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Recent Developments in Urban Wastewater Management—Insights, Recommendations, and Future Perspectives

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ABSTRACT

Rapid population growth and intensified human activities such as mining operations, industrial discharge, ore smelting, fossil fuel combustion—particularly coal—along with the agricultural use of arsenic-contaminated water, pesticides, herbicides, and fertilizers have significantly compromised freshwater resources intended for human use. Urban wastewater is characterized by the presence of numerous contaminants that pose toxicity risks to both microorganisms and higher life forms, thereby necessitating effective treatment strategies. Among emerging solutions, microalgae have received considerable scientific attention due to their strong potential to remove pollutants from both industrial and domestic wastewater streams. Researchers emphasize microalgal-based remediation approaches because of the organisms' capacity to adapt, grow, and remain metabolically active under diverse and harsh environmental conditions. In addition to pollutant removal, microalgae contribute to carbon dioxide sequestration, offering an added environmental benefit. Their integration into wastewater treatment systems aligns closely with circular bioeconomy principles, as microalgal processes enable the simultaneous generation of valuable bio-based products during conventional treatment operations. This systematic review examines the role of microalgae in urban wastewater treatment, focusing on remediation mechanisms, pollutant removal strategies, and operational approaches. Furthermore, the study explores future opportunities for incorporating microalgal technologies into circular bioeconomy frameworks alongside sustainable wastewater management.

Keywords: Urban Wastewater Treatment; Microalgae-Based Remediation; Nutrient Recovery; Circular Bio Economy; Sustainable Water Management

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1. Introduction

Accelerated industrial expansion and increasing human settlements have led to a substantial rise in waste generation, resulting in pronounced adverse effects on natural ecosystems and global climate systems. The uncontrolled discharge of industrial wastewater is a key contributor to environmental contamination, introducing heavy metals, pesticides, pharmaceutical residues, and petroleum-derived compounds into natural surroundings. In addition to these pollutants, industrial effluents also contain organic substances such as amino acids, carbohydrates, lipids, and volatile fatty acids. Elevated concentrations of inorganic constituents—including chlorine, magnesium, potassium, sulfur, and sodium—are likewise introduced into ecosystems through wastewater discharge ^[1].

Urban and industrial wastewater commonly contains a mixture of organic compounds, including proteins, fats, carbohydrates, and amino acids, as well as volatile acids and inorganic ions such as ammonium salts, arsenic, bicarbonate, calcium, phosphate, and sodium. Furthermore, wastewater environments host diverse microbial populations comprising both non-pathogenic and pathogenic organisms. While certain bacteria, fungi, and protozoa contribute to natural wastewater treatment processes, the presence of pathogenic microorganisms remains a major concern due to their role in spreading waterborne diseases such as cholera, dysentery, hepatitis, tuberculosis, and typhoid. The release of untreated wastewater into natural water bodies significantly elevates toxicity levels and biological oxygen demand, ultimately disrupting aquatic ecosystems ^[2].

Effective wastewater treatment is therefore essential for mitigating environmental and public health risks associated with toxic pollutants. Urban wastewater treatment facilities are primarily designed to reduce organic load and lower pathogenic microbial concentrations. The configuration of these treatment plants depends on wastewater characteristics, industrial effluent quality, land availability, and economic constraints. Conventional treatment systems generally focus on primary and secondary treatment processes, often excluding advanced tertiary treatments involving specialized microorganisms ^[3]. Evidence suggests that traditional treatment approaches are frequently insufficient for the complete removal of persistent contam-

inants such as heavy metals, pharmaceutical compounds, and pesticides. Additionally, conventional methods generate substantial volumes of sludge, which pose secondary environmental challenges and require further treatment or disposal strategies ^[4].

In response to these limitations, microalgae-based wastewater treatment technologies have emerged as environmentally sustainable and economically viable alternatives. Microalgae utilize nitrogen, phosphorus, and other organic and inorganic nutrients present in wastewater for growth, thereby reducing pollutant concentrations while simultaneously producing oxygen through photosynthesis. These characteristics make microalgae particularly attractive for integrated wastewater treatment applications. This review examines the significance of microalgae in urban wastewater management and evaluates their contribution to circular bioeconomy development through sustainable resource recovery ^[5].

Microalgae are microscopic, photosynthetic organisms widely distributed across freshwater and marine environments. Their photosynthetic efficiency is comparable to that of terrestrial plants, largely due to their cellular architecture and aquatic habitat. One of the key biochemical attributes of microalgae is their ability to synthesize fatty acids, which has driven growing interest in microalgae-based technologies. The production of polyunsaturated fatty acids is often enhanced when microalgae are exposed to environmental stress conditions. Species such as *Nannochloropsis oculata* and *Porphyridium purpureum* have demonstrated increased synthesis of polyunsaturated fatty acids under nutrient-limited conditions. Phosphate deprivation, in particular, alters lipid metabolism by stimulating desaturase enzyme activity, thereby modifying fatty acid composition ^[6].

The microalgal cell wall is primarily composed of cellulose along with proteins, polysaccharides, and lipids. Various functional groups—including amino, hydroxyl, carboxyl, carbonyl, phosphate, and sulfhydryl groups—confer a net negative charge to the cell surface and facilitate metal ion binding. The chemical composition and structural properties of the cell wall play a critical role in determining heavy metal uptake efficiency. Microalgae exhibit remarkable tolerance to toxic metal concentrations due to their adaptive physiological mechanisms. Survival

in contaminated environments is supported by genetic regulation, chelation processes, immobilization strategies, and exclusion mechanisms [7].

Once metal ions enter microalgal cells, protein-metal complexes form, triggering the secretion of antioxidants such as phycochelatins and specialized enzymes. The synthesis of phytochelatin further contributes to metal detoxification. In addition, microalgae produce extracellular

polymeric substances (EPS), which significantly enhance bioremediation efficiency [8]. EPS contains polysaccharides and proteins with functional groups capable of binding metal ions. For example, *Chlorella pyrenoidosa* secretes EPS that effectively interacts with arsenic ions in freshwater systems. The advantages and limitations associated with microalgae-based urban wastewater treatment are summarized in **Table 1**.

Table 1. Benefits and drawbacks of microalgae utilization in urban wastewater treatment.

S. No.	Category	Description
1	Benefits	The pollutants are used as nutrients up to 70–90%.
		Environmentally friendly process without production of sludge.
		Growth rate of microalgae is elevated in wastewater treatment plants.
		Production of value-added byproducts.
2	Drawbacks	Technique is easy to execute.
		Not all strains of microalgae are efficient in the remediation technique for all types of wastewater.
		A higher land footprint is required for execution.
		Sensitive towards the pathogenic microorganisms such as bacteria and protozoa.

2. Literature Review

2.1. Environmental Applications of Microalgae

The high photosynthetic efficiency of microalgae enables them to actively capture, sequester, and recycle atmospheric carbon dioxide, contributing to the generation of biofuels and a range of valuable bioproducts. When compared with higher terrestrial plants, microalgae demonstrate superior carbon fixation efficiency due to rapid growth rates and efficient cellular metabolism. Carbon dioxide released from industrial activities can be absorbed by microalgae and converted into organic compounds such as carbohydrates, proteins, and lipids through photosynthetic pathways [9].

In recent years, microalgae have gained substantial recognition within the field of environmental biotechnology. Their bioremediation capacity frequently surpasses that of conventional chemical treatment methods. A distinguishing advantage of microalgal systems is their ability to assimilate environmental contaminants directly as nutrient sources, thereby reducing pollutant concentrations while sustaining cellular growth. Microalgae are well adapted to extreme environmental conditions and often establish

synergistic interactions with other microorganisms and plants. These symbiotic relationships enhance resilience to environmental fluctuations and improve long-term system sustainability in industrial applications. Although microalgal remediation processes typically require longer operational periods than chemical treatments, they offer superior cost-effectiveness and environmental compatibility [10].

Microalgae employ two primary mechanisms—bioaccumulation and biosorption—for the removal of toxic metal pollutants from contaminated water sources. Bioaccumulation involves metabolically active cells that internalize heavy metals through intracellular binding, methylation, or precipitation processes. In contrast, biosorption relies on metabolically inactive biomass that functions as a biological adsorbent capable of binding metal ions to cell surface structures [11,12]. Both approaches are environmentally benign and effective in reducing metal concentrations. Previous studies have demonstrated that *Spirulina platensis* can remove copper and cadmium with efficiencies ranging from 91% to 98%, while species such as *Chlorella* and *Scenedesmus* have shown the ability to eliminate calcium, cadmium, copper, zinc, manganese, and magnesium from polluted environments [13]. The efficiency of metal uptake is strongly influenced by pH, which affects both cell surface charge and metal ion

speciation. Temperature and contact time may also influence removal efficiency, particularly when live cells are involved ^[14].

The removal of synthetic dyes from industrial effluents represents another critical environmental challenge addressed through microalgal biomass application. Industrial dyes, once discharged into the environment, pose serious ecological and health risks. Microalgal dye removal efficiency is influenced by several parameters, including pH, temperature, contact duration, dye concentration, species selection, and biomass density. Traditional wastewater dye treatment methods—such as adsorption, flocculation, oxidation, ultrafiltration, and coagulation—often suffer from technical limitations and high operational costs ^[15]. Consequently, microbial-based interventions have emerged as promising alternatives. Microalgae offer advantages including operational simplicity, economic feasibility, high adsorption capacity, and reliance on readily available materials. Their solar-driven metabolism further reduces energy consumption. In addition to dyes, microalgae have demonstrated potential in degrading pharmaceutical compounds released through hospital and domestic wastewater streams ^[15].

2.2. Applications of Microalgae in Urban Wastewater Treatment

Urban wastewater management generally involves three treatment stages: primary, secondary, and tertiary treatment. Primary treatment focuses on the physical removal of suspended solids, while secondary treatment employs microbial processes to degrade organic matter. These treatment stages often require substantial operational investment and infrastructure. Conventional chemical treatment methods frequently rely on metal salts such as aluminum and iron for pollutant precipitation, generating large volumes of sludge that require additional handling and disposal. Similarly, biological treatment systems necessitate complex infrastructure and high capital expenditure for sludge management ^[16,17].

The inherent limitations of chemical and biological treatment approaches have accelerated interest in alternative and more sustainable wastewater management strategies. Microalgae-based remediation has emerged as an

effective substitute for conventional treatment technologies due to its capacity to treat both liquid and solid waste streams while converting pollutants into valuable biomass. Integrating microalgal harvesting with wastewater treatment significantly reduces operational costs. Microalgae efficiently assimilate nutrients present in wastewater and convert them into biomass suitable for commercial applications. Compared to vascular plants, microalgae exhibit faster growth rates and can be cultivated without causing adverse environmental effects ^[18].

Under optimized laboratory-scale and controlled pilot-scale conditions, microalgal biomass has been reported to double within approximately 13 h. Such growth rates are typically achieved under ideal nutrient availability, light intensity, and temperature control, and may not be directly reproducible under full-scale operational conditions. Microalgae also exhibit tolerance to adverse environments, enabling cultivation in wastewater systems without competing for agricultural land resources.

Microalgal cultivation may occur under autotrophic, heterotrophic, or mixotrophic growth modes. In autotrophic systems, carbon dioxide serves as the primary carbon source, contributing to greenhouse gas mitigation. Reported carbon dioxide sequestration capacities—approximately 1.8 pounds of CO₂ per unit biomass—are generally derived from optimized experimental conditions. Obligate heterotrophic microalgae utilize organic carbon sources such as acetate, ethanol, glucose, and glycerol derived from industrial waste streams, while mixotrophic species combine both pathways to enhance biomass productivity ^[19,20]. **Figure 1** describes the process involved in wastewater management.

During wastewater treatment, microalgae assimilate carbon dioxide, nitrogen, and phosphorus, converting them into carbohydrates, proteins, lipids, and other bio-based products. The nutrient-rich composition of wastewater enables cost-effective microalgal cultivation while significantly reducing carbon emissions ^[21]. Microalgae have been successfully applied to agricultural, municipal, and industrial wastewater treatment systems. Treatment efficiency depends on factors such as nutrient availability, carbon dioxide supply, pH, temperature, and salinity, which collectively influence microalgal growth and biomolecule production ^[22].

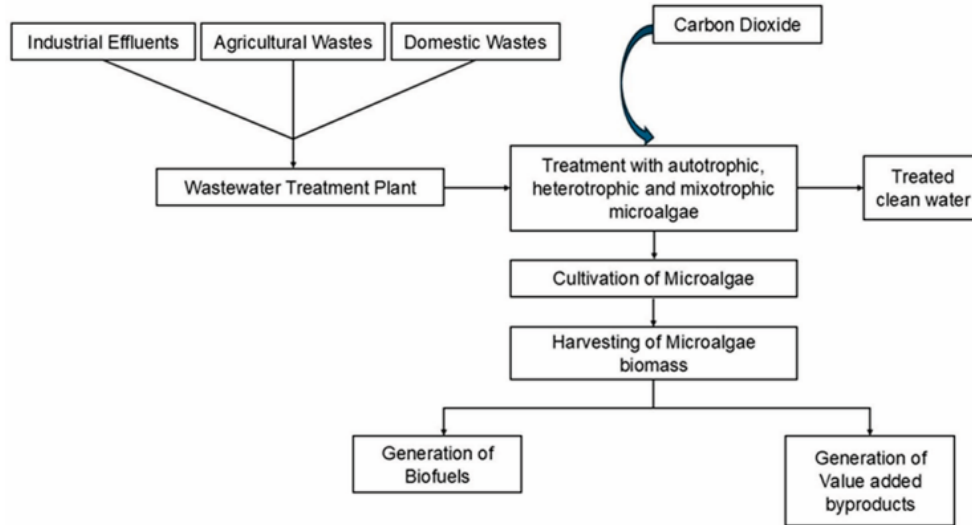


Figure 1. Process involved in wastewater management using microalgal approach.

Despite their advantages, microalgae-based wastewater treatment systems face challenges related to biomass harvesting, biomolecule recovery, and potential exposure to toxic compounds such as antibiotics and pesticides. In some cases, self-flocculation occurs due to EPS-mediated cell aggregation, partially simplifying harvesting. Nev-

ertheless, the low energy demand, adaptability to diverse conditions, and ability to convert pollutants into high-value products make microalgae an attractive option for sustainable urban wastewater management [23]. Table 2 presents the application of microalgae in the remediation of contaminants from urban wastewater.

Table 2. Application of microalgae in the remediation of contaminants from urban wastewater.

S. No.	Microalgae Used	Contaminants Removed	% Remediation	References
1	Consortium of Microalgae (<i>Scenedesmus</i> sp. and <i>Chlorella</i> sp.)	Carbamazepine	20	Abdelfattah et al. [1]
2	<i>Selenastrum capricornutum</i>	Estradiol, 17 α ethinylestradiol	88–100, 60–95	
3	Consortium of Microalgae	Acetaminophen, Carbamazepine, Ibuprofen	62, 99, 99	
4	Microalgae co-culture	Nitrate and Phosphate	93, 99	Verma et al. [24]
5	<i>Spirulina platensis</i> in combination with other algae	Nitrate and Phosphate		Jain and Varma [3]
6	<i>Chlorella vulgaris</i>	Nitrate, Phosphate and Ammonia	95, 97.6, 99.3	Chawla et al. [6]
7	<i>Heterochlorella</i> sp.	Manganese	84	Plöhn et al. [21]

2.3. Remediation Strategies Employed by Microalgae

Microalgal remediation of wastewater contaminants is primarily achieved through three fundamental mechanisms: bioaccumulation, biosorption, and biodegradation. Each approach operates through distinct biological and physicochemical pathways, enabling the effective removal of a wide spectrum of pollutants.

2.3.1. Bioaccumulation

Bioaccumulation is an energy-dependent, metabol-

ically active process occurring within living microalgal cells. Although this mechanism generally proceeds at a slower rate compared to passive remediation techniques, it enables the internal sequestration and transformation of contaminants. During bioaccumulation, pollutants are transported into microalgal cells, where they are either stored in intracellular compartments or metabolized as part of normal cellular functions [25].

Microalgae are capable of assimilating a diverse range of organic and inorganic contaminants, including heavy metals, nitrates, phosphates, sulfates, and other nutrient-based compounds. These substances enter the cells

alongside essential nutrients and micronutrients required for growth. Due to their high tolerance to hostile environments, microalgae can efficiently remove pollutants even at relatively low concentrations. This adaptability contributes to their elevated bioremediation potential in urban wastewater systems ^[26,27].

The effectiveness of bioaccumulation is often quantified using the bioconcentration factor, which represents the ratio of pollutant concentration within the biomass relative to that in the surrounding medium. The initial stage of bioaccumulation involves surface-level adsorption, where contaminants bind to the cell wall before being transported into the intracellular environment. Certain filamentous and unicellular algae have demonstrated exceptional accumulation capacities for pharmaceuticals and radioactive substances. Pollutant transport may occur through passive diffusion, particularly for nonpolar, lipid-soluble, low-molecular-weight compounds, while larger or polar molecules typically require active transport mechanisms. The interaction between contaminants and cellular membranes can alter membrane permeability, leading to physiological responses such as depolarization or hyperpolarization ^[24].

2.3.2. Biosorption

Biosorption is a passive remediation process that does not rely on metabolic activity and is typically conducted using dead or inactivated biological material. In this approach, microalgal biomass serves as a biosorbent that binds contaminants from the liquid phase onto its surface. The process is governed by mass transfer phenomena and continues until equilibrium is established between pollutant concentrations in the wastewater and on the biosorbent surface. Multiple mechanisms contribute to biosorption, including physical adsorption, chemical binding, electrostatic attraction, ion exchange, precipitation, and surface complexation. This method has been extensively applied for the removal of heavy metals from wastewater systems. Interestingly, trace amounts of certain metals can stimulate microalgal growth and enzymatic activity, as elements such as iron, copper, zinc, manganese, and cobalt play essential roles in cellular metabolism ^[13,28].

Microalgal cell walls are rich in functional groups derived from polysaccharides, proteins, lipids, and extracellular polymeric substances. These functional groups—such as carboxyl, hydroxyl, sulfate, and amine groups—

provide numerous binding sites for both cationic and anionic metal species. Biosorption generally occurs in two stages: a rapid initial phase involving reversible surface binding, followed by a slower phase characterized by intracellular diffusion or stronger complex formation. The efficiency of biosorption is influenced by wastewater composition, metal speciation, pH, temperature, and operational conditions. The presence of EPS significantly enhances biosorption capacity by increasing surface area and binding site availability ^[29].

2.3.3. Biodegradation

Biodegradation involves the enzymatic breakdown of complex and toxic compounds into simpler, less harmful end products. Unlike bioaccumulation and biosorption, which primarily immobilize contaminants, biodegradation results in chemical transformation through mineralization or partial conversion. Complete mineralization produces end products such as carbon dioxide and water, whereas transformation yields intermediate compounds with reduced toxicity. Biodegradation by microalgae can occur through metabolic degradation, in which contaminants serve as sources of carbon or electrons, or through enzyme-mediated metabolism involving intracellular or extracellular enzymes. Both intracellular and extracellular degradation pathways have been observed in microalgal systems. Extracellular polymeric substances play a crucial role by increasing pollutant bioavailability and facilitating emulsification.

Microalgal biodegradation generally proceeds through three sequential stages. The first stage involves oxidation or reduction reactions mediated by enzymes such as monooxygenases, hydrolases, and carboxylases, which enhance contaminant hydrophilicity. The second stage includes conjugation reactions facilitated by enzymes like glutathione-S-transferases, protecting cells from oxidative stress. The final stage results in the formation of non-toxic or low-toxicity end products through the action of dehydrogenases, transferases, laccases, and related enzymes. Even artificial intelligence can help achieve sustainability ^[19,30].

3. Impact of Co-Culturing Strategies in Wastewater Treatment

Co-culturing, also referred to as co-cultivation,

involves the simultaneous growth of two or more microbial species within a shared environment, enabling synergistic interactions that enhance wastewater treatment efficiency. This approach has gained increasing attention for its ability to improve contaminant removal and simplify biomass harvesting. One widely studied co-culturing strategy involves the integration of microalgae with filamentous fungi. This system typically operates through pellet formation followed by pellet recovery. Two primary methods are employed: the introduction of fungal spores into microalgal cultures or the addition of pre-formed fungal pellets. Both approaches promote bioflocculation, facilitating easier separation of biomass

from treated water.

Beyond fungi, bacterial-assisted microalgal harvesting has also demonstrated promising results. In some systems, bacteria, fungi, and microalgae are combined to form complex consortia that enhance biomass aggregation and pollutant removal. Such systems are particularly advantageous in industrial wastewater treatment, where sterilization is impractical and diverse microbial populations coexist naturally. Hydrophobic interactions between microbial surfaces—especially those mediated by fungal proteins—play a key role in promoting flocculation and stable pellet formation. **Figure 2** below shows the inclusion of fungal spores in the microalgae harvest.

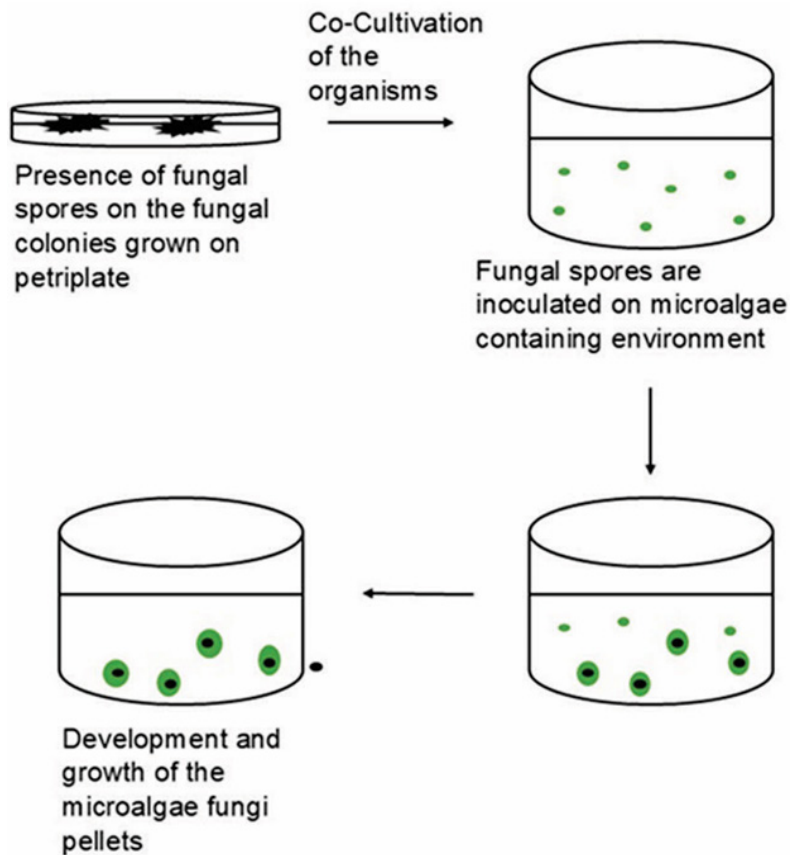


Figure 2. Inclusion of fungal spores in the microalgae harvest.

Nutrient-rich wastewater serves as an effective growth medium for co-cultured microbial systems. The combination of microalgae and fungi offers several advantages, including reduced operational costs, accelerated contaminant removal, and improved environmental sustainability. Excess nutrients such as nitrogen and phosphorus, which can otherwise cause eutrophication, are efficiently

assimilated through co-cultivation. Moreover, microalgae supply oxygen via photosynthesis, supporting aerobic fungal metabolism, while fungi release carbon dioxide that enhances algal photosynthesis. This reciprocal gas exchange strengthens system stability and efficiency.

Filamentous fungi further contribute by degrading complex organic matter and releasing extracellular en-

zymes that convert high-molecular-weight compounds into simpler substrates readily assimilated by microalgae. Co-cultivation also enhances heavy metal remediation. While microalgae can adsorb and accumulate metals, recovering these metals from algal biomass alone can be costly. The inclusion of fungi, which possess strong metal-binding capabilities, improves removal efficiency and simplifies biomass handling. Studies have shown that algal–fungal consortia outperform monocultures in heavy metal adsorption, highlighting the industrial relevance of co-culturing strategies.

4. Concept of a Circular Bioeconomy

Traditional refinery models are designed to convert raw materials into a limited range of value-added products, primarily focusing on economic output. In contrast, microalgal biorefineries represent an advanced and sustainable framework in which algal biomass is utilized to generate multiple products while simultaneously addressing environmental challenges. The incorporation of microalgae into wastewater treatment systems contributes to carbon dioxide mitigation, nutrient recovery, and the production of renewable biofuels and bioproducts such as chemicals, fertilizers, and dietary supplements.

Microalgae offer several advantages over conventional biomass sources, as they are not used as staple food crops and do not compete with agricultural land resources. Their rapid growth rates and high photosynthetic efficiency further enhance their suitability for integrated biorefinery applications. Increasing attention has been directed toward zero-waste biorefinery models, where both liquid and solid industrial effluents serve as feedstocks for microalgal cultivation and product recovery. The integration of microalgal systems with renewable energy technologies, such as solar-based processes, has the potential to enable near-zero carbon industrial operations.

Economic viability is a key consideration for the widespread adoption of microalgal biorefineries. Cost efficiency can be significantly improved by maximizing the utilization of all process outputs and optimizing downstream processing steps. Ongoing research aims to enhance biomass productivity and product yields while reducing

operational expenses. Certain microalgal species, including *Spirulina*, contain exceptionally high protein content and exhibit functional properties beneficial to human health, such as anti-inflammatory, antiviral, and antidiabetic effects. When cultivated in nutrient-rich wastewater environments, these species may also serve as valuable sources of essential minerals, provided appropriate safety and quality controls are implemented. Other commercially important microalgae, such as *Chlorella*, *Dunaliella*, and *Haematococcus*, are capable of producing bioactive compounds, including beta-carotene and astaxanthin, which have well-established health benefits. These attributes support the application of microalgal biomass in aquaculture feed, animal nutrition, and sustainable feedstock development. Further research into genetic enhancement and bioprocess optimization is necessary to expand agricultural and industrial applications.

Microalgae also present a promising alternative to fossil fuel-derived chemicals. Given growing concerns over the environmental impacts of petrochemical plastics, microalgal biomass is increasingly explored for the production of biodegradable polymers and bioplastics. The high lipid, carbohydrate, and starch content of certain microalgal strains supports efficient conversion into bio-based materials. Effective process management and product evaluation are essential to ensure economic feasibility and market competitiveness. In addition to material production, microalgae play a significant role in renewable energy generation, including biodiesel, biohydrogen, and biofertilizer production. Microalgal biofertilizers enhance seed germination and plant growth through bio-stimulatory effects, although broader market adoption requires improved strain selection and metabolite optimization. Under optimal cultivation conditions, microalgal systems can yield substantial quantities of biodiesel per hectare annually. Furthermore, wastewater-based cultivation can facilitate biohydrogen production through photobiological processes.

Despite their considerable theoretical potential, microalgal biorefineries face challenges related to scaling, capital investment, and limited industrial demonstration. Most existing studies remain confined to laboratory or pilot-scale experiments. To fully realize the benefits of circular bioeconomy integration, future research must prioritize large-scale operational data and real-world implementation

to validate technical and economic performance.

4.1. Research Gaps Identified from the Review

Despite extensive research on microalgae-based wastewater treatment, several critical gaps remain that hinder large-scale implementation in urban contexts. First, limited empirical evidence is available on the long-term operational stability of microalgal systems under fluctuating wastewater characteristics, seasonal variations, and prolonged exposure to toxic compounds. Most reported studies are conducted under controlled laboratory or short-term pilot conditions, which do not fully reflect real operational environments.

Second, challenges associated with scaling up microalgal wastewater treatment from laboratory and pilot scales to full-scale commercial applications remain insufficiently addressed. Issues related to reactor design, biomass harvesting efficiency, land requirements, and process integration continue to constrain practical deployment.

Third, the integration of microalgal treatment systems with existing urban wastewater treatment infrastructure requires further investigation. Limited studies evaluate how microalgal processes can be retrofitted into conventional treatment trains without disrupting existing operations or significantly increasing capital costs.

Finally, comprehensive economic feasibility analyses and life-cycle assessments are scarce. While many studies highlight environmental benefits, fewer evaluate long-term cost efficiency, energy balance, and environmental trade-offs associated with large-scale microalgal systems. Addressing these gaps is essential for advancing microalgae-based technologies from experimental concepts to viable solutions for sustainable urban wastewater management.

4.2. Discussions

Future research should prioritize innovation in integrated monitoring systems, data-driven early warning mechanisms, and digital decision-support tools. Advances in remote sensing, real-time analytics, and participatory platforms offer opportunities to enhance anticipatory capacity and adaptive management. Interdisciplinary approaches combining engineering, data science, and governance studies are particularly promising.

5. Conclusions

The pervasive presence of environmental pollutants in wastewater represents a serious threat to ecosystems and public health. Extensive research has demonstrated that microalgae-based wastewater treatment offers substantial advantages over conventional treatment technologies. Microalgae are capable of removing a wide range of contaminants from diverse wastewater sources without generating secondary pollution or activated sludge. Beyond pollutant removal, microalgae enable the recovery of valuable resources and support the development of circular bioeconomy models. Biomass generated during wastewater treatment can be repurposed for the production of biofuels, biofertilizers, pharmaceuticals, and nutritionally valuable products, contributing to both economic growth and energy conservation. The integration of microalgal biorefineries into urban wastewater treatment infrastructure presents a promising pathway toward sustainable environmental management.

However, challenges related to biomass harvesting, contaminant recovery, and process optimization remain. Addressing these limitations through targeted research and technological innovation is essential for advancing large-scale implementation. With continued development, microalgae-based systems have the potential to transform wastewater treatment into a resource-efficient and environmentally responsible process.

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Conceptualization, methodology, validation, A.J.; investigation, writing—original draft preparation, H.V.; writing—review and editing, M.K. All authors have read and agreed to the published version of the manuscript.

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References

- [1] Abdelfattah, A., Ali, S.S., Ramadan, H., et al., 2023. Microalgae-Based Wastewater Treatment: Mechanisms, Challenges, Recent Advances, and Future Prospects. *Environmental Science and Ecotechnology*. 13, 100205. DOI: <https://doi.org/10.1016/j.ese.2022.100205>
- [2] Almomani, F., Judd, S., Bhosale, R.R., et al., 2019. Integrated Wastewater Treatment and Carbon Bio-Fixation from Flue Gases Using *Spirulina platensis* and Mixed Algal Culture. *Process Safety and Environmental Protection*. 124, 240–250. DOI: <https://doi.org/10.1016/j.psep.2019.02.009>
- [3] Jain, A., Varma, H., 2025. Fusing Wellness and Innovation within Eco-Friendly Structures: An Exhaustive Critique on Tracking and Enhancing Interior Air Conditions. *Urban Resilience and Sustainability*. 3(4), 306–327. DOI: <https://doi.org/10.3934/urs.2025016>
- [4] Behera, B., Supraja, K.V., Paramasivan, B., 2021. Integrated Microalgal Biorefinery for the Production and Application of Bio Stimulants in Circular Bioeconomy. *Bioresource Technology*. 339, 125588. DOI: <https://doi.org/10.1016/j.biortech.2021.125588>
- [5] Chai, W.S., Tan, W.G., Munawaroh, H.S.H., et al., 2021. Multifaceted Roles of Microalgae in the Application of Wastewater Biotreatment: A Review. *Environmental Pollution*. 269, 116236. DOI: <https://doi.org/10.1016/j.envpol.2020.116236>
- [6] Chawla, P., Malik, A., Sreekrishnan, T.R., et al., 2020. Selection of Optimum Combination via Comprehensive Comparison of Multiple Algal Cultures for Treatment of Diverse Wastewaters. *Environmental Technology & Innovation*. 18, 100758. DOI: <https://doi.org/10.1016/j.eti.2020.100758>
- [7] Chia, W.Y., Tang, D.Y.Y., Khoo, K.S., et al., 2020. Nature's Fight against Plastic Pollution: Algae for Plastic Biodegradation and Bioplastics Production. *Environmental Science and Ecotechnology*. 4, 100065. DOI: <https://doi.org/10.1016/j.ese.2020.100065>
- [8] Crini, G., Lichtfouse, E., 2019. Advantages and Disadvantages of Techniques Used for Wastewater Treatment. *Environmental Chemistry Letters*. 17, 145–155. DOI: <https://doi.org/10.1007/s10311-018-0785-9>
- [9] Estevam, R., Gonçalves, R.F., Cipriano, D.F., et al., 2025. Single-Step Sustainable Production of Activated Carbon from Microalgal Biomass: An Approach to Waste Recovery from Urban Wastewater. *Algal Research*. 87, 103977. DOI: <https://doi.org/10.1016/j.algal.2025.103977>
- [10] Ferronato, N., Torretta, V., 2019. Waste Mismanagement in Developing Countries: A Review of Global Issues. *International Journal of Environmental Research and Public Health*. 16(6), 1060. DOI: <https://doi.org/10.3390/ijerph16061060>
- [11] Goswami, R.K., Mehariya, S., Verma, P., et al., 2021. Microalgae-Based Biorefineries for Sustainable Resource Recovery from Wastewater. *Journal of Water Process Engineering*. 40, 101747. DOI: <https://doi.org/10.1016/j.jwpe.2020.101747>
- [12] Hena, S., Gutierrez, L., Croué, J.P., 2021. Removal of Pharmaceutical and Personal Care Products (PPCPs) from Wastewater Using Microalgae: A Review. *Journal of Hazardous Materials*. 403, 124041. DOI: <https://doi.org/10.1016/j.jhazmat.2020.124041>
- [13] Javed, F., Al-Zuhair, S., 2025. Role of Microalgae and Activated Sludge in the Removal of Fats, Oils, and Grease (FOG) in Municipal Wastewater. *Chemical Engineering Journal Advances*. 22, 100737. DOI: <https://doi.org/10.1016/j.ceja.2025.100737>
- [14] Leong, Y.K., Chang, J.S., 2020. Bioremediation of Heavy Metals Using Microalgae: Recent Advances and Mechanisms. *Bioresource Technology*. 303, 122886. DOI: <https://doi.org/10.1016/j.biortech.2020.122886>
- [15] Lin, W., Chen, L., Tan, Z., et al., 2022. Application of Filamentous Fungi in Microalgae-Based Wastewater Remediation for Biomass Harvesting and Utilization: From Mechanisms to Practical Application. *Algal Research*. 62, 102614. DOI: <https://doi.org/10.1016/j.algal.2021.102614>
- [16] Maryjoseph, S., Ketheesan, B., 2020. Microalgal-Based Wastewater Treatment for the Removal of

- Emerging Contaminants: A Review of Challenges and Opportunities. *Case Studies in Chemical and Environmental Engineering*. 2, 100046. DOI: <https://doi.org/10.1016/j.cscee.2020.100046>
- [17] Mohsenpour, S.F., Hennige, S., Willoughby, N., et al., 2021. Integrating Micro-Algae into Wastewater Treatment: A Review. *Science of the Total Environment*. 752, 142168. DOI: <https://doi.org/10.1016/j.scitotenv.2020.142168>
- [18] Mojiri, A., Baharlooeian, M., Kazeroon, R.A., et al., 2020. Removal of Pharmaceutical Micropollutants with Integrated Biochar and Marine Microalgae. *Microorganisms*. 9(1), 4. DOI: <https://doi.org/10.3390/microorganisms9010004>
- [19] Nápoles-Armenta, J., Romero-Soto, I.C., Samaniego-Moreno, L., et al., 2025. Advanced Municipal Wastewater Treatment and Bioproduct Generation via Optimized Autotrophic and Mixotrophic Microalgal Cultivation. *Sustainability*. 17(14), 6539. DOI: <https://doi.org/10.3390/su17146539>
- [20] Orejuela-Escobar, L., Gualle, A., Ochoa-Herrera, V., et al., 2021. Prospects of Microalgae for Biomaterial Production and Environmental Applications at Biorefineries. *Sustainability*. 13(6), 3063. DOI: <https://doi.org/10.3390/su13063063>
- [21] Plöhn, M., Spain, O., Sirin, S., et al., 2021. Wastewater Treatment by Microalgae. *Physiologia Plantarum*. 173(2), 568–578. DOI: <https://doi.org/10.1111/ppl.13427>
- [22] Priyadharshini, S.D., Babu, P.S., Manikandan, S., et al., 2021. Phycoremediation of Wastewater for Pollutant Removal: A Green Approach to Environmental Protection and Long-Term Remediation. *Environmental Pollution*. 290, 117989. DOI: <https://doi.org/10.1016/j.envpol.2021.117989>
- [23] Rempel, A., Gutkoski, J.P., Nazari, M.T., et al., 2021. Current Advances in Microalgae-Based Bioremediation and Other Technologies for Emerging Contaminants Treatment. *Science of the Total Environment*. 772, 144918. DOI: <https://doi.org/10.1016/j.scitotenv.2020.144918>
- [24] Verma, K., Kumar, P.K., Krishna, S.V., et al., 2020. Phycoremediation of Sewage Contaminated Lake Water Using Microalgae–Bacteria Co-Culture. *Water, Air, & Soil Pollution*. 231, 299. DOI: <https://doi.org/10.1007/s11270-020-04652-5>
- [25] Reddy, A.P., Mankal, N., Hoque, M.E., et al., 2025. Recent Advancements in Urban Wastewater Management—Recommendations and Future Directions. *Journal of Water Management Modeling*. 33, C565. DOI: <https://doi.org/10.14796/JWMM.C565>
- [26] Salama, E.S., Roh, H.S., Dev, S., et al., 2019. Algae as a Green Technology for Heavy Metals Removal from Various Wastewater. *World Journal of Microbiology and Biotechnology*. 35, 75. DOI: <https://doi.org/10.1007/s11274-019-2648-3>
- [27] Sutherland, D.L., Ralph, P.J., 2019. Microalgal Bioremediation of Emerging Contaminants: Opportunities and Challenges. *Water Research*. 164, 114921. DOI: <https://doi.org/10.1016/j.watres.2019.114921>
- [28] Wang, J., Chen, R., Fan, L., et al., 2021. Construction of Fungi-Microalgae Symbiotic System and Adsorption Study of Heavy Metal Ions. *Separation and Purification Technology*. 268, 118689. DOI: <https://doi.org/10.1016/j.seppur.2021.118689>
- [29] Wen, X., Chen, F., Lin, Y., et al., 2020. Microbial Indicators and Their Use for Monitoring Drinking Water Quality—A Review. *Sustainability*. 12(6), 2249. DOI: <https://doi.org/10.3390/su12062249>
- [30] Jain, A., Babu, K.A., 2025. Reviewing the Green Building Concepts along with the Applications of AI and IoT for Environmental Monitoring and Designing Sustainable Infrastructures. *Journal of Informatics and Mathematical Sciences*. 17(1), 123–145. DOI: <https://doi.org/10.26713/jims.v17i1.3056>