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Grand Challenge

Grand Challenges in Application of Microalgae for Nutrient Recovery

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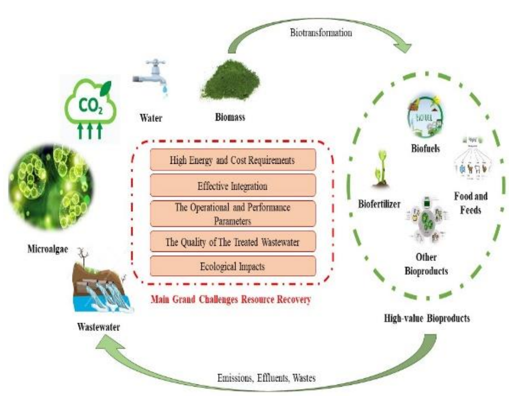
ABSTRACT

Microalgae-based wastewater treatment systems have emerged as a promising solution for the treatment of wastewater due to their potential to provide a sustainable and cost-effective solution. Studies have demonstrated that these systems can achieve high removal efficiencies for nutrients and organic pollutants, with microalgae capable of removing up to 99% of nitrogen and 100% of phosphorus from wastewater. However, there are several grand challenges associated with the implementation and scalability of these systems. These challenges include the need for more efficient microalgae cultivation and harvesting methods, effective wastewater pre-treatment and post-treatment methods, strategies to minimize the impact of microalgae-based treatment on natural water bodies, and the integration of these systems with existing infrastructure. Addressing these challenges will require continued research and development efforts, as well as collaborations among stakeholders from various sectors. By overcoming these challenges, microalgae-based wastewater treatment systems can play an important role in addressing the growing need for sustainable and cost-effective wastewater treatment solutions, while providing additional benefits such as the production of biofuels and other value-added products. This paper highlights the main grand challenges associated with microalgae-based wastewater treatment and provides an overview of the current status of research in addressing these challenges. The paper also presents some suggestions for future research to overcome these challenges and promote the implementation and scalability of microalgae-based wastewater treatment systems.

KEYWORDS: Microalgae, Wastewater Treatment, Nutrient Recovery, Grand Challenge.

GRAPHICAL ABSTRACT



HIGHLIGHTS

- Enhanced microalgae cultivation and harvesting methods.
- Advanced wastewater pre-treatment technologies.
- Post-treatment for nutrient removal and disinfection.
- Environmental impact assessment and mitigation strategies.
- Integration and scalability of microalgae systems.

1. Introduction

1.1. Microalgae for wastewater treatment

Microalgae-based wastewater treatment is an emerging technology that utilizes photosynthetic microorganisms to remove pollutants from wastewater (Abdelfattah et al., 2022). This approach has gained attention due to its potential to provide an energy-efficient and sustainable solution to the

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increasing global demand for wastewater treatment (Kabir et al., 2022). Microalgae can effectively remove nutrients (e.g., Nitrogen, Phosphorus, Carbon, etc.), organic compounds (e.g., Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Phenols, etc.), heavy metals, and emerging contaminants (e.g., Pharmaceuticals, Microplastics, etc.) from wastewater, while also offering the potential for bioenergy production and carbon capture (Kishor et al., 2021) As such, microalgae-based wastewater treatment represents a promising alternative to conventional treatment methods, which can be energy-intensive and costly (Ahmed et al., 2022). Figure 1 demonstrates the timeline of progress and milestones for microalgae-based wastewater treatment.

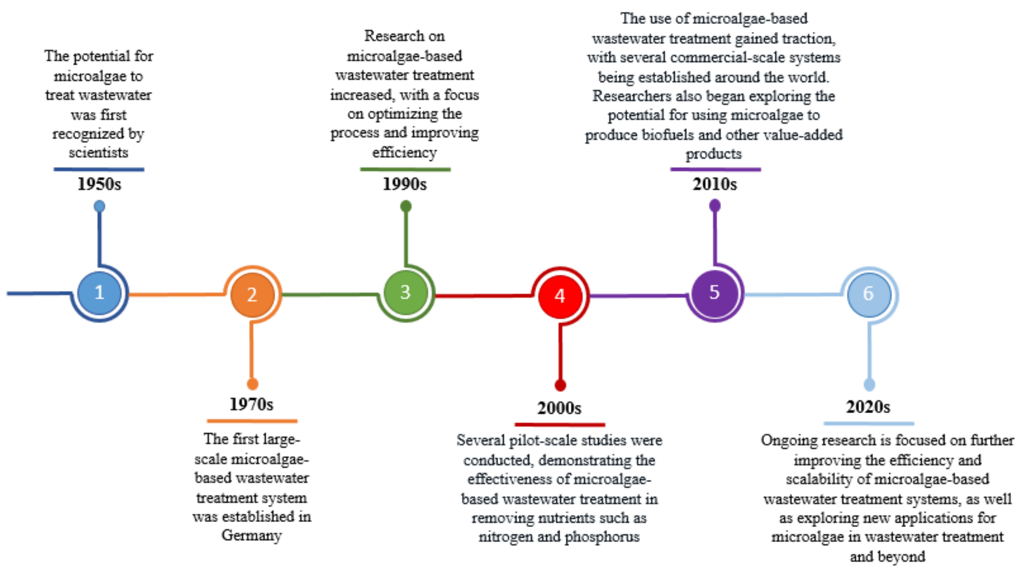

Fig. 1. Evolutionary timeline and noteworthy milestones in microalgae-based wastewater treatment.

1.2. Background and current status

The use of microalgae for wastewater treatment has been studied for several decades, but recent advancements in technology and growing concerns about environmental sustainability have sparked renewed interest in this area of research (Yap et al., 2021; Thanigaivel et al., 2022; Lutzu et al., 2021). This technology can offer numerous advantages, such as efficient removal of nutrients, production of valuable biomass, low energy requirements, and reduced greenhouse gas emissions (Yap et al., 2021). Among them, however, is its ability to remove nutrients such as nitrogen (N) and phosphorus (P), which are major contributors to eutrophication, a process that can lead to harmful algal blooms and other environmental issues (Azizi et al., 2021a; Tom et al., 2021). Microalgae-based systems are highly effective at removing N and P from wastewater, which is critical for protecting aquatic ecosystems and public health. This is because excess N and P can cause algal blooms, which can lead to oxygen depletion, fish kills, and other negative impacts on water quality (Azizi et al., 2021b). In contrast, microalgae can remove N and P from wastewater by incorporating them into their biomass, which can then be harvested and used for various purposes (Abdelfattah et al., 2022). Additionally, microalgae can grow rapidly and require minimal energy inputs, making them an attractive option for wastewater treatment in both developed and developing countries (Lutzu et al., 2021).

Currently, there are several pilot-scale and full-scale microalgae-based wastewater treatment systems in operation around the world, with varying levels of success (Duque et al., 2021). For example, AlgaePARC facility in the Netherlands: This pilot-scale system was established in 2010 and has since undergone several upgrades, with the most recent one completed in 2019. The system has a treatment capacity of 50 liters of wastewater per day and uses a high-rate algal pond to remove nutrients from the wastewater. The system is fed with synthetic wastewater containing nitrogen and phosphorus, simulating the nutrient concentrations in municipal wastewater (Senatore et al., 2021).

The Algae-Water Treatment Plant in the United States: This full-scale system was constructed in 2016 and is located in Santa Fe, New Mexico. The system has a treatment capacity of 450,000 liters per day and uses an algae-based treatment process to remove nutrients from the wastewater. The system is fed with municipal wastewater from the city of Santa Fe (Li et al., 2019).

Both of these systems have shown promising results in terms of nutrient removal and biomass production. However, it is important to note that the design and operation of microalgae-based systems can vary widely depending on factors such as the type of wastewater, climate, and available resources. Therefore, each system must be carefully tailored to its specific context to achieve optimal performance.

Despite all these mentioned advantages, some challenges associated with this technology including the need for efficient microalgae cultivation and harvesting methods, as well as the high capital costs involved in implementing these systems (Udayan et al., 2022). Furthermore, there is a need for continuous research and development to optimize the efficiency and productivity of microalgae-based systems, as well as to address potential environmental concerns such as the risk of algal blooms and the impact on aquatic ecosystems (Yong et al., 2021). Additionally, the scalability of microalgae cultivation systems remains a challenge, as large-scale production requires significant space and resources. Despite these challenges, ongoing efforts are being made to overcome them and unlock the full potential of microalgae technology in various industries, including biofuel production, wastewater treatment, and nutraceuticals (Duque et al., 2021). Nonetheless, ongoing research and development in this field are expected to lead to improved efficiency and cost-effectiveness, making microalgae-based wastewater treatment an increasingly viable option for sustainable wastewater management (Kalra et al., 2021; Bhatia et al., 2021).

In this grand challenge paper, we will discuss the key topics and present the main findings. Firstly, we will delve into a detailed discussion of the challenges and issues related to the grand challenge. This section aims to provide a comprehensive understanding of the background, scope, and significance of the research.

Secondly, we will present innovative approaches, methodologies, or solutions that have been developed to address the challenges discussed earlier. These solutions will be showcased and analyzed, highlighting their effectiveness, limitations, and potential impact on the field. By presenting these findings, this paper aims to contribute to the knowledge and understanding of the grand challenge, as well as inspire further research and advancements in the area.

Through a thorough discussion of the challenges and the presentation of innovative solutions, this paper seeks to shed light on the complexities of the grand challenge and stimulate further exploration and collaboration in order to tackle the identified problem effectively.

1.3. Advantages

Microalgae can effectively assimilate nutrients as they grow, thereby reducing their concentration in the wastewater. This not only improves the quality of the treated wastewater but also provides a valuable resource in the form of nutrient-rich algal biomass, which can be used as a fertilizer or animal feed supplement (Mu et al., 2021; Ahmad et al., 2022).

Another advantage of microalgae-based wastewater treatment is its potential for bioenergy production. As microalgae grow, they accumulate energy-rich compounds that can be converted into biofuels such as biodiesel and biogas (Thanigaivel et al., 2022; Sarwer et al., 2022). This provides a renewable and sustainable source of energy, which can help to reduce dependence on fossil fuels. In addition, microalgae can also capture carbon dioxide (CO_2) from the atmosphere as they grow, thereby contributing to efforts to mitigate climate change (Sarwer et al., 2022; Prasad et al., 2021). These organisms exhibit rapid growth rates, making them one of the swiftest expanding photosynthetic life forms on the planet. Some species have a doubling time of less than 24 hours. By providing certain microalgal species with 4% CO_2 at a flow rate of 0.3 L/min, a carbon biofixation rate of 14.6 g/L/day and a growth rate of 30.2 g/L can be achieved (Mondal et al., 2016). They possess the ability to capture CO_2 from various sources, including the environment, flue gases emitted from a specific location, and fixed CO_2 in the form of carbonates (Zuccaro et al., 2020).

Overall, the use of microalgae for wastewater treatment offers a promising solution for sustainable wastewater management that can provide multiple benefits (Kalra et al., 2021).

2. Grand challenges associated with microalgae-based wastewater treatment

Microalgae-based wastewater treatment offers great potential for addressing water pollution and resource recovery. However, several grand challenges need to be addressed to fully realize its benefits. Figure 2 shows some of the main challenges associated with microalgae-based wastewater treatment.

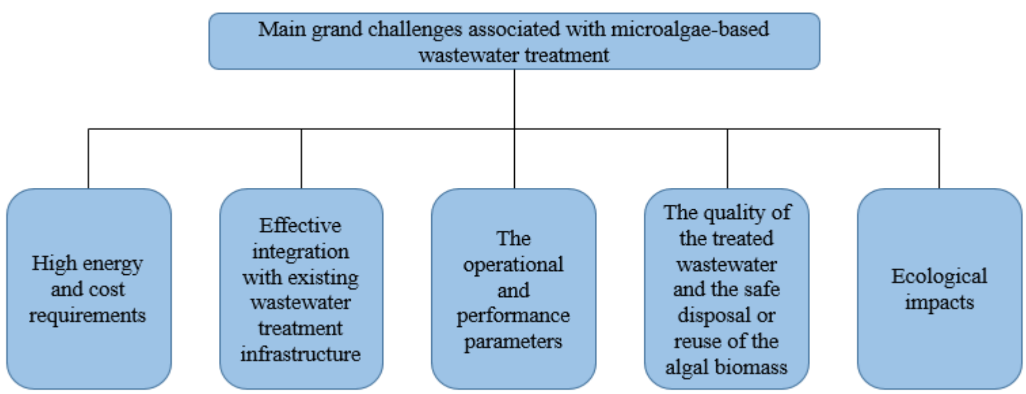

Fig. 2. Main grand challenges associated with microalgae-based wastewater treatment.

2.1. High energy and cost requirements

One major hurdle in the utilization of microalgae-based wastewater treatment is the high energy and cost requirements for microalgae cultivation and harvesting (Bhatia et al., 2021). Microalgae need specific amounts of light, nutrients, and CO_2 to grow, and maintaining optimal growth conditions can be challenging and costly. Additionally, harvesting microalgae from wastewater can be energy-intensive and expensive, particularly at a large scale (Azizi et al., 2021b). The estimated production costs for supplying CO_2 to support microalgae cultivation are approximately 50% lower compared to the costs associated with biomass production. A cost-effective option involves utilizing biogas, a byproduct of anaerobic digestion, which typically contains 20%-40% CO_2, or CO_2 generated from alcoholic fermentation. Additionally, flue gas emitted by coal-fired plants, cement production plants, or natural gas combustion, containing approximately 10%-25% CO_2, can be considered. However, these flue gases also contain inhibitors such as NOx and SOx, which can be eliminated through purification processes like the reaction to form sodium or ammonium bicarbonate and urea. It should be noted that the main drawback of these sources is the potential increase in pH and ionic strength. On the other hand, an advantage lies in their higher solubility compared to pure CO_2. For instance, Na_2HCO_3 exhibits a solubility exceeding 90 g/L at 25°C, making these processes attractive, despite their threefold greater economic impact compared to the use of CO_2 (Zhao et al., 2023).

Furthermore, inexpensive carbon sources (e.g., glucose, acetate, glycerol) commonly employed in fermentation processes and derived from low-cost feedstocks or wastewater can be utilized. Moreover, the ability to achieve high cell density allows for cost reduction in the dewatering stage during harvesting. However, it is important to note that only a limited number of microalgae strains, such as *C. vulgaris, Chlorella protothecoides, Crypthecodinium cohnii*, and *Schizochytrium limacinum*, can be successfully cultivated under these specific conditions (Christenson et al., 2011).

Research efforts have focused on developing more efficient microalgae cultivation and harvesting methods that can minimize energy and cost requirements (Mathushika, Judy, and Chandima Gomes, 2022). Regarding cultivation issues, some promising strategies include using wastewater as a low-cost food source. For example, *Chlorella sp.* can effectively remove nutrients from municipal wastewater, contributing to wastewater treatment while producing biomass rich in lipids and proteins. Studies have reported nutrient removal efficiencies of up to 99% for N compounds and 100% for P compounds (Leong et al., 2023). Similarly, studies have demonstrated that *Scenedesmus sp.* thrives in food processing wastewater, utilizing the organic compounds as a nutrient source and producing biomass rich in proteins and carbohydrates. Removal efficiencies of 85% for organic matter, 75% for sugars, 70% for fats, and 80% for proteins have been reported (Hariz et al., 2019; Ahmad et al., 2023). In the case of agricultural wastewater from livestock farms, *Nannochloropsis sp.* has shown potential for treating the wastewater while producing lipid-rich biomass. Removal efficiencies of up to 90% for organic matter, 80% for N compounds, and 75% for P compounds have been observed (Ma et al., 2016; Emparan et al., 2020; Mitra et al., 2019). Additionally, *Desmodesmus sp.* has been found to tolerate and remove dyes and organic pollutants from textile wastewater, providing a potential solution for wastewater treatment and producing biomass with potential applications. Removal efficiencies of 95% for dyes and 85% for organic pollutants have been reported (Rai et al., 2022).

It is important to note that the efficiency of nutrient removal and biomass production can vary depending on the specific conditions, operational parameters, and characteristics of the wastewater. Further research and optimization are necessary to maximize the benefits and overcome challenges associated with wastewater-based cultivation systems. The development of advanced cultivation systems like photobioreactors and membrane bioreactors could provide several benefits, such as higher yields of biomass or bio-products, improved control over growth conditions, and increased efficiency and sustainability of the cultivation process. Additionally, these systems can offer opportunities for research and innovation in the field of biotechnology (Hashemi et al., 2020; Azizi et al., 2021c). For example, Sarma et al. (2021) investigated a photobioreactor system and the productivity of different microalgae species, including Heterotrophic *Chlorella protothecoides* and *Chlorella vulgaris.* The former was found to be highly productive, with lipid and biomass productivities ranging from 1.2 to 3.7 g/L/day and 2.2 to 7.4 g/L/day, respectively. In contrast, *Chlorella vulgaris* had lower lipid productivity of 22.0 to 54.0 mg/L/day when grown in sunlight with glucose and glycerol as carbon sources. The study also examined the use of different types of wastewater as a nutrient source for microalgal growth and lipid production, with varying results depending on the microalgal species and the wastewater source used. For instance, *Botryococcus braunii* cultured in domestic wastewater had a biomass productivity of 0.28 grams per liter per day and lipid content up to 25% of dry weight. However, when grown in synthetic medium, its biomass productivity decreased to 0.22 g/L/day, with a higher lipid content of 47% of dry weight. Other studies found that *Chlorella vulgaris* grown in urban wastewater had higher lipid productivity than when grown in a synthetic medium. Dairy wastewater was also identified as a suitable nutrient source for microalgal growth, with *Chlorella sp.* and *Ascochloris sp.* having biomass productivities of 0.11 and 0.207 g/L/day, respectively. Furthermore, *Ascochloris sp.* grown in raw dairy wastewater had a lipid content reaching up to 34.98% of dry weight, according to the cited studies. Table 1 shows a number of wastewater used as a source of nutrition for the production of microalgae biomass.

Moreover, research has also aimed to develop new harvesting methods, such as membrane technology (e.g., microfiltration, MF, and ultrafiltration, UF) and electrocoagulation, that can be more energy-efficient and cost-effective (Sarwer et al., 2022). Its implementation has significantly contributed to the economic sustainability of microalgal cultivation by reducing energy consumption. In the field of microalgae harvesting, current studies have achieved the lowest energy consumption level at 0.67 Wh/m^3 by utilizing vibrating, negatively charged, patterned PSf membranes along with flocculation before filtration in an MMV system. However, there is still potential for optimization since the operational flux (95 L/m^2 h) has not reached its maximum capacity. Cost assessments have revealed that the total electrical cost represents a minimal fraction (3.05%) of the overall production cost, assuming an energy cost of 0.1 €/kWh during that period. Factors such as CO_2 and labor have been identified as key contributors to the high production cost. Membrane-based microalgal biofilm systems have recently gained considerable attention due to their ability to facilitate low-cost simultaneous microalgae cultivation and harvesting a mutually beneficial approach. Moreover, these systems offer versatility in other domains, including wastewater treatment and biochemical production. To achieve optimal performance and cost-effectiveness, this review suggests that future research should not only focus on developing new technologies but also explore the synergies that can be harnessed by combining existing technologies (Zhao et al., 2022). To overcome this challenge, future research could concentrate on developing innovative technologies and optimizing existing ones to increase the efficiency of microalgae cultivation and harvesting. In terms of a sustainable cultivation, this could involve the use of renewable energy sources such as solar or wind power to provide energy for photobioreactors, or the use of waste streams such as CO_2 emissions as a source of carbon for microalgae growth. Moreover, the development of closed-loop systems that recycle water and nutrients could help to reduce the environmental impact of microalgae cultivation and minimize resource consumption.

Regarding the microalgae harvesting step, microalgae harvesting is a crucial step in the cultivation process that involves separating microalgae biomass from the growth medium. The small size of the microalgae cells and the low biomass concentration in the growth medium pose challenges to the harvesting process. Various methods have been developed to overcome these challenges, including passive methods such as sedimentation and flotation, and active methods such as centrifugation, filtration, flocculation, and electrocoagulation. Researchers are also exploring novel harvesting techniques such as acoustic-based methods and microfluidic devices. The choice of method depends on factors such as the microalgae species, biomass concentration, and downstream processing requirements. Overall, efficient and sustainable microalgae harvesting techniques are necessary to optimize the production of microalgae-based products. This could include the development of more efficient lighting systems, the use of genetically modified microalgae with higher growth rates, and the optimization of nutrient uptake and CO_2 fixation. Furthermore, research could focus on developing novel harvesting methods that can reduce energy and cost requirements, such as the use of magnetic nanoparticles or acoustic waves to separate microalgae from wastewater (Lutzu et al., 2021).

Table 1
Types of wastewater used as a source of nutrition for the production of microalgae biomass.

Types of wastewater	Microalgae strain	Nutrient removal (%)	Biomass productivity (mg/L/day)	Lipid content of total dry biomass (%)	Reference
Dairy wastewater	*Chlorella pyrenoidosa*	N: 88% P: 85% COD: 77%	24.44	10.36	(Brar et al., 2019)
Industrial wastewater	*Spirulina platensis*	N: 35.4-58% P: - BOD: 51-94.6%	123	25.3	(Gupta et al., 2019)
	Scenedesmus dimorphus	N: 75% P: 96% BOD: 92%	227	13	(lage et al., 2018)
Municipal wastewater	*Chlorella vulgaris*	N: 52.1% P: 99.2% COD: 83%	99.21	26.2	(Xu et al., 2019)

2.2. Effective integration with existing wastewater treatment infrastructure

Another grand challenge associated with microalgae-based wastewater treatment is the need for effective integration with existing wastewater treatment infrastructure. Microalgae-based treatment systems may require significant modifications to existing treatment plants, including the addition of new infrastructure for microalgae cultivation, harvesting, and post-treatment. The integration of microalgae-based treatment systems with existing infrastructure can be complex and may require significant investment.

Based on the 2008 Clean Watersheds Needs Survey, it was found that the reported wastewater flow in the United States amounts to 32,345 million gallons per day (MGD) (U.S. EPA, 2008). When considering average domestic wastewater composition, each liter contains sufficient amounts of nitrogen (N) and phosphorus (P) to generate 0.6 grams of algae, resulting in a total of 77.6 million kilograms per day. Assuming a 90% removal of the nutrient that limits growth, a 10% (w/w) biodiesel yield (based on the lipid content of mixed cultures grown in municipal wastewater, as reported by Woertz et al., (2009) a biodiesel density of 0.801 kilograms per liter, and 9 months of operation per year, an estimated average biodiesel production of approximately 1.7 million gallons per day (equivalent to 6.5 million liters per day) is calculated. Although this represents only a small fraction of the daily 378 million gallons of transportation fuel consumed in the United States (U.S. EIA, 2009), wastewater treatment plants still hold great potential as testbeds for the future development of large-scale algae biofuel facilities (Christenson et al., 2011).

Research in this area has focused on developing strategies for the effective integration of microalgae-based treatment systems with existing infrastructure. Some approaches include the use of modular systems that can be easily integrated into existing treatment plants, as well as the development of new treatment trains that can accommodate microalgae-based treatment systems (Lutzu et al., 2021). In addition, research has also focused on developing new business models and financing mechanisms to support the implementation of microalgae-based treatment systems (Kumar and Verma, 2021).

To address this challenge, future research could focus on developing more efficient and cost-effective strategies for the integration of microalgae-based treatment systems with existing infrastructure. This could include the development of new modular systems that can be easily integrated into existing treatment plants, as well as the use of advanced modeling and optimization tools to identify the most efficient and cost-effective integration strategies.

2.3. The operational and performance parameters

Another significant challenge associated with microalgae-based wastewater treatment is the effective management of operational and performance parameters of the treatment system. The successful implementation of microalgae-based treatment systems requires careful monitoring and control of various parameters such as light intensity, nutrient concentration, pH, and temperature to ensure optimal microalgae growth and nutrient uptake (Ahmed et al., 2022). As an example, the production of biomass and the removal of nutrients from wastewater can be influenced by light intensity (Azizi et al., 2021a). The optimal light intensity required for algal species or biomass concentrations can vary (Keramati and Azizi et al., 2021). In the case of culturing *Nannochloropsis salina*, it was observed that increasing light intensity promoted biomass production. However, once a threshold of 150 μmol/m^2 s of photons was reached, the stimulating effect became insignificant, and higher light intensity actually inhibited growth (Luo et al., 2017). Another study demonstrated that the uptake of nutrients by S. obliquus was more dependent on the internal nutrient content of the biomass rather than on light intensity. The impact of light intensity on nutrient uptake was only significant once the biomass had reached its maximum capacity for nutrient storage, which occurred at approximately 8% nitrogen and 2% phosphorus in the cell (Luo et al., 2017). Additionally, the performance of the treatment system must be continuously monitored to ensure that it meets the required effluent quality standards (Ahmad et al., 2021).

Researchers have been focusing on developing effective strategies for managing microalgae-based treatment systems. Some of these approaches include using advanced monitoring and control systems that can continuously monitor and adjust the operational parameters of the treatment system. Additionally, new modeling and optimization tools have been developed to predict the performance of the treatment system and identify opportunities for improvement (Wang et al., 2022).

To address this challenge, future research could focus on developing more efficient and cost-effective strategies for managing microalgae-based treatment systems. This could include the development of new monitoring and control systems that can integrate with existing plant automation systems. Additionally, advanced modeling and optimization tools could be used to improve the performance of the treatment system. Furthermore, research could focus on developing new training programs and certification processes to ensure that operators and maintenance personnel have the necessary knowledge and skills to effectively manage microalgae-based treatment systems.

2.4. The quality of the treated wastewater and the safe disposal or reuse of the algal biomass

Another grand challenge associated with microalgae-based wastewater treatment is the need for effective post-treatment methods to ensure the quality of the treated wastewater and the safe disposal or reuse of the algal biomass. Although microalgae can effectively remove nutrients and other contaminants from wastewater, the resulting algal biomass can contain residual contaminants and pathogens that may require further treatment or disposal (Lutzu et al., 2021).

Researchers have been focusing on developing post-treatment methods that can efficiently remove residual contaminants from the algal biomass and ensure its safe disposal or reuse. Some promising approaches include using physical and chemical treatments, such as drying and thermal treatment, to remove residual contaminants and pathogens from the algal biomass. Additionally, research has focused on developing new applications for the algal biomass, such as the production of biofuels and animal feed supplements (Behera et al., 2021). In a study by Nayak et al. (2019), pharmaceutical wastewater was pretreated using *Scenedesmus abundans* microalgae in a photobioreactor (PBR). The pretreated effluent was then post-treated in a photosynthetic microbial fuel cell (PMFC) to produce biomass and electricity. The pretreatment removed approximately 77% of the chemical oxygen demand (COD), along with significant nitrate and phosphate removal. In the PMFC, an additional 88% COD removal was achieved, resulting in an overall COD removal of 97.24%. The biomass generated in both the PBR and PMFC processes showed the presence of saturated and unsaturated fatty acids suitable for biodiesel production. This study highlights the potential of microalgal pretreatment for effective bioremediation of pharmaceutical wastewater and bioelectricity generation.

To address this challenge, future research could focus on developing more efficient and sustainable post-treatment methods that can effectively remove residual contaminants from the algal biomass while minimizing energy and cost requirements. Innovative technologies such as microwave-assisted pyrolysis and hydrothermal liquefaction could be used to convert the algal biomass into biofuels and other value-added products. Additionally, research could focus on developing new applications for the algal biomass, such as the production of bioplastics and other bio-based materials, to further enhance the sustainability and economic viability of microalgae-based wastewater treatment.

2.5. Ecological impacts

One of the primary challenges of microalgae-based wastewater treatment is the potential for ecological impacts, such as algal blooms, when nutrient-rich effluent is discharged into natural water bodies. While microalgae-based treatment systems can remove nutrients and other contaminants from wastewater effectively, the discharge of this treated wastewater into natural water bodies can contribute to eutrophication and the formation of harmful algal blooms (Kishor et al., 2021)

To address this challenge, researchers have been developing strategies to minimize the impact of microalgae-based wastewater treatment on natural water bodies. These strategies include the use of tertiary treatment methods such as membrane filtration and reverse osmosis to remove residual nutrients and contaminants from the effluent before discharge. Additionally, researchers have focused on developing new microalgae strains that are less likely to cause algal blooms and other ecological impacts (Yadav et al., 2021).

To make microalgae-based wastewater treatment a more sustainable and effective technology, future research could focus on developing more efficient and cost-effective strategies for microalgae cultivation and harvesting. Furthermore, researchers could explore alternative uses for the treated effluent, such as irrigation and aquaculture, to further reduce the nutrient load on natural water bodies. By addressing these challenges, microalgae-based wastewater treatment has the potential to become a valuable tool for sustainable wastewater management.

3. The practical solutions for the grand challenges associated with microalgae-based wastewater treatment

The solutions for the grand challenges associated with microalgae-based wastewater treatment require a multidisciplinary and collaborative approach involving researchers, engineers, policymakers, and stakeholders from various sectors. Some potential solutions include:

1. Developing more efficient and cost-effective microalgae cultivation and harvesting methods by optimizing existing technologies and exploring new approaches such as genetic engineering and innovative harvesting methods like acoustic waves or magnetic nanoparticles.

2. Developing effective wastewater pre-treatment methods to remove solids and other contaminants that can inhibit microalgae growth and reduce treatment efficiency, by exploring advanced oxidation processes and developing new microalgae strains that are more tolerant to contaminants.

3. Improving our understanding of the long-term environmental impacts of microalgae-based wastewater treatment systems, by developing monitoring systems and assessing the impact of changes in water chemistry and the release of metabolites on downstream ecosystems.

4. Developing more efficient and sustainable post-treatment methods that can effectively remove residual contaminants from the algal biomass while minimizing energy and cost requirements, by exploring innovative technologies such as microwave-assisted pyrolysis and hydrothermal liquefaction.

5. Developing more effective and sustainable strategies to minimize the impact of microalgae-based wastewater treatment on natural water bodies, by developing new tertiary treatment methods that are more efficient and cost-effective, as well as the use of advanced monitoring systems to detect and mitigate the formation of algal blooms and other ecological impacts.

6. Developing more efficient and cost-effective strategies for the integration of microalgae-based treatment systems with existing infrastructure, by developing new modular systems that can be easily integrated into existing treatment plants, as well as the use of advanced modeling and optimization tools to identify the most efficient and cost-effective integration strategies.

Addressing these grand challenges will require continued research and development efforts, as well as collaborations among stakeholders to ensure the successful implementation and scalability of microalgae-based wastewater treatment systems.

4. Conclusion

In conclusion, microalgae-based wastewater treatment systems have demonstrated their potential as sustainable and cost-effective solutions for wastewater treatment. The results obtained from various studies highlight their effectiveness in removing contaminants, such as chemical oxygen demand (COD), nitrate, and phosphate. However, to ensure the successful implementation and scalability of these systems, several grand challenges need to be addressed. These challenges include the development of more efficient microalgae cultivation and harvesting methods to increase biomass production, the implementation of effective pre-treatment and post-treatment techniques to enhance treatment efficiency, the mitigation of environmental impacts on natural water bodies, and the integration of microalgae-based systems with existing infrastructure. To overcome these challenges, continued research and development efforts are needed, along with collaboration among stakeholders from various sectors. By addressing these challenges, microalgae-based wastewater treatment systems can not only provide sustainable and cost-effective solutions but also offer additional benefits such as biofuel production and the potential to mitigate greenhouse gas emissions. Furthermore, these systems can contribute to the promotion of circular economy models. Therefore, it is essential to invest in research and development in this field to fully unlock the potential of microalgae-based wastewater treatment systems and address the pressing need for sustainable wastewater management.

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