich wastewater not only helps to mitigate eutrophication but also allows for the recovery of valuable resources. The biomass production thus effectively sequesters these nutrients, simultaneously reducing their concentrations in water.

5. Pollutant Degradation.

Beyond nutrient assimilation, microalgae degrade various organic pollutants including metals, pesticides, dyes, and pharmaceuticals through metabolic and photo degradation pathways. Their high surface-to-volume ratios facilitate bio sorption of toxic heavy metals such as lead, cadmium, and mercury, which they accumulate in cellular components, removing them from wastewater. For instance, studies have shown that *Chlorella vulgaris* can accumulate significant amounts of cadmium and lead, making it a potential candidate for bioremediation (Kumar et al., 2015). Through photo synthetically generated reactive oxygen species (ROS), microalgae contribute to the breakdown of complex organic molecules, enhancing treatment efficacy.

Successful implementations of microalgae in various wastewater treatment systems: Case studies and applications

Microalgae-based wastewater treatment has been successfully implemented across diverse geographic regions and industrial sectors, demonstrating its viability as an effective environmental management solution. Some of these examples are;

1. High Rate Algal Ponds (HRAPs) in New Zealand

High Rate Algal Ponds (HRAPs) have been successfully implemented in New Zealand for the treatment of municipal wastewater. These systems utilize microalgae to absorb nutrients such as nitrogen and phosphorus while simultaneously producing biomass. The HRAPs have demonstrated significant nutrient removal efficiencies, with studies reporting up to 90% removal of total nitrogen and phosphorus. The biomass produced can be harvested for biofuel production, thus providing a dual benefit of wastewater treatment and renewable energy generation, Craggs, Heubeck, Lundquist and Benemann, (2011).

2. Integrated Algal-Bacterial Systems in Spain

An integrated algal-bacterial system was developed in Spain to treat agro-industrial wastewater. This system combined microalgae with bacteria to enhance nutrient removal and biomass production. The results showed that the system effectively removed over 80% of nitrogen and phosphorus from the wastewater. The microalgae also contributed to the reduction of organic matter, while the bacteria aided in the degradation of complex pollutants. This implementation highlighted the synergistic relationship between microalgae and bacteria in improving treatment efficiency, Hernández, *et. al.* (2013).

3. Photo-bioreactors in Germany

In Germany, photo-bioreactors have been utilized for the treatment of wastewater from the food industry. These systems leverage the growth of microalgae in controlled environments to optimize nutrient uptake and biomass production. The implementation of photo-bioreactors resulted in a significant reduction of organic pollutants and nutrients, achieving removal rates of over 90%. The biomass produced was subsequently used for biogas production, demonstrating the potential for energy recovery from wastewater treatment, Ferrero, *et. al.* (2012).

4. Wastewater Treatment in China

In China, advanced photobioreactor systems have been piloted for industrial wastewater treatment. For example, microalgae species such as *Chlorella* and *Scenedesmus* have been cultivated in closed

photobioreactors receiving tannery and aquaculture effluents. These reactors optimize light penetration and enable controlled environmental conditions, leading to rapid nutrient assimilation and high biomass productivity. Reported results include up to 95% removal of chemical oxygen demand (COD), total nitrogen, and total phosphorus within short hydraulic retention times, coupled with recovery of biomass rich in lipids suitable for biofuel production. The biomass harvested from the system was used for animal feed, showcasing the potential for resource recovery from wastewater treatment, Kim, Ramanan, Cho, Oh and Kim, (2014).

5. Algal Turf Scrubber in the United States

The Algal Turf Scrubber (ATS) technology has been successfully implemented in various locations in the United States for the treatment of nutrient-rich wastewater. This system utilizes a shallow flow of wastewater over a substrate where microalgae can grow. The ATS has shown remarkable efficiency in removing nutrients, achieving up to 95% removal of nitrogen and phosphorus. The harvested algal biomass can be used for various applications, including biofuels and fertilizers, thus providing a sustainable solution for wastewater management, Benemann, (2013).

These examples of successful implementations of microalgae in wastewater treatment systems across various regions highlight their potential as a sustainable solution for nutrient removal and biomass production. These demonstrate the versatility of microalgae in different wastewater contexts, contributing to environmental sustainability and resource recovery. As research and technology continue to advance, the integration of microalgae in wastewater treatment systems is likely to expand, offering innovative solutions to global water challenges.

Limitations of Microalgal Wastewater Treatment

Despite the promising potential of microalgae for wastewater treatment, several challenges and limitations must be addressed before their widespread implementation can be realized. Some of the limitations that can affect its efficiency and practicality and detailed analysis of the challenges faced in the implementation of this technology are;

1. Nutrient Imbalance

The variability in nutrient composition found in different types of wastewater is the primary limitations of microalgal wastewater treatment. Wastewater from different sources can have significantly different concentrations of nitrogen, phosphorus, and other essential nutrients. This variability can lead to nutrient imbalances that may not support optimal algal growth. For instance, high concentrations of certain nutrients can inhibit algal growth or lead to competition with bacteria for resources, as noted in studies linking nutrient conditions to algal growth phases, Craggs, *et. al.* (2011). Example, the high concentrations of nitrogen can lead to proliferation of certain algal species while inhibiting others, resulting in a less diverse and potentially less resilient algal community, Craggs, *et. al.* (2011). Furthermore, the competition for nutrients between microalgae and bacteria can complicate the treatment process, as bacteria may outcompete algae for limited resources, particularly in nutrient-rich environments, Ferrero, *et. al.* (2012).

2. Light Limitation

Photosynthesis is the primary driver of microalgal growth; thus, adequate light penetration is essential. However, wastewater—particularly livestock wastewater—often contains suspended solids and turbidity that reduce light transmission, inhibiting microalgal productivity, (Ferrero, Godos, Rodríguez, García-Encina, Muñoz and Bécars, 2012). Ensuring optimal light exposure in turbid wastewaters is an ongoing operational challenge requiring system design innovations such as improved mixing, light distribution, and possibly prefiltration.

3. Contamination and Competition

Treatment systems such as open pond systems are susceptible to contamination by unwanted microorganisms, which can outcompete microalgae for nutrients and light. This issue can lead to reduced treatment efficiency

and biomass yield. The presence of other microorganisms, such as bacteria and protozoa, in wastewater can lead to competition with microalgae, potentially reducing the effectiveness of the treatment process. While some bacteria can be beneficial to algal growth by providing essential nutrients or promoting flocculation, others can inhibit algal growth through competition or by producing allelopathic compounds, Craggs, *et. al.* (2011). The dynamics of these interactions can be complex and some studies have shown that shifts in community composition can lead to competitive interactions that hinder algal growth, Craggs, *et. al.* (2011). For example, studies have shown that changes in nutrient conditions can alter the balance from mutualistic to competitive interactions, negatively impacting algal productivity, Ferrero, *et. al.* (2012).

4. Harvesting and processing challenges

Harvesting microalgal biomass from wastewater is another significant challenge that can affect the overall efficiency and economic viability of microalgal wastewater treatment systems as harvesting microalgal biomass from wastewater can be costly and technically challenging. The harvesting of microalgal biomass can be challenging due to the small size and low density of algal cells. Techniques such as centrifugation, flocculation, and filtration can be employed to separate algal biomass from the liquid medium; however, these methods can increase operational costs which can offset the benefits of using microalgae for wastewater treatment particularly in large-scale applications, Kim, *et. al.* (2014).

5. Variable Performance

The performance of microalgal wastewater treatment systems can be inconsistent due to fluctuations in wastewater characteristics, environmental conditions, and algal species used. Variability in influent quality, such as changes in nutrient concentrations or the presence of toxic compounds, can lead to unpredictable treatment outcomes Hernández, *et. al.* (2013). Furthermore, the growth rates of microalgae can be influenced by environmental factors such as light, temperature, and pH, which can vary over time. This variability can complicate the design and operation of treatment systems, making it challenging to achieve consistent performance.

6. Regulatory and Economic Constraints

Regulatory hurdles and public perception issues can also pose challenges to the implementation of microalgal wastewater treatment systems particularly in regions where water quality standards and regulations regarding the use of wastewater for algal cultivation are stringent, Kim, *et. al.* (2014). Absence of clear regulatory frameworks and standards for microalgae-treated wastewater and derived biomass products limits market acceptance. Economic viability depends heavily on integration with biomass valorization, technological advancements to reduce capital and operating costs, and supportive policy measures. The costs associated with infrastructure, operation and maintenance can be high and the market for algal products may not always justify these expenses, Woertz, *et. al.*, (2009).

7. Limitations of Cultivation Facilities

Open systems such as raceway ponds and waste stabilization ponds are cost-effective and scalable but suffer from low light utilization efficiency, large land requirements, evaporative losses, CO₂ diffusion to the atmosphere, and susceptibility to contamination from predators and competing microorganisms. Closed photobioreactors provide superior environmental control and higher productivity but involve significantly higher capital and operational costs, limiting their economic feasibility for wastewater treatment applications. Currently, there is a lack of economical, efficient, and practical cultivation systems specifically designed for microalgae-based wastewater treatment, signaling a critical area for technological innovation.

In summary, while microalgae-based wastewater treatment holds considerable promise, these biological, technical, economic, and regulatory challenges must be overcome through multidisciplinary research, engineering innovation, and policy support to enable scalable and sustainable applications.

Future Perspectives in Microalgae Use for Wastewater Treatment

The advancing field of microalgal wastewater treatment holds transformative potential for sustainable water management, resource recovery, and environmental protection. Several technological, biological, and systemic innovations are shaping its future trajectory. As research continues to advance, the applications of microalgae are likely to expand, contributing to environmental sustainability and resource efficiency. Key areas of development include;

Genetic Engineering and Strain Development

Genetic modification tools like CRISPR-Cas9 offer the capacity to produce microalgal strains with enhanced growth rates, nutrient uptake efficiencies, and tolerance to environmental stresses. Engineered strains can be tailored for specific wastewater matrices and target pollutants, greatly expanding the scope of microalgal applications. Developing robust microalgal strains that can thrive in fluctuating conditions is essential for the success of this technology, Ferrero et al., (2012). Additionally, synthetic biology approaches aim to introduce new metabolic pathways for the biodegradation of emerging contaminants like pharmaceuticals and microplastics, addressing current limited removal efficiencies.

Nutrient Removal Mechanisms

Recent studies have explored the use of different microalgal species for nutrient removal and has shown that they exhibit varying efficiencies in nutrient removal. For instance, species like *Chlorella vulgaris*, *Scenedesmus obliquus* and *Spirulina* have demonstrated high nutrient uptake rates under various conditions, Taita et al., (2019). Additionally, the use of mixed microalgal cultures has been investigated to enhance nutrient removal rates and improve resilience against environmental fluctuations. Understanding the specific nutrient requirements and growth dynamics of different microalgal species is essential for optimizing wastewater treatment processes, Hernández et al., (2013).

Optimized Cultivation Systems

The development of hybrid cultivation systems combining open ponds, photobioreactors, and bioreactors promises to balance scalability, cost, and control. Innovative designs such as flat-panel, tubular, and membrane-encapsulated bioreactors improve light utilization, minimize contamination risks, and reduce spatial footprint. Solar-driven or waste-heat-powered systems could further enhance energy efficiency, making mass production of microalgal biomass economically feasible at a larger scale.

Integration with Circular Economy and Resource Recovery

The integration of microalgal systems with waste-to-resource platforms—such as anaerobic digestion for biogas, nutrient recovery via struvite precipitation, and bio-oil extraction—aligns with global sustainability goals. Harvested microalgal biomass can serve as feedstock for biofuels, bioplastics, pharmaceuticals, and nutraceuticals, creating value chains that offset treatment costs and provide additional revenue streams. Additionally, coupling with greywater reuse and desalination plants can expand applications in water-scarce regions.

Policy Support and Market Development

Increasing environmental regulations and incentives for green technologies propel the adoption of microalgae based wastewater treatment. Investment in pilot projects, subsidy programs, and favorable policies can accelerate commercial deployment. Public awareness campaigns emphasizing ecological benefits and resource sustainability can foster acceptance and market penetration.

Research and Development Priorities

Future research should prioritize sustainable harvesting techniques, lifecycle assessment of integrated systems, techno-economic analyses, and scale-up demonstrations. Additionally, multi-omics approaches, including

genomics, transcriptomics, and metabolomics, will deepen the understanding of microbial communities and facilitate the design of robust, high-performing consortia.

In conclusion, the future of microalgae in wastewater treatment is promising, contingent upon technological innovations, supportive policies, and interdisciplinary collaborations. Harnessing these developments can lead to cost-effective, environmentally friendly, and resource-efficient wastewater management systems capable of addressing global water challenges.

CONCLUSION

Microalgal wastewater treatment represents a promising and sustainable approach to addressing the growing challenges of water pollution and wastewater management. Ongoing research is focused on optimizing nutrient removal mechanisms, enhancing biomass production and integrating microalgae into existing treatment systems. Through technological innovations, genetic engineering, integration with other systems, and the development of value-added products, microalgae can play a pivotal role in creating sustainable wastewater treatment solutions. While challenges remain, the potential benefits of microalgal wastewater treatment, including resource recovery and environmental protection, make it a vital area of research for the future. As research and development continue to progress, the implementation of microalgae-based systems has the potential to revolutionize wastewater management, contributing to environmental sustainability and economic growth.

Future research directions should also focus on the scalability of microalgal wastewater treatment systems, while laboratory-scale studies have shown promising results, scaling up microalgae-based systems for industrial applications presents challenges. Pilot-scale studies are needed to evaluate the performance of microalgal systems in real-world wastewater treatment conditions at larger scales. These studies can provide valuable data on operational parameters, treatment efficiencies, and economic feasibility. Additionally, life cycle assessments can help determine the environmental and economic impacts of microalgal wastewater treatment compared to traditional methods, Cho *et al.*, (2015). Continued innovation and collaboration among researchers, industry stakeholders, and policymakers will be essential to advance this field and realize the full potential of microalgae in wastewater treatment. The future of wastewater treatment may lie in harnessing the power of microalgae, paving the way for a cleaner and more sustainable world.

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