

Microalgae-Based Wastewater Treatment as Green Solution for Sustainable Degradation and Its Challenges: A Review

Eva Musifa^{1*}, Neza Rahayu Palapa¹, Bijak Riyandi Ahadito¹

¹Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Ogan Ilir, 30662, Indonesia

*Corresponding author e-mail: evamusifa@mipa.unsri.ac.id

Abstract

Releasing polluted water directly into the environment causes serious problems because it contains harmful substances that can damage aquatic life and human health. To reduce these risks, it is important to treat and clean wastewater effectively. Microalgae have shown promise as a natural and sustainable way to treat wastewater. The microalgae help to remove pollutants and can also recover useful resources and energy from the water. The study used a systematic review methodology to identify and evaluate the role of microalgae wastewater treatment. The method was used since it provides a structures and transparent framework for selection, assessment and synthesise of evidence from relevant literature. This review highlights the benefits of using microalgae for wastewater treatment, as well as the challenges involved. Ongoing research focuses on improving these methods, including combining microalgae with bacteria to make the process more efficient and scalable. Despite some difficulties like contamination risks and regulatory issues, future advances especially in genetic engineering and hybrid systems are expected to improve microalgae-based wastewater treatment and make it a key tool for protecting the environment, while multidisciplinary collaboration combining molecular biology research, environmental engineering, public policy, and utilization of this technology at the industrial and societal levels that should be under consideration.

Keywords

Microalgae, Wastewater, Degradation Treatment, Challenges

Received: 23 April 2025, Accepted: 4 August 2025

<https://doi.org/10.26554/ijems.2025.9.4.171-182>

1. INTRODUCTION

Water is a vital resource and an important material in various industries, including pharmaceutical, electronics, food and beverage, petrochemical, agrochemical, oil and gas, and other domestic applications. Significant environmental hazards can be caused by direct discharge of contaminated water and are of increasing concern due to the presence of numerous pollutants (Morseletto et al., 2022). Wastewater contains several chemicals that are highly hazardous to aquatic life and humans. In addition, significant increases in chemical oxygen demand (COD) and biological oxygen demand (BOD) are seen as large amounts of inorganic and organic nutrients are discharged into the environment as evidenced by *p. Eutrophication* of aquatic ecosystems due to excessive input of phosphorus (P) and (N) causes environmental problems, as well as production of unwanted solid waste and air emissions (Chen et al., 2020). It also facilitates the spread of detrimental bacteria that adversely affect other aquatic creatures and deteriorates the quality of drinking water, consequently exacerbating prevalent health

issues in regions around the discharge site (Hena et al., 2021). Heavy metals are the predominant group of pollutants in wastewater. The adverse effects are a major health risk and increase the possibility of cancer development when inhalation, consumption, and direct contact with these toxic compounds occur, even at minimal concentrations (Mo et al., 2022; Abidli et al., 2022). In recent years, there has been increasing concern about the presence of new pollutants in water bodies, along with their associated risks and impacts on human health and aquatic organisms (Singh et al., 2021). New pollutants are synthetic organic compounds that have long been present in the environment, but have only recently become recognized due to increased awareness of their dangers and improvements in analytical techniques. (Ali et al., 2021b; Munyaneza et al., 2022). Contaminants include several categories, including polyfluoroalkyl substances (PFAS), flame retardants, pharmaceutical compounds (PCs), illicit drugs, pesticides, and artificial sweeteners (Hena et al., 2021; Singh et al., 2021). Their adverse effects on human health and the environment are not yet fully understood (Ali et al., 2021a; Mastropetros et al., 2022).

Microalgae have come as one of the promising solutions for wastewater degradation, especially in the context of environmental protection and sustainable development. The convergence of ecological engineering and biotechnological innovation can be seen in the utilization of microalgae for wastewater treatment, for example, degrading organic compounds and recovering nutrients in wastewater. According to Wirth et al. (2020) the ability of microalgae to absorb excessive nutrients, especially nitrogen and phosphorus, which have an important role in eutrophication in aquatic systems is one of the main advantages in using microalgae for wastewater treatment. Previous studies indicate that microalgae can effectively remove organic matter while producing biomass that can be used for biofuel production or other high-value products. In line with further research where when the combination of microalgae cultivation with anaerobic digestion processes, the potential of microalgae increases in converting organic waste into methane and other bio products, which encourages waste reduction and energy sustainability (Rajagopal et al., 2021).

Experimental studies have shown success in the use of microalgae species for bioremediation of wastewater from various industrial sources, such as palm oil and tapioca processing industries (Baihaqi and Pratama, 2023), so that the microalgae species such as *Chlorella* and *Spirulina* have been well known for their high growth rates and rapid nutrient uptake, making them suitable candidates for industrial-scale bioremediation efforts (Mehariya et al., 2021). The combination of microalgae with anaerobic digestion also shows promise not only in purifying wastewater but also in developing overall biogas production, so that the resource potential of food processing waste and agricultural waste is maximized (Sendžikienė and Makarevičienė, 2022; Xiarchis et al., 2024). In addition, the development of innovative strategies in improving microalgae in wastewater environments can create significant research materials such as in optimizing culture conditions and exploring microalgae-bacteria consortium interactions. This aims to make the rate of organic compound removal in the liquid waste processing process more efficient and can reduce the negative effects of conventional waste processing which tends to require a lot of energy and funds (Zhao et al., 2022). Another study from (Mo et al., 2022) reveals that bacteria and microalgae that are involved in POME treatment, microalgae give high removal of colour (93%) and ammoniacal nitrogen (95%). This since microalgae and bacteria can effectively degrade waste through a symbiotic relationship. Bacteria break down organic pollutants, releasing nutrients that microalgae utilize for growth, while microalgae, through photosynthesis, produce oxygen that supports bacterial respiration and growth. This interplay creates a mutually beneficial system for wastewater treatment and resource recovery (Abdelfattah et al., 2023). The studies provide an important insight into developing an efficient and environmentally friendly method to treat wastewater by incorporating green technology in the treat-

ment system

The role of microalgae in answering the challenges of wastewater is not only able to remove pollutants, but also able to restore resources and energy including a holistic approach to such recovery. Microalgae can contribute to the circular economy sector by being able to provide raw materials for biofuels, animal feed, and biochemical through their potential in producing biomass (Musifa et al., 2023). This integration not only creates opportunities for the developing bio economy but also supports a sustainable environment. Microalgae are not only an innovative solution for liquid waste biodegradation but are also able to be an environmentally friendly alternative that is in line with a sustainable environment (El-Sheekh et al., 2025). Continuous research and development in this field has been proven to be able to optimize the use of microalgae in liquid waste management, so that it is very effective in pollutant degradation and recovery of high-value resources and paves the way for a sustainable and cleaner ecosystem (Ramírez Mérida and Rodríguez Padrón, 2023). Therefore, this review highlights the potential of microalgae in acting as a sustainable and effective solution in wastewater degradation and the challenges of wastewater degradation processes using microalgae as well as investigation into enzymatic pathways and hybrid systems, such as algal-bacterial consortia, that improve their scalability and solidify microalgae's role as a vital instrument in environmental remediation.

2. MATERIALS AND METHODS

2.1 Research Design

The study used a systematic review methodology to identify and evaluate the role of microalgae wastewater treatment. The method was used because it provides a structures and transparent framework for selection, assessment and synthesize of evidence from relevant literature (Tedja et al., 2024).

2.2 Inclusion and Exclusion

2.2.1 Inclusion Criteria

The inclusion criteria are articles published from 2015 to 2025, studies focused on microalgae wastewater treatment, peer-reviewed articles and studies that used for type of mechanism of liquid waste degradation, microalgae cultivation for wastewater treatment and synergies between microalgae in bioremediation techniques (Tedja et al., 2024).

2.2.2 Exclusion Criteria

The exclusion criteria are articles not relevant to the topic of microalgae wastewater treatment and incomplete article.

2.3 Study Selection

Initial selection was done by screening the title and abstracts of articles obtained from literature searches. Articles that met the inclusion criteria were then further evaluated by reading the full text.

2.4 Literature Search Strategy

Literature searches were conducted in several scientific data bases, including PubMed, Scopus, Web of Science and Google Scholar. The keywords used include: “microalgae wastewater treatment, “nutrient removal, “bioremediation”, and “sustainable degradation.” The Search also included combination of the keywords using logical operators (AND, OR) to expand and refine the searching result (Tedja et al., 2024).

2.5 Data Extraction

Data extracted from selected article include: type of microalgae, type of degradation used by microalgae, and consortia for wastewater treatment. The extracted data are arranged in tabular form to facilitate analysis.

2.6 Data Analysis

The extracted data were analyzed qualitatively to identify common patterns, successes, and challenges in the use of microalgae for wastewater treatment. In addition, eligible articles were analyzed descriptively to develop a comprehensive narrative on the microalgae wastewater treatment. The result systematic review will be synthesized to provide original insights into the type of mechanism of liquid waste degradation, microalgae cultivation for wastewater treatment and synergies between microalgae in bioremediation techniques.

3. RESULTS AND DISCUSSION

Following a literature search using databases as PubMed, Scopus, Web of Science and Google Scholar with relevant keywords, a total of 135 articles were identified. After screening titles and abstract, 60 articles met inclusion and exclusion criteria. Out of 60 articles, 40 were evaluated and 24 articles related to microalgae wastewater treatment were selected in analysis. The characteristics of the studies included in this review encompass the type of mechanism of liquid waste degradation, microalgae cultivation for wastewater treatment and synergies between microalgae in bioremediation techniques.

3.1 Mechanisms of Liquid Waste Degradation

3.1.1 Nutrient Removal

Microalgae employ intricate metabolic processes to treat wastewater and remove elements like nitrogen and phosphorus. This positively influences the provision of a sustainable, ecologically friendly alternative to conventional wastewater treatment methods. These organisms work to convert inorganic nutrients into biomass while reducing contaminants through enzymatic and physicochemical mechanisms, aided by their adaptation to various wastewater conditions (Al-Dahhan et al., 2018; Touliabah et al., 2022). Nitrogen removal occurs mostly through incorporation into proteins and nucleic acids, while in previous studies microalgae such

as *Chlorella vulgaris* absorbed ammonium (NH_4^+) and nitrate (NO_3^-) through active transport (Al-Dahhan et al., 2018). Enzymes such as nitrate reductase and glutamine synthetase catalyze the transformation of nitrate into ammonium and its subsequent integration into amino acids (Touliabah et al., 2022). The process of photosynthesis significantly contributes to the elevation of wastewater pH and promotes the volatilization of ammonium into ammonia (NH_3), thereby diminishing nitrogen concentrations and impeding pathogen growth. The phosphorus removal process comprises two mechanisms: direct uptake as phosphate (PO_4^{3-}) for ATP and phospholipid synthesis, and chemical precipitation of calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$) under alkaline conditions, aided by microalgae. Studies demonstrate that strains such as *Chlorella* can get over 90% phosphate removal in municipal wastewater (Al-Dahhan et al., 2018). Microalgae incorporate inorganic nitrogen (NH_4^+ , NO_3^-) through enzymatic mechanisms. *Chlorella vulgaris* converts nitrate to ammonium by the action of nitrate reductase and nitrite reductase, then integrating NH_4^+ into amino acids such as glutamine via an ATP-dependent mechanism. The elevation of pH due to photosynthesis above 10 volatilizes ammonia, hence preventing pathogens like *E. coli* (Ramírez Mérida and Rodríguez Padrón, 2023). Studies demonstrate that strains such as *Chlorella* sp. FACHB-31 have achieved $\text{NH}_4^+ - \text{N}$ removal rates of 97% in anaerobic digestion wastewater (Chen et al., 2021). Furthermore, phosphorus is assimilated as PO_4^{3-} for the production of ATP and nucleic acids. *Chlorella vulgaris* removes more than 90% of phosphate from urban wastewater, while alkaline conditions ($\text{pH} > 8$) facilitate the formation of calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$). On the other side, co-culturing with bacteria enhances the phosphorus cycle through the accumulation of polyphosphate (Abdelfattah et al., 2023), which substantially aids the waste degradation process. The Table 1 displays the comparative efficacy of microalgae strains.

3.1.2 Heavy Metal Removal

Microalgae have emerged as a viable alternative for the extraction of heavy metals from wastewater owing to their significant biosorption capability, environmentally favorable characteristics, and economic efficiency. Various strains demonstrate differing efficacy contingent upon their cell wall composition, functional groups, and environmental circumstances. *Chlorella vulgaris* has shown the capacity to eliminate up to 94.1% of lead (Pb) and 81.7% of copper (Cu) from wastewater within 10 days, whereas *Scenedesmus acutus* attained 98% Pb removal in a shorter timeframe. The biosorption process depends on functional groups, including carboxyl ($-\text{COOH}$), amino ($-\text{NH}_2$), hydroxyl ($-\text{OH}$), and phosphate ($-\text{PO}_4$), located on the microalgae cell walls, which serve as binding sites for metal ions via ion exchange or electrostatic interactions (Spain et al., 2021a; Mahlangu et al., 2024b; Sultana et al., 2020).

Environmental conditions substantially affect biosorp-

Table 1. Microalgae in Nutrient Removal

Species	Nitrogen Removal	Phosphorus Removal	Biomass Yield (g/L)	References
<i>Chlorella vulgaris</i>	97.8	91	2.03	(Kundu et al., 2024)
<i>Scenedesmus</i> sp.	89	85	1.2-1.8	(Mostafaei et al., 2023)
<i>Chlamydomonas</i> sp.	83	78	1.0-1.5	(Mostafaei et al., 2023)

tion efficacy. Optimal pH levels, generally alkaline circumstances ranging from pH 6 to 9, augment metal solubility and binding capacity, while temperatures between 20 and 30°C, along with sufficient light intensity, boost enzyme activity and photosynthesis (Sultana et al., 2020). Pre-treatment methods, including biomass cross-linking with chemicals such as polysulfane or formaldehyde, enhance the mechanical strength and chemical resilience of microalgae biomass, hence simplifying its separation from effluent. Nonetheless, cross-linking may diminish sorption capacity and impede metal uptake rates (Salam, 2019). *Chlorella kessleri* also exhibits significant biosorption efficacy for metals such as cadmium (Cd) and chromium (Cr), whereas *Nostoc punctiforme* attained a lead (Pb) removal rate of up to 98%. Research employing response surface methodology (RSM) has refined biosorption settings, pinpointing factors including pH 6.34, temperature 27.71°C, and biomass dose of 1.5 g/L to achieve a maximum lead removal rate of 99.54%. Notwithstanding these encouraging outcomes, issues including scalability, biomass reusability, and interaction with traditional treatment systems persist as topics necessitating additional research (Mahlangu et al., 2024a). Therefore, microalgae-based biosorption presents a sustainable alternative to conventional heavy metal remediation techniques. Ongoing investigation into strain-specific optimization, practical applications, and hybrid systems may improve its feasibility for extensive wastewater treatment. Table 2 shows the comparison of the ability of microalgae to absorb heavy metals

Microalgae utilize many ways to decompose liquid waste and eliminate heavy metals, chiefly through biosorption, bioaccumulation, and biotransformation. Biosorption is an expedited process in which heavy metal ions adhere to the surfaces of microalgae cells, frequently incorporating functional groups such as carboxyl and amino groups. This technique is reversible and can take place in both living and non-living cells, rendering it a cost-effective and environmentally sustainable method for the removal of metals such as lead (Pb), cadmium (Cd), and mercury (Hg) (Rinanti et al., 2021; Joseph et al., 2024). Bioaccumulation entails the active transfer of heavy metals into cells, where they are sequestered, thereby diminishing their bioavailability in the environment. This procedure necessitates viable cells and ideal growing circumstances, hence improving the efficacy of metal removal, specifically chromium (Cr) and arsenic (As) (Chakravorty et al., 2023; Leong and Chan, 2020).

Biotransformation, however less prevalent, entails the enzymatic conversion of hazardous metals into less harmful forms, providing a more enduring remedy for heavy metal contamination (Sattayawat et al., 2021). Microalgae, including *Chlorella*, *Spirulina*, and *Scenedesmus*, have been recognized as efficient biosorbents for numerous heavy metals, with *Chlorella* demonstrating significant removal efficiency for lead and cadmium. Explorations in synthetic biology are underway to augment these systems by genetically modifying microalgae to exhibit enhanced tolerance to heavy metals and improved removal efficiency (Chakravorty et al., 2023). Microalgae-based systems present a viable alternative for heavy metal remediation, owing to their environmental sustainability and capacity for resource recovery. Table 3 summarizing the mechanisms of liquid waste degradation by microalgae in heavy metal removal.

3.1.3 Biodegradation of Organic Pollutants

Microalgae exhibit considerable potential for the biodegradation of detrimental organic pollutants, such as detergents, pesticides, medicines, and industrial waste, through enzymatic mechanisms and metabolic flexibility. This method utilizes biosorption, bioaccumulation, and biodegradation strategies to convert complex substances into less dangerous by-products, making them environmentally sustainable for wastewater treatment (Kundu et al., 2024; Sharma et al., 2024). The biosorption method begins with the attachment of pollutants to the microalgae cell walls through ion exchange or electrostatic interactions, while the biodegradation process occurs via enzymatic decomposition, which consists of three stages: oxidation or hydrolysis by cytochrome P450 enzymes, formation of conjugated compounds with neutralizing agents such as glutathione, and the eventual breakdown into non-toxic metabolites by enzymes like lactase. Microalgae can remove contaminants or pollutants either directly through co-metabolism or as a carbon source in metabolic biodegradation (Nie et al., 2019). *Chlorella vulgaris* has shown a removal efficiency of more than 90% for the pollutant compounds fluoranthene and pyrene within a period of seven days. Research indicates that surfactants like nonylphenol are biodegraded by organisms such as *Chlorella sorokiniana* and *Scenedesmus quadricauda*, with efficiencies ranging from 43% to 91%. Microalgae, including *Navicula* sp., have demonstrated efficacy in degrading pharmaceuticals like antibiotics via extracellular polymeric substances (EPS) that facilitate enzymatic absorption and

Table 2. Microalgae in Heavy Metal Removal

Species	Heavy Metal	Removal Efficiency (%)	References
<i>Chlorella vulgaris</i>	Cd	88-91	(Spain et al., 2021a)
<i>Chlorella vulgaris</i>	Pb	84-89	(Spain et al., 2021b)
<i>Chlorella vulgaris</i>	Hg	Not specified	(Chakravorty et al., 2023)
<i>Scenedesmus acutus</i>	Cd	94	(Chakravorty et al., 2023)
<i>Scenedesmus acutus</i>	Pb	89	(Chakravorty et al., 2023)
<i>Lyngbya spiralis</i>	Hg	96	(Chakravorty et al., 2023)
<i>Lyngbya heironymusii</i>	Cd	97	(Chakravorty et al., 2023)
<i>Nostoc punctiforme</i>	Pb	98	(Chakravorty et al., 2023)
<i>Chlamydomonas variabilis</i>	Cd	97.9 (oven dried)	(El-Awamri et al., 2015)
<i>Chlamydomonas variabilis</i>	Pb	96.1 (oven dried)	(El-Awamri et al., 2015)
<i>Anabaena constricta</i>	Cd	95.1 (oven dried)	(El-Awamri et al., 2015)
<i>Anabaena constricta</i>	Pb	93.7 (oven dried)	(El-Awamri et al., 2015)

Table 3. Mechanism of Wastewater Treatment by Microalgae in Heavy Metal Removal

Mechanism	Description	Heavy Metals Affected	Efficiency Factors	References
Biosorption	Binding of heavy metals to microalgae cell surfaces via functional groups like carboxyl and amino groups.	Cd, Pb, Hg, Cr, Cu	pH, Temperature, Biomass Preparation	(Sattayawat et al., 2021)
Bioaccumulation	Active transport and intracellular storage of heavy metals.	Cd, Pb, Hg, As	Nutrient Availability, Light Intensity	(Joseph et al., 2024)
Biotransformation	Enzymatic conversion of toxic metals into less toxic forms.	As, Hg	Specific Enzymes, Redox Conditions	(Kundu et al., 2024; Wang et al., 2019)
Phytoremediation	Use of microalgae to remove pollutants through biosorption and bioaccumulation.	Pb, Cr, Hg, As, Cd, Cu	Microalgae Species, Environmental Conditions	(Wang et al., 2019; Joseph et al., 2024)
Synthetic Biology Enhancements	Genetic engineering to improve heavy metal removal efficiency.	Mn, Fe, Cu, Zn, As, Cd, Hg, Pb	Genetic Parts, Bioengineering Approaches	(Sattayawat et al., 2021)

disintegration. Factors such as environmental conditions, including pH, light intensity, temperature, and nutrient ratios, strongly influence the efficacy of this process. Elevated pH levels resulting from CO₂ absorption enhance pollutant solubility and enzyme activity, whereas optimal light and temperature conditions (20–30°C) facilitate photosynthetic efficiency. Research indicates that an ideal carbon-nitrogen-phosphorus ratio (100:18:2) enhances enzymatic activity and biomass production (Goncu et al., 2025). The benefits of microalgae-based biodegradation encompass its capacity to eradicate secondary pollution by transforming toxins into valuable biomass for biofuels or bioplastics, as well as its cost-effectiveness relative to chemical treatments. Nonetheless, obstacles persist in the secure disposal of toxin-contaminated biomass following bioaccumulation and in enhancing enzyme kinetics for industrial scaling. Notwithstanding these constraints, microalgae-based systems present a viable solution

for mitigating stubborn organic pollutants (Sharma et al., 2024).

3.2 Microalgae Cultivation for Wastewater Treatment

3.2.1 Cultivation Methods

The growth of microalgae for wastewater treatment predominantly utilizes two principal methods: open ponds and closed photobioreactors (PBRs). Each approach possesses unique advantages and limitations, rendering them appropriate for particular applications contingent upon cost, efficiency, and environmental circumstances. Open ponds represent one of the most ancient and fundamental techniques for microalgae cultivation. These systems comprise natural water bodies (e.g., lakes, lagoons) or artificial constructs such as raceway ponds and circular tanks. Raceway ponds, a prevalent design, have shallow canals equipped with paddlewheels to

circulate water and inhibit sedimentation. Open ponds are extensively utilized owing to their minimal building, operational, and maintenance expenses. They are energy-efficient and readily scalable for processing substantial quantities of wastewater (González-Camejo et al., 2021).

Nonetheless, open ponds encounter considerable obstacles. The open design of these systems renders them particularly vulnerable to contamination by protozoa, bacteria, or other pathogens. Environmental variables, including rainwater runoff, temperature swings, and variations in light intensity, might impede the growth of microalgae. Moreover, these systems necessitate extensive land expanses, which may be impractical in urban or space-restricted environments. Notwithstanding these constraints, open ponds continue to be an economical solution for extensive wastewater treatment in areas with appropriate climatic conditions (Tan et al., 2020). On the other hand, photobioreactors are enclosed devices engineered to create regulated conditions for the production of microalgae. They are available in multiple formats, including tubular, flat-panel, and columnar designs. In contrast to open ponds, PBRs provide meticulous regulation of growth parameters like light intensity, temperature, nutrient availability, and gas exchange. This management improves biomass productivity and pollutant removal efficacy while reducing contamination risk (Xiao and Luo, 2022).

The principal drawback of PBRs is their elevated capital and operational expenses relative to open ponds. The intricate design necessitates sophisticated materials and technology for creation and upkeep. Challenges such as biofouling (the deposition of microorganisms on surfaces), thermal overload, and oxygen accumulation might impede their efficiency if not adequately addressed. Notwithstanding these obstacles, PBRs are optimal for applications necessitating high-quality biomass production or in scenarios with spatial constraints (Chanquia et al., 2022). Therefore, Open ponds and photobioreactors possess distinct advantages that render them appropriate for various wastewater treatment contexts. Open ponds are economically viable for extensive operations in conducive conditions, although they pose increased hazards of pollution and environmental disturbances. Conversely, photobioreactors provide enhanced control over cultivation conditions and increased efficiency, but at a much elevated cost. The selection of these technologies is contingent upon criteria including financial limitations, land accessibility, wastewater properties, and the required quality of biomass (Narala et al., 2016). The Table 4 depicts the comparison of cultivation methods for microalgae in wastewater treatment.

3.2.2 Optimization Factors of Microalgae Growth

Enhancing microalgae growth for liquid waste processing entails several critical parameters, each essential for optimizing biomass production and nutrient removal efficacy. The principal optimization factors are as follows:

3.2.2.1 Luminous Intensity

Luminous intensity is crucial for microalgae development in wastewater treatment systems, as it directly affects photosynthesis and biomass production. Microalgae necessitate ideal light conditions to enhance their growth rates and nutrient removal efficiency. At low light intensities, microalgal development is constrained, but excessive light may cause photoinhibition, impairing the photosynthetic system and diminishing photosynthetic efficiency (Maltsev et al., 2021). Research indicates that augmenting light intensity to a saturation threshold improves biomass production and lipid accumulation in microalgae. For example, elevating light intensity from 50 to 300 $\mu\text{E m}^2 \text{s}^{-1}$ markedly enhanced biomass and fatty acid synthesis in various microalgal species (Maltsev et al., 2021; Nzayisenga et al., 2020). The ideal light intensity differs among species like *Chlorella vulgaris* that attains optimal development at intensities of 2000 $\mu\text{mol/m}^2 \text{s}$ (Ge et al., 2013). The wavelength of light influences microalgal growth, with red light frequently proving more effective for nutrient removal than blue, white, or yellow light. Red light has been demonstrated to improve nitrogen removal effectiveness in high-strength wastewater. The utilization of artificial light sources, such as LEDs, facilitates regulated lighting conditions, essential for enhancing microalgae proliferation and wastewater treatment efficacy (Katam et al., 2022). Optimizing light intensity and wavelength is crucial for enhancing microalgae growth and nutrient removal in wastewater treatment systems.

3.2.2.2 Thermal Measurement

Temperature modulation is crucial for enhancing microalgae proliferation in wastewater treatment, as temperature directly influences metabolic activity, nutrient uptake, and biomass production. The ideal growth temperatures for the majority of species range from 20°C to 35°C, with mesophilic strains capable of withstanding temperatures up to 40°C before incurring cellular damage (Chowdury et al., 2020). For instance, *Scenedesmus almeriensis* attains maximum productivity at 35°C but experiences death over 45°C, whereas *Chlorella vulgaris* demonstrates optimal development at 25-30°C (Ahmad et al., 2020). Thermal measurements employing techniques such as oxygen production/respiration analysis and fluorescence quenching facilitate the swift identification of temperature optimal, with photosynthetic activity closely linked to growth rates (Ranglová et al., 2019). Elevated temperatures impair enzyme activity and chloroplast efficiency, diminishing lipid production and resulting in reduced cell size, whereas inadequate temperatures below 20°C hinder nutrient absorption and elevate carbohydrate and fat content in certain species. Thermal stress modifies biomass composition: *S. acutus* cultivated at 15°C exhibited a 10% increase in fatty acid content relative to cultures at 30°C, albeit reduced growth rates (Chaisutyakorn et al., 2017). Extensive outdoor systems have difficulties due to diurnal and seasonal variations,

Table 4. The Comparison of Cultivation Methods for Microalgae

Aspect	Open Ponds	Photobioreactors (PBRs)
Cost	Low construction and operational costs (Zhang et al., 2024; Tan et al., 2020)	High capital and operational costs (Al-Dailami et al., 2022)
Contamination Risk	High due to exposure to the environment (Bani et al., 2020; Narala et al., 2016)	Low due to closed system design (Ting et al., 2017)
Control over conditions	Limited (e.g., temperature, light) (Narala et al., 2016)	Excellent control over growth parameters (Ting et al., 2017)
Land Requirement	Requires large land areas (Zhang et al., 2024; Tan et al., 2020)	Compact; suitable for urban settings (Ting et al., 2017)
Efficiency	Moderate; affected by environmental factors. (Bani et al., 2020; Narala et al., 2016)	High; optimized for maximum productivity
Scalability	Easy to scale up for large volumes (Zhang et al., 2024; Tan et al., 2020)	Limited by cost and complexity (Narala et al., 2016)
Environmental Factors	Susceptible to weather fluctuations (Bani et al., 2020; Narala et al., 2016)	Protected from external environmental changes (Ting et al., 2017)
Maintenance	Simple and inexpensive (Tan et al., 2020; Narala et al., 2016)	Complex and requires advanced technology (Ting et al., 2017)
Biomass Quality	Variable; lower quality due to contamination risk (Narala et al., 2016)	High-quality biomass with minimal contamination (Ting et al., 2017)
Applications	Suitable for large-scale, low-cost wastewater treatment in favorable climates (Zhang et al., 2024)	Ideal for high-value biomass production or space-constrained areas ((Ting et al., 2017)

requiring solutions such as groundwater heat exchangers to regulate temperatures in harsh climates. These observations highlight the essential importance of temperature regulation in promoting the growth and sustainability of microalgae cultures, which are crucial for their use in bioenergy and environmental remediation.

3.2.2.3 pH Level

The pH level is a crucial growth determinant for microalgae in wastewater treatment systems, affecting nutrient uptake, biomass yield, and biochemical composition via species-specific processes. Most microalgae flourish in neutral to slightly alkaline environments (pH 7-9), although optimal ranges differ. *Scenedesmus* sp. attains optimal biomass at pH 7.0-7.5 (Fitriani, 2019), whereas *Parachlorella* prevails in mixed cultures even in severely acidic environments (pH <3) (Yu et al., 2022). pH changes in wastewater directly affect the efficiency of nitrogen and phosphorus removal. Maintaining a pH between 7 and 8 optimizes biological $\text{NH}_4^+ - \text{N}$ removal by up to 87.77% and phosphorus assimilation by 92.05% (Larsdotter, 2006), but an uncontrolled pH beyond 8.6 poses a risk of ammonia volatilization, hence diminishing nutrient recovery. Microalgae also regulate pH via metabolic processes: CO_2 absorption during photosynthesis increases pH, resulting in phosphorus precipitation and ammonia removal, whereas the production of organic acids decreases pH (Yu et al., 2022). pH stress methods can enhance lipid accumulation for biofuel production. Under pH 8 stress during famine, *Scenedesmus acutus* attains a

total lipid productivity of 26.93% (Alkhamis et al., 2022), while acidic circumstances (pH 6) in *Chlorella sorokiniana* increase lipid content but diminish biomass output. In contrast, alkaline stress (pH >9) impairs food availability and photosynthetic efficiency, diverting energy towards fat accumulation in nitrogen-deficient cells. Extreme pH levels (<5 or >9) impede growth by denaturing enzymes, modifying cell shape, and restricting CO_2 solubility (Ramírez Mérida and Rodríguez Padrón, 2023). In wastewater treatment, pH regulation equilibrates microbial competition and biomass sedimentation. Cultures sustained at pH 7-8 demonstrate enhanced biomass production (e.g., *Scenedesmus* sp. generates 1.24 g/L dry biomass) relative to uncontrolled systems (Fitriani, 2019; Chowdury et al., 2020). Furthermore, pH-induced alkalinity (≥ 9) disinfects wastewater by inactivating pathogens such as *E. coli* through increased dissolved oxygen and toxin generation (Srimongkol et al., 2022). These dynamics highlight the necessity for species pH tuning to enhance nutrient removal, biomass production, and metabolite generation in industrial applications.

3.2.2.4 Salinity

In wastewater treatment systems, salinity has a major impact on the growth dynamics of microalgae, with species-specific reactions influencing lipid accumulation and biomass production. Microalgae have a wide range of ideal salinity ranges: the viability of biofuel is increased by *Chlorella vulgaris*'s higher lipid content (16.1% vs. 11.5% in low salinity) and improved settling rates (0.11 m/day⁻¹), despite

Table 5. Microalgae-Bacterial Consortia in Bioremediation Applications

Microalgae-Bacteria Used	Medium Condition	Biomass Yield (%)	Removal efficiency (%)	Findings	References
<i>C. sorokiniana</i> and <i>Chlorella</i> sp. with <i>Klebstella pneumoariae</i> and <i>Acinetobacter calcoaceti</i>	Artificial wastewater (AWW) and raw dairy wastewater (RDWW)	2.87 g/L	COD : 90.49%	Enhanced growth, biomass, nutrient/COD removal over monoculture	(Makut et al., 2019)
<i>C. sorokiniana</i> with <i>Streptomyces thermocarboxydus</i>	Wastewater treatment	Bioflocculation efficiency : 93%, Biomass productivity: Increased 33% Lipid Productivity: 80% increase due to the co-cultivation of <i>Streptomyces</i> and microalgae cells	NA	Higher algal biomass and lipid content, suitable for biodiesel	(Lakshmikandan et al., 2021)
<i>Chlorella</i> sp. with four bacterial strains	Parmaceutical waste degradation	NA	In dark condition: biodegradation was faster with a lag phase of 10 h, COD: 41%, Toxicity reduction: 82%	Effective ketoprofen degradation, reduces COD and Toxicity	(Ismail et al., 2016)
<i>T.obliquus</i> and <i>Coelastrella</i> sp. with <i>V.paeadoxus</i>	Modified Bold's basal medium	NA	nitrate: 88-99%, Phosphate: 92-95%	Improved microalgae growth, nutrient uptake nitrate and phosphate and biochemical composition.	(Adhiwarie et al., 2022)
<i>C.vulgaris</i> with various bacterial strains	Wastewater treatment	Biomass growth rate: 0.196 d ⁻¹ , mean daily biomass productivity 0.098 gL ⁻¹ d ⁻¹ (for 10:1 ratio of S395-2 to <i>C.vulgaris</i>)	NA	Provided the industrialization of microalgae-based wastewater remediation	(Xu et al., 2020)
Consortia with microalgae	Photoreactor for wastewater treatment	Chlorophyll: 64% increased	NH ₄ ⁺ -N: 64% (with the change of light density)	Reduced aeration requirements due to inhibition of nitrate oxidizing bacteria	(Wang et al., 2015)
Microalgae-bacteria photoreactor system	Ammonium removal	TSS: 1006 mg/L-1930 mg/L	NH ₄ ⁺ oxidized to NO ₂ at the rate of 8.09 mg NH ₄ ⁺ NL ⁻¹ h ⁻¹ -1	Innovative method for nitrogen removal without external	(Arun et al., 2019)

<i>T. obliquus</i> IS2 and <i>V. paradoxus</i> ISI	Nutrient removal	NA	Total N (>92%), PO ₄ ³⁻ , P(>89%) and COD (84%)	Enhanced bioremediation of effluents with sustainable production of biomass and biodiesel	(Perera et al., 2022)
<i>Chlorella</i> sp. and <i>Lysinibacillus</i> sp.	Pollutant removal	Biomass 0.85 g/L	(TOC: 39.05%, IC: 85.92%, NH ₄ ⁺ -N: 97.82%, TN: 83.32%, TP: 39.25%	provides an environmentally-friendly strategy with low carbon emission and energy consumption	(Lu et al., 2022)
<i>Tetraselmis indica</i> - <i>Pseudomonas aeruginosa</i>	Dairy wastewater	Biomass yield 1454.88 mg/L	7.49%, 83.76%, and 79.83% of chemical oxygen demand (COD)	utilized in biofuel technology	(Talapatra et al., 2023)
<i>Chlorella sorokiniana</i> and <i>Shinellafusca</i>	Mineral salt medium	NA	64.2% chemical oxygen demand (COD) N-NH ₄ ⁺ 71.4%, P-PO ₄ ³⁻ 68.3%	reduced the metabolic capability of the photo bioreactor	(Barreiro-Vescovo et al., 2021)
<i>C. vulgaris</i> and <i>B. licheniformis</i>	Municipal river	NA	Dissolved phosphorus 80.28%, COD 86.55% and Dissolved nitrogen 88.95%	Contribute to a better understanding of the interaction between algae and bacteria	(Ji et al., 2018)
<i>Desmodesmus</i> sp. and nitrifying bacteria (<i>Rhodobacter</i> , <i>Micrococcus</i> , <i>Pseudomonas</i>)	Piggery wastewater	NA	chemical oxygen demand (COD) 78.3% NH ₄ ⁺ -N 35.0 mg/L	Benefited for the microalgal growth and nutrient removal	(Wang et al., 2020)
Microalgae (<i>Chlorella vulgaris</i> and <i>Phormidium keutzingium</i>) with activated sludge	Synthetic municipal wastewater	247.68 mg/L	Fats, oils and grease removal (FOG) 99%	Reduced energy consumption and enhanced sustainability	(Javed and Al-Zuhair, 2025)

its slower growth rates (0.003 day⁻¹ per S/cm⁻¹) at ~45 g/L salinity (Church et al., 2017). *Scenedesmus abundans*, on the other hand, has exceptional salt tolerance in reverse osmosis concentrate (ROC) wastewater, generating methane outputs of up to 422 mL CH₄/g VS and sustaining nitrogen removal rates of 11.5-18 mg/L/day at 15 g TDS/L in nutrient remediation (Mohseni et al., 2021). Marine species such as *Nannochloropsis salina* outperform freshwater strains because they can adapt to high salinity (15 g/L) with no growth inhibition. However, physiological trade-offs are triggered by

severe salinity (>60%): as a stress response mechanism to preserve osmotic balance, *Euchlorocystis marina* transitions from peak development at 15°C (cell density: 507.96×10⁴ cells/mL) to lipid and polysaccharide accumulation at 60°C (Pan et al., 2024). Similarly, under salinity stress, *Anabaena fertilissima* exhibits increased protein (15-20%) and lipid synthesis but decreasing chlorophyll concentration (El Din, 2015). High salinity (150 mM NaCl) decreases the efficacy of *Desmodesmus communis* nutrient removal (N: 81%, P: 5.9%) while increasing the stearic acid content (56.87%)

for biodiesel, posing difficulties for industrial applications (Alalawy et al., 2023). Co-culturing *Chlorella-Scenedesmus* improves lipid synthesis (1.7-fold) and COD removal (89%) in mariculture wastewater (Singh et al., 2023), while two-stage cultivation of *Scenedesmus* sp. maximizes biomass (0.8 g/L) and lipid yields (29.5%) under salt stress (Singh et al., 2023). These results highlight how crucial species selection and salinity control are to striking a balance between the recovery of bioresources and wastewater treatment effectiveness.

3.2.2.5 Nutrient Density

Microalgae-based wastewater treatment enhances nutritional density by regulating nitrogen-to-phosphorus (N:P) ratios, chemical nutrient forms, pH, carbon availability, and strain selection to optimize growth and purification efficacy. The optimal nitrogen to phosphorus (N:P) ratio for microalgae is roughly 16:1; however, wastewater streams frequently diverge from this standard. For instance, swine wastewater presents N:P ratios ranging from 12 to 17, with total nitrogen levels reaching 2,300 mg/L and phosphorus levels up to 230 mg/L (Ramírez Mérida and Rodríguez Padrón, 2023). Modifying these ratios via phosphorus supplementation (e.g., for nitrogen-rich wastewaters) or nitrogen addition (e.g., urea for phosphorus-rich streams) improves nutrient assimilation, as evidenced by *Chlorella vulgaris*, which attained removal rates exceeding 90% for nitrate, nitrite, phosphate, and ammonium ions in municipal wastewater (Mostafaei et al., 2023). The bioavailability of nutrients is additionally affected by chemical speciation: ammoniacal nitrogen (NH_4^+) is preferentially absorbed but volatilizes at elevated pH levels, whereas orthophosphates (PO_4^{3-}) precipitate in alkaline environments, requiring pH regulation between 7 and 8.5 to enhance solubility and metabolic function (Kundu et al., 2024). The availability of carbon is crucial, as inorganic carbon (CO_2) supplementation (5-15%) increases lipid formation in *Scenedesmus obliquus* by up to 0.38 g/L and improves nitrogen removal to 99.8% in basic city wastewater (Srimongkol et al., 2022). The selection of strains is crucial; mixed microalgal-bacterial consortia surpass monocultures by enhancing nutrient absorption and sustaining microbial symbiosis. The co-cultivation of *Scenedesmus* sp. with activated sludge enhanced chemical oxygen demand (COD) reduction by 77.1% (Ramírez Mérida and Rodríguez Padrón, 2023). Operational characteristics such as hydraulic retention time (HRT ≥ 5 days) and turbulence are essential for light penetration and nutrient diffusion, especially in high-turbidity agricultural wastewaters. Challenges encompass variable nutrient loads that disturb steady-state growth and competing processes such as phosphorus precipitation that diminish bioavailability. Notwithstanding these challenges, optimized systems attain over 75% nitrogen removal and nearly total phosphorus removal, simultaneously generating valuable biomass that can be transformed into biofuels or fertilizers (Srimongkol et al., 2022). This method corresponds

with sustainability objectives by decreasing dependence on freshwater and industrial nutrients.

3.2.2.6 Carbon Source

Carbon sources in wastewater substantially impact microalgae growth by influencing biomass productivity, lipid accumulation, and nutrient removal efficacy. Microalgae generally necessitate 1.8-2.0 kg of CO_2 per kilogram of biomass; however, ambient CO_2 concentrations (0.03%) are inadequate for optimal growth, thus requiring supplementing by CO_2 -rich industrial emissions or bicarbonate salts (Magrassi, 2023). *Ettlia* sp. attains peak biomass ($28 \pm 1.5 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) at 8% CO_2 , whereas *Chlorella vulgaris* flourishes at 6.5% CO_2 (Chowdury et al., 2020). Excessive CO_2 can decrease pH, affecting nutritional availability: ammonium transforms into volatile ammonia at elevated pH, diminishing nitrogen absorption, while phosphorus precipitates as calcium phosphate in alkaline environments. In contrast, organic carbon sources such as glycerol (derived from biodiesel waste) and xylose (obtained from pulp and paper industries) facilitate mixotrophic growth, thereby augmenting biomass in Nordic strains like *Chlorella vulgaris* and *Chlorococcum* sp., which exhibited a tenfold increase in lipid productivity when cultivated in industrial sludge wastewater relative to synthetic media (Rather et al., 2023). Carbon produced from wastewater enhances nutrient removal; the adjustment of N:P ratios by phosphate supplementation in lagoon effluent elevated chlorophyll-a levels by 50% and augmented nitrogen/phosphorus removal efficiencies to over 90% (Lee et al., 2013). Moreover, utilizing CO_2 from industrial flue gases decreases treatment expenses by 30-40% while alleviating greenhouse gas emissions (Magrassi, 2023). These solutions emphasize the dual function of wastewater as a carbon source and fertilizer provider, enhancing microalgae development for biofuel production and eutrophication management.

3.2.2.7 Blending and Aeration

Aeration is essential for enhancing microalgae growth and nutrient removal efficacy in wastewater treatment systems by controlling dissolved oxygen (DO), carbon dioxide (CO_2) availability, and hydrodynamic conditions. Research indicates that moderate aeration rates (4.5 L/min) significantly improve biomass productivity, reaching 0.605 g/L in *Chlorella* cultures, in contrast to 0.207 g/L in non-aerated systems (Tighiri et al., 2017). Reduced aeration rates (0.2 L/min) enhance algal-bacterial symbiosis, increasing nitrogen and phosphorus removal by 18.9% and 46.7%, respectively, while decreasing energy consumption. Continuous aeration (24 hours) enhances growth rates (0.1295/day) and chemical oxygen demand (COD) elimination efficiency (75.2%) in comparison to intermittent or absent aeration (Tang et al., 2016). Intermittent aeration techniques, such as 12-hour cycles, optimize oxygen supply and CO_2 consumption, resulting in 73.9% COD elimination and averting pH

extremes that hinder nutrient absorption (Cahyonugroho et al., 2024). Nocturnal aeration promotes heterotrophic bacteria, hence augmenting the breakdown of organic pollutants, whereas diurnal aeration benefits nitrification-denitrification bacteria, promoting nitrogen cycling. Excessive aeration (>9.0 L/min) diminishes biomass output due to hydraulic shear stress and light attenuation caused by turbulent mixing (Tang et al., 2016). Optimal aeration facilitates CO₂ sequestration from industrial flue gases, decreasing treatment expenses by 30-40% while preserving pH levels favorable for ammonium and phosphate bioavailability (Wollmann et al., 2019). *Chlorella pyrenoidosa* attains a pigment accumulation of 20.49 mg/L under high intermittent aeration (200 mL/min), surpassing mixed cultures in continuous modes (Li et al., 2025). These findings highlight the necessity for species-specific aeration procedures to optimize wastewater treatment and biofuel potential.

3.3 Synergies Between Microalgae in Bioremediation Techniques

The collaboration between microalgae and bacteria in co-culture systems provides substantial benefits in bioremediation, especially in wastewater treatment. This symbiotic interaction improves microalgal biomass production and nutrient removal efficiency by enabling intricate nutrient cycling patterns. Bacteria can enhance microalgal growth by generating growth-promoting chemicals, vitamins, and cofactors, whereas microalgae supply oxygen and organic compounds that facilitate bacterial metabolism (Aditya et al., 2022). In wastewater treatment, the co-cultivation of microalgae with bacteria, such as activated sludge bacteria, enhances nutrient and dissolved oxygen efficiency, hence aiding in microalgal harvesting (Rasheed et al., 2023). Microalgal-bacterial consortia facilitate the removal of complex organics from municipal wastewater, with algae-bacteria interactions being essential to the degradation process (Shi et al., 2024). These consortia can endure diverse environmental conditions, providing stability and defense against invasive species, which is advantageous for bioremediation applications. Microalgal synergies depicts in the Table 5 (Phat et al., 2024).

3.4 Challenges and Limitations

Microalgae-based wastewater treatment encounters substantial problems and limits, including contamination hazards, operational obstacles, and regulatory complications.

3.4.1 Contamination Risks Stem from Toxic Pollutants Such as Microplastics

Which adsorb heavy metals and antibiotics in wastewater, releasing detrimental additives (e.g., bisphenol A) that diminish microalgae's photosynthetic efficiency by as much as 50% and elevate oxidative stress, thereby compromising nutrient removal rates. Residual algal cells remaining after inadequate harvesting (10–90% recovery efficiency for sedimentation techniques) provide additional risks to aquatic

environments by undermining biodiversity (Gao et al., 2023).

3.4.2 Operational

Elevated costs and inefficiencies endure: open systems (e.g., raceway ponds) experience evaporative losses, CO₂ diffusion, and contamination by predators, whereas closed photobioreactors entail exorbitant installation and maintenance costs. Harvesting continues to be a significant bottleneck, as centrifugation (>90% recovery) is energy-intensive, while membrane filtering (70–90% recovery) necessitates frequent maintenance. Technological constraints encompass the necessity for wastewater pretreatment (e.g., anaerobic digestion, UV radiation) to manage fluctuating nutrient profiles and toxins, along with the inadequacy of algae strains that demand genetic engineering or adaptive evolution to improve nutrient absorption and toxin resistance (Li et al., 2023).

3.4.3 Regulatory Obstacles Encompass Rigorous Compliance Mandates for Effluent Discharge Thresholds

Environmental impact assessments (EIAs) assessing carbon equilibrium and habitat disturbance, and zoning disputes arising from land-use pressures. The lack of defined rules for microalgae-specific systems hinders commercialization, despite potential remedies like as public-private partnerships and tax incentives. Collectively, these obstacles underscore the necessity for cohesive progress in strain engineering, economical harvesting technologies, and synchronized regulatory frameworks to achieve scale microalgae-based wastewater treatment systems (Chetankumar, 2024).

3.5 Future Directions and Innovations

Future advancements in microalgae-based wastewater treatment are increasingly centered on the integration of advanced genetic engineering with hybrid system designs to enhance contaminant resilience, operational efficiency, and scalability. Genetic engineering techniques such as CRISPR/Cas9 and targeted mutagenesis facilitate the creation of microalgal strains with improved contaminant resistance and metabolic efficacy. Engineered *Chlorella sorokiniana* strains demonstrate 20–30% enhanced nitrogen/phosphorus removal rates through the optimization of transporter proteins and stress-response genes (such as superoxide dismutase), enabling their proliferation in wastewater contaminated with heavy metals (such as cadmium) and hydrocarbons (Hassanien et al., 2023). These strains exhibit enhanced CO₂ fixation (15–25% increase) due to improvements in the RuBisCO enzyme, facilitating carbon capture in photobioreactors. Nonetheless, obstacles remain in the public acceptability of genetically modified organisms (GMOs) and the regulatory frameworks governing their commercial deployment (Sproles et al., 2020). Hybrid systems are also emerging as a remedy for operational inefficiencies, integrating photobioreactors with anaerobic digestion or biofilm reactors to improve nutrient recovery and minimize land utilization. For instance, the

merging of biofilm with photobioreactors enhances biomass output by 2.6 times and improves harvesting efficiency to 61% relative to traditional systems (Srimongkol et al., 2022). Internally lighted photobioreactors employing red LEDs (660 nm) enhance light absorption for chlorophyll a/b while reducing energy expenditures. Modular solutions, exemplified as Frontship's container-based designs, employ industrial CO₂ emissions to enhance biomass yields by 30–40%, thereby integrating wastewater treatment with circular economy principles (Nour et al., 2024).

Microalgae-based wastewater treatment holds great promise through the integration of advanced genetic engineering and the design of future hybrid systems. Strategically, this approach can enhance microalgae resistance to contaminants, operational efficiency, and scalability for industrial applications. The use of technologies such as CRISPR/Cas9 and targeted mutagenesis, for example, has enabled the development of microalgae strains. However, challenges remain, particularly regarding public acceptance of genetically modified organisms (GMOs) and regulations governing their commercial use, which require well-thought-out policies and educational approaches. The development of hybrid systems, such as combining photo bioreactors with biofilm reactors or anaerobic digestion, has demonstrated significant improvements in biomass productivity and harvest efficiency, while reducing land requirements. Other innovations have also been shown to reduce energy consumption, signaling technological advances oriented toward efficiency and economic sustainability. This review provides a comprehensive and optimistic overview of the future of wastewater treatment using genetically engineered microalgae and hybrid systems. Wastewater treatment is highly relevant and strategic, combining cutting-edge biotechnology with practical solutions to global environmental challenges. However, as a trick, for widespread implementation, multidisciplinary collaboration combining molecular biology research, environmental engineering, public policy, and public education is needed to ensure optimal acceptance and utilization of this technology at the industrial and societal levels.

4. CONCLUSIONS

Experimental studies have shown success in the use of microalgae species for bioremediation of wastewater from various industries. Mechanism of liquid waste degradation for nutrient removal convert inorganic nutrients into biomass while reducing contaminants through enzymatic and physicochemical mechanisms, aided by their adaptation to various wastewater conditions. Moreover, microalgae exhibit considerable potential for the biodegradation of detrimental organic pollutants, such as detergents, pesticides, medicines, and industrial waste, through enzymatic mechanisms and metabolic flexibility. Microalgae utilize many ways to decompose liquid waste and eliminate heavy metals, chiefly through biosorption, bioaccumulation, and biotransformation. Microalgae are cultivated in open ponds or closed photobiore-

actors, with important factors such as light, temperature, pH, salinity, and aeration being considered. Co-cultivation with bacteria improves the efficiency of microalgae processing and harvesting. While promising, challenges such as contamination and operational constraints remain. In the future, the integration of genetic engineering and hybrid systems is expected to increase efficiency and scalability.

5. ACKNOWLEDGEMENT

The authors wish to express their gratitude to the department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya for supporting this work.

REFERENCES

- Abdelfattah, A., S. S. Ali, H. Ramadan, E. I. El-Aswar, R. Eltawab, S. H. Ho, T. Elsamahy, S. Li, M. M. El-Sheekh, M. Schagerl, M. Kornaros, and J. Sun (2023). Microalgae-Based Wastewater Treatment: Mechanisms, Challenges, Recent Advances, and Future Prospects. *Environmental Science and Ecotechnology*, **13**; 100205
- Abidli, A., Y. Huang, Z. B. Rejeb, A. Zaoui, and C. B. P. (2022). Sustainable and Efficient Technologies for Removal and Recovery of Toxic and Valuable Metals From Wastewater: Recent Progress, Challenges, and Future Perspectives. *Chemosphere*, **292**; 133102
- Adhiwarie, I., P. Sudharsanam, S. R. Subashchandrabose, and K. Venkateswarlu (2022). Combined Inorganic Nitrogen Sources Influence the Release of Extracellular Compounds That Drive Mutualistic Interactions in Microalgal-Bacterial Co-Cultures. *Journal of Applied Phycology*; 1311–1322
- Aditya, L., T. M. I. Mahlia, L. N. Nguyen, H. P. Vu, and L. D. Nghiem (2022). Microalgae-Bacteria Consortium for Wastewater Treatment and Biomass Production. *Science of the Total Environment*, **838**(Pt 1); 155871
- Ahmad, S., R. Kothari, R. Shankarayan, and V. V. Tyagi (2020). Temperature Dependent Morphological Changes on Algal Growth and Cell Surface With Dairy Industry Wastewater: An Experimental Investigation. *3 Biotech*, **10**(1); 1–12
- Al-Dahhan, M., F. Al-Ani, and A. Al-Saned (2018). Biodegradation of Phenolic Components in Wastewater by Microalgae: A Review. In *MATEC Web of Conferences*, volume 162. page 05009
- Al-Dailami, A., I. Koji, I. Ahmad, and M. Goto (2022). Potential of Photobioreactors (PBRs) in Cultivation of Microalgae. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, **27**(1); 32–44
- Alalawy, A. I., Y. Yang, F. M. Almutairi, H. A. E. Rabey, M. A. Al-Duais, A. Abomohra, and E. S. Salama (2023). Freshwater Microalgae-Based Wastewater Treatment Under Abiotic Stress. *AIMS Environmental Science*, **10**(4); 504–515
- Ali, S. S., T. Elsamahy, R. Al-Tohamy, D. Zhu, Y. A. Mah-

- moud, and M. A. Metwally (2021a). Plastic Wastes Biodegradation: Mechanisms, Challenges and Future Prospects. *Science of the Total Environment*; 146590
- Ali, S. S., T. Elsamahy, E. Kuotra, M. K. Abdelkarim, M. El-Sheekj, D. Zhu, and J. S. (2021b). Degradation of Conventional Plastic Wastes in the Environment: A Review on Current Status of Knowledge and Future Perspectives of Disposal. *Science of the Total Environment*, **771**; 144719
- Alkhamis, Y. A., R. T. Mathew, G. Nagarajan, S. M. Rahman, and M. M. Rahman (2022). pH Induced Stress Enhances Lipid Accumulation in Microalgae Grown Under Mixotrophic and Autotrophic Condition. *Frontiers in Energy Research*, **10**; 1033068
- Arun, S., N. A. Manikandan, K. Pakshirajan, and G. Pugazhenth (2019). Novel Shortcut Biological Nitrogen Removal Method Using an Algae-Bacterial Consortium in a Photo-Sequencing Batch Reactor: Process Optimization and Kinetic Modelling. *Journal of Environmental Management*, **250**; 109401
- Baihaqi, R. A. and W. D. Pratama (2023). Feasibility Study of Utilization of Palm Oil Mill Effluent (POME) as a Source for Microalgae Nutrients. *J. Emerg. Sci. Eng.*, **1**(1); 1–5
- Bani, A., K. Parati, A. Pozzi, C. Previtali, G. Bongioni, A. Pizzera, E. Ficara, and M. Bellucci (2020). Comparison of the Performance and Microbial Community Structure of Two Outdoor Pilot-Scale Photobioreactors Treating Digestate. *Microorganisms*, **8**(11); 1754
- Barreiro-Vescovo, S., C. González-Fernández, and I. de Godos (2021). Characterization of Communities in a Microalgae-Bacteria System Treating Domestic Wastewater Reveals Dominance of Phototrophic and Pigmented Bacteria. *Algal Research*, **59**; 102447
- Cahyonugroho, O. H., E. N. Hidayah, and E. A. Rahma (2024). Effect of Intermittent Aeration on Characteristic of Effluent Organic Matter in Oxidation Ditch Microalgae *Chlorella* sp. (*Journal Name Not Provided*)
- Chaisutyakorn, P., J. Praiboon, and C. Khumkratok (2017). The Effect of Temperature on Growth and Lipid and Fatty Acid Composition on Marine Microalgae Used for Biodiesel Production. *Journal of Applied Phycology*, **30**; 37–45
- Chakravorty, M., M. Nanda, B. Bisht, R. Sharma, S. Kumar, A. Mishra, M. S. Vlaskin, P. K. Chauhan, and V. Kumar (2023). Heavy Metal Tolerance in Microalgae: Detoxification Mechanisms and Applications. *Aquatic Toxicology*
- Chanquia, S. N., G. Vernet, and S. Kara (2022). Photobioreactors for Cultivation and Synthesis: Specifications, Challenges, and Perspectives. *Engineering in Life Sciences*, **22**(12); 712–724
- Chen, M., L. Chang, J. Zhang, F. Guo, J. Vymazal, Q. He, and Y. Chen (2020). Global Nitrogen Input on Wetland Ecosystem: The Driving Mechanism of Soil Labile Carbon and Nitrogen on Greenhouse Gas Emissions. *Environmental Science and Ecotechnology*, **4**; 100063
- Chen, Z., Y. Xiao, T. Liu, M. Yuan, G. Liu, J. Fang, and B. Yang (2021). Exploration of Microalgal Species for Nutrient Removal from Anaerobically Digested Swine Wastewater and Potential Lipids Production. *Microorganisms*, **9**(12); 2469
- Chetankumar, J. (2024). Microalgae-Based Wastewater Treatment: A Techno-Economic Analysis of High Rate Algal Ponds Construction. (*Journal Name Not Provided*)
- Chowdury, K. H., N. Nahar, and U. K. Deb (2020). The Growth Factors Involved in Microalgae Cultivation for Biofuel Production: A Review. *Computational Water, Energy, and Environmental Engineering*, **9**(4); 185–215
- Church, J., J.-H. Hwang, K.-T. Kim, R. McLean, Y.-K. Oh, B. Nam, J. C. Joo, and W. H. Lim (2017). Effect of Salt Type and Concentration on the Growth and Lipid Content of *Chlorella vulgaris* in Synthetic Saline Wastewater for Biofuel Production. *Bioresource Technology*
- El-Awamri, A. A., H. M. Abd El Fatah, S. A. Badr, A. A. Ashmawy, I. Y. El-Sherif, and R. M. Moghazy (2015). Comparative Study on the Biosorption and Desorption of Three Selected Toxic. *Egyptian Journal of Phycology*, **16**; 25–46
- El Din, S. M. (2015). Effect of Seawater Salinity Concentrations on Growth Rate, Pigment Contents and Lipid Concentration in *Anabaena Fertilissima*. *Catrina-The International Journal of Environmental Sciences*, **11**(1); 59–65
- El-Sheekh, M. M., H. Y. El-Kassas, and S. S. Ali (2025). Microalgae-Based Bioremediation of Refractory Pollutants: An Approach Towards Environmental Sustainability. *Microbial Cell Factories*, **24**(1); 19
- Fitriani, N. (2019). *Scenedesmus* sp. Growth in Wastewater Treatment. *Cakrawala*
- Gao, N., R. Ning, and X. Deng (2023). Feasibility, Challenges, and Future Prospects of Microalgae-Based Bioremediation Technique for Removing Microplastics from Wastewater. *Frontiers in Bioengineering and Biotechnology*, **11**; 1–4
- Ge, Z., H. Zhang, Y. Zhang, C. Yan, and Y. Zhao (2013). Purifying Synthetic High-Strength Wastewater by Microalgae *Chlorella Vulgaris* Under Various Light Emitting Diode Wavelengths and Intensities. *Environmental Health*, **11**(1); 1
- Goncu, S., B. S. Uygun, and S. Atakan (2025). Nitrogen and Phosphorus Removal from Wastewater Using *Chlorella vulgaris* and *Scenedesmus quadricauda* Microalgae with a Batch Bioreactor. *International Journal of Environmental Science and Technology*; 1–16
- González-Camejo, J., J. Ferrer, and R. Barat (2021). Outdoor Microalgae-Based Urban Wastewater Treatment: Recent Advances, Applications, and Future Perspectives. *Environmental Science and Ecotechnology*, **8**(3); 1518
- Hassanien, A., I. Saadaoui, K. Schipper, S. Al-Marri, T. Dalgamouni, M. Aouida, S. Saeed, and H. M. Al-Jabri (2023).

- Genetic Engineering to Enhance Microalgal-Based Produced Water Treatment with Emphasis on CRISPR/Cas9: A Review. *Frontiers in Bioengineering and Biotechnology*, **10**; 1104914
- Hena, S., L. Gutierrez, and J. P. Croué (2021). Removal of Pharmaceutical and Personal Care Products (PPCPs) from Wastewater Using Microalgae: A Review. *Journal of Hazardous Materials*, **403**; 124041
- Ismail, M. M., T. M. Essam, and Y. El-Mamoun (2016). Biodegradation of Ketoprofen Using a Microalgal-Bacterial Consortium. *Biotechnology Letters*, **38**; 1493–1502
- Javed, F. and S. Al-Zuhair (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
- Ji, X., M. Jiang, J. Zhang, X. Jiang, and Z. Z. (2018). The Interaction of Algae-Bacteria Symbiotic System and Its Effects in Nutrients Removal from Synthetic Wastewater. *Bioresource Technology*; 44–50
- Joseph, I., B. C. David, and A. L. Abershi (2024). A Review of Phycoremediation of Heavy Metals in Industrial Waste Water. *Journal of Multidisciplinary Science: MIKAILAL-SYS*, **2**(1); 78–109
- Katam, K., R. Ananthula, S. Anumala, M. Sriariyanun, and D. Bhattacharyya (2022). The Impact of Light Intensity and Wavelength on the Performance of Algal-Bacterial Culture Treating Domestic Wastewater. *E3S Web of Conferences*, **320**; 02003
- Kundu, P., N. Dutta, and S. Bhattacharya (2024). Application of Microalgae in Wastewater Treatment with Special Reference to Emerging Contaminants: A Step Towards Sustainability. *Frontiers in Environmental Science*, **12**; 1513153
- Lakshmikandan, M., S. Wang, A. G. Murugesan, and M. S. G. Subramanian (2021). Co-Cultivation of *Streptomyces* and Microalgal Cells as an Efficient System for Biodiesel Production and Biofloculation Formation. *Bioresource Technology*
- Larsdotter, K. (2006). Wastewater Treatment with Microalgae—A Literature Review. *Vatten*, **62**; 31–38
- Lee, S. H., C. Y. Ahn, B. H. Jo, S. A. Lee, J. Y. Park, K. G. An, and H. M. Oh (2013). Increased Microalgae Growth and Nutrient Removal Using Balanced N:P Ratio in Wastewater. *Journal of Microbiology and Biotechnology*, **23**(1); 92–98
- Leong, Y. K. and J.-S. Chan (2020). Bioremediation of Heavy Metals Using Microalgae: Recent Advances and Mechanisms. *Bioresource Technology*, **303**; 122886
- Li, L., K. Gao, M. Yang, Q. Zheng, M. Zhang, and X. Deng (2023). Challenges and Potential Solutions of Microalgae-Based Systems for Wastewater Treatment and Resource Recovery. *Frontiers in Bioengineering and Biotechnology*, **11**; 1210228
- Li, P., Y. Luo, F. Ming, J. Zheng, Z. Pan, R. Wang, Y. He, M. Zhou, X. Xiong, C. Zhang, Y. Lei, Z. Wang, H. Zhou, Y. Chen, Z. Tan, and X. Li (2025). Aeration Strategies for Microalgae in Wastewater Treatment: Enhancing Pollutant Removal and Community Dynamics. *Journal of Environmental Management*, **377**; 124629
- Lu, R., H. Yan, Y. Liu, Y. Wang, X. Cui, X. Wu, Z. Yu, R. Ruan, and Q. Zhang (2022). Enhancement of Nutrients Recovery and Cell Metabolism in Piggery Anaerobic Digestate by the Co-Cultivation of Indigenous Microalgae and Bacteria. *Journal of Cleaner Production*, **375**; 134193
- Magrassi, F. (2023). Efficient Wastewater Treatment Using Microalgae: A FRONTSHIP Approach to Eutrophication and CO₂-Rich Gases Management
- Mahlangu, D., K. Mphahlele, F. De Paola, and N. H. Mthombeni (2024a). Microalgae-Mediated Biosorption for Effective Heavy Metals Removal from Wastewater: A Review — Biorremediación Mediada Por Microalgas Para La Eliminación Efectiva De Metales Pesados Del Agua Residual: Una Revisión. *Water (Switzerland)*, **16**(5); 1–5
- Mahlangu, D., K. Mphahlele, F. D. Pitsi, and N. H. Mpenyana-Monyatsi (2024b). Microalgae-Mediated Biosorption for Effective Heavy Metals Removal from Wastewater: A Review. *Water*
- Makut, B. B., D. Das, and G. Ghosh (2019). Production of Microbial Biomass Feedstock via Co-Cultivation of Microalgae-Bacteria Consortium Coupled with Effective Wastewater Treatment: A Sustainable Approach. *Algal Research*, **37**; 228–239
- Maltsev, Y., K. Maltsev, M. K., and S. M. (2021). Influence of Light Conditions on Microalgae Growth and Content of Lipids, Carotenoids, and Fatty Acid Composition. [*Journal Name Missing*]; 1–24
- Mastropetros, S. G., E. Koutra, M. Amouri, M. Aziza, S. S. Ali, and D. G. Karpouzas (2022). Comparative Assessment of Nitrogen Concentration Effect on Microalgal Growth and Biochemical Characteristics of Two *Chlorella* Strains Cultivated in Digestate. *Marine Drugs*, **20**; 415
- Mehariya, S., R. K. Goswami, P. Verma, R. Lavecchia, and A. Zuurro (2021). Integrated Approach for Wastewater Treatment and Biofuel Production in Microalgae Biorefineries. *Energies*, **14**(8); 2282
- Mo, Z., D. Tai, H. Zhang, and A. Shahab (2022). A Comprehensive Review on the Adsorption of Heavy Metals by Zeolite Imidazole Framework (ZIF-8) Based Nanocomposite in Water. *Chemical Engineering Journal*, **443**
- Mohseni, A., L. Fan, and F. A. Roddick (2021). Impact of Microalgae Species and Solution Salinity on Algal Treatment of Wastewater Reverse Osmosis Concentrate. *Chemosphere*, **2851**; 131487
- Morseletto, P., C. E. Mooren, and S. Munaretto (2022). Circular Economy of Water: Definition, Strategies and Challenges. *Circular Economy and Sustainability*, **2**(4); 1463–1477
- Mostafaei, H., A. Samimi, S. Shokrollahzadeh, S. K. Yazdanabad, and A. Sheikhhinejad (2023). Nutrients Removal

- From Raw Municipal Wastewater Using *Chlorella vulgaris* Microalgae. *Advances in Environmental Technology*, **9**(1); 47–57
- Munyanza, J., Q. Jia, F. A. Qaraah, M. F. C. W. Z. Hossain, and G. Xiu (2022). A Review of Atmospheric Microplastics Pollution: In-Depth Sighting of Sources, Analytical Methods, Physiognomies, Transport and Risks. *Science of the Total Environment*
- Musifa, E., A. J. Kusnanda, A. Dharma, N. Sciences, U. Andalas, and K. Limau (2023). Monosodium Glutamate (MSG) as Metabolic Stressors Stimulate the Production of Valuable Compounds in *Spirulina Platensis*. *Unknown Journal*, **27**(2); 731–743
- Narala, R. R., S. Garg, K. K. Sharma, S. R. Thomas-Hall, M. Deme, Y. Li, and P. M. Schenk (2016). Comparison of Microalgae Cultivation in Photobioreactor, Open Raceway Pond, and a Two-Stage Hybrid System. *Frontiers in Energy Research*, **4**; 1–10
- Nie, J., Y. Sun, Y. Zhou, M. Kumar, M. Usman, J. Li, J. Shao, L. Wang, and D. C. W. Tsang (2019). Bioremediation of Water Containing Pesticides by Microalgae: Mechanisms, Methods, and Prospects for Future Research. *Science of the Total Environment*
- Nour, A. H., A. A. B. Mokaizh, M. Y. D. Alazaiza, M. J. K. Bashir, S. E. Mustafa, and A. O. Baarimah (2024). Innovative Strategies for Microalgae-Based Bioproduct Extraction in Biorefineries: Current Trends and Future Solutions Integrating Wastewater Treatment. *Sustainability (Switzerland)*, **16**(23)
- Nzayisenga, J. C., X. Farge, S. L. Groll, and A. Sellstedt (2020). Effects of Light Intensity on Growth and Lipid Production in Microalgae Grown in Wastewater. *Biotechnology for Biofuels*; 1–8
- Pan, Y., D. K. Amenorfenyo, M. Dong, N. Zhang, X. Huang, C. Li, and F. Li (2024). Effects of Salinity on the Growth, Physiological and Biochemical Components of Microalga *Euchlorocystis Marina*. *Frontiers in Marine Science*, **11**; 1–9
- Perera, I. A., S. Abinandan, L. Panneerselvan, S. R. Subashchandrabose, K. Venkateswarlu, R. Naidu, and M. Megharaj (2022). Co-Culturing of Microalgae and Bacteria in Real Wastewaters Alters Indigenous Bacterial Communities Enhancing Effluent Bioremediation. *Algal Research*, **64**; 102705
- Phat, T., S. Danaee, C. Chaiwong, B. Tran, N. Poddar, M. Kim, U. Kuzhiumparambil, C. Songsomboon, M. Pernice, H. Hao, P. J. Ralph, and P. H. N. Vo (2024). Microalgae-Bacteria Consortia for Organic Pollutants Remediation From Wastewater: A Critical Review. *Journal of Environmental Chemical Engineering*, **12**
- Rajagopal, R., M. Mousavi, B. Goyette, and S. K. Adhikary (2021). Coupling of Microalgae Cultivation With Anaerobic Digestion of Poultry Wastes: Toward Sustainable Value Added Bioproducts. *Bioengineering*, **8**(5); 57
- Ramírez Mérida, L. G. and R. A. Rodríguez Padrón (2023). Application of Microalgae in Wastewater: Opportunity for Sustainable Development. *Frontiers in Environmental Science*, **11**; 1–12
- Ranglová, K., G. E. Lakatos, J. A. C. Manoel, T. Grivalský, and J. Masojídek (2019). Rapid Screening Test to Estimate Temperature Optima for Microalgae Growth Using Photosynthesis Activity Measurements. *Folia Microbiologica*, **64**(5); 615–625
- Rasheed, R. N., A. Pourbakhtiar, M. M. Allaf, M. Baharlooiean, N. Ra, and F. V. Winck (2023). Microalgal Co-Cultivation: Recent Methods, Trends in Omic-Studies, Applications, and Future Challenges. *Frontiers in Bioengineering and Biotechnology*; 1–25
- Rather, S. U., M. Davoodbasha, H. S. Bamufleh, H. Alhumade, U. Saeed, A. A. Taimoor, A. A. Sulaimon, W. Al-Alaya, and A. M. Shariff (2023). Utilization of Wastewater as a Nutritional Source for the Production of Algal Biomass. *International Journal of Energy Research*
- Rinanti, A., M. F. Fachrul, R. Hadisoebroto, S. Desty, R. Rahmadhania, D. A. Widyaningrum, and N. A. Saad (2021). Heavy Metal Pollutant Sorption in Aquatic Environment by Microalgae Consortium. *Indonesian Journal of Urban and Environmental Technology*, **5**(1); 51–71
- Salam, K. A. (2019). Towards Sustainable Development of Microalgal Biosorption for Treating Effluents Containing Heavy Metals. *Biofuel Research Journal*, **6**(2); 948–961
- Sattayawat, P., I. S. Yunus, N. Noirungsee, N. Mukjang, W. Pathom-Aree, J. Pekkoh, and C. Pumas (2021). Synthetic Biology-Based Approaches for Microalgal Bio-Removal of Heavy Metals from Wastewater Effluents. *Frontiers in Environmental Science*, **9**; 1–12
- Sendžikienė, E. and V. Makarevičienė (2022). Application of Liquid Waste From Biogas Production for Microalgae *Chlorella* sp. Cultivation. *Cells*, **11**(7); 1206
- Sharma, M., A. Sharma, and N. Batra (2024). Persistent Organic Pollutants in Water and Their Microalgae Based Bioremediation. **21**(September); 913–928
- Shi, Y., C. Xu, B. Ji, A. Li, X. Zhang, and Y. Liu (2024). Microalgal-Bacterial Granular Sludge Can Remove Complex Organics From Municipal Wastewater With Algae-Bacteria Interactions. *Communications Earth & Environment*; 1–10
- Singh, D. V., R. A. Bhat, A. K. Upadhyay, R. Singh, and D. P. S. Singh (2021). Microalgae in Aquatic Environs: A Sustainable Approach for Remediation of Heavy Metals and Emerging Contaminants. *Environmental Technology & Innovation*, **21**; 101340
- Singh, R. P., P. Yadav, A. Kumar, A. Hashem, G. D. Avila-Quezada, E. F. Abd.Allah, and R. K. Gupta (2023). Salinity-Induced Physiochemical Alterations To Enhance Lipid Content in Oleaginous Microalgae *Scenedesmus* sp. BHU1 via Two-Stage Cultivation for Biodiesel Feedstock. *Microorganisms*, **11**(8); 1064
- Spain, O., M. Plöhn, and C. Farres (2021a). The Cell Wall of Green Microalgae and Its Role in Heavy Metal Removal.

- Physiologia Plantarum*, **173**(2); 526–535
- Spain, O., M. Plöhn, and C. Funk (2021b). The Cell Wall of Green Microalgae and Its Role in Heavy Metal Removal. *Physiologia Plantarum*, **173**(2); 526–535
- Sproles, A. E., F. J. Fields, T. N. Smalley, C. H. Le, A. Badary, and P. Stephen (2020). Version of Record; 1–83
- Srimongkol, P., P. Sangtanoo, P. Songserm, W. Watsuntorn, and A. Karnchanatat (2022). Microalgae-Based Wastewater Treatment for Developing Economic and Environmental Sustainability: Current Status and Future Prospects. *Frontiers in Bioengineering and Biotechnology*, **10**(September); 1–18
- Sultana, N., S. M. Z. Hossain, M. E. Mohammed, M. F. Irfan, B. Haq, M. O. Faruque, S. A. Razzak, and M. M. Hossain (2020). Experimental Study and Parameters Optimization of Microalgae Based Heavy Metals Removal Process Using a Hybrid Response Surface Methodology-Crow Search Algorithm. *Scientific Reports*, **10**(1); 1–15
- Talapatra, N., R. Gautam, V. Mittal, and U. K. Ghosh (2023). A Comparative Study of the Growth of Microalgae-Bacteria Symbiotic Consortium With the Axenic Culture of Microalgae in Dairy Wastewater Through Extraction and Quantification of Chlorophyll. *Materials Today: Proceedings*, **80**; 2268–2273
- Tan, J. S., S. Y. Lee, K. W. Chew, M. K. Lam, J. W. Lim, S. H. Ho, and P. L. Show (2020). A Review on Microalgae Cultivation and Harvesting, and Their Biomass Extraction Processing Using Ionic Liquids. *Bioengineered*, **11**(1); 116–129
- Tang, C. C., W. Zuo, Y. Tian, N. Sun, Z. W. Wang, and J. Zhang (2016). Effect of Aeration Rate on Performance and Stability of Algal-Bacterial Symbiosis System to Treat Domestic Wastewater in Sequencing Batch Reactors. *Bioresource Technology*, **222**; 156–164
- Tedja, B., M. Al Musadieq, A. Kusumawati, and E. Yulianto (2024). Systematic Literature Review Using PRISMA: Exploring the Influence of Service Quality and Perceived Value on Satisfaction and Intention to Continue Relationship. *Future Business Journal*, **10**(1); 1–9
- Tighiri, H. O., N. East, and E. A. Erkurt (2017). New Trends and Issues Proceedings on Humanities Feedstock and Wastewater Treatment. *New Trends and Issues Proceedings on Humanities and Social Sciences*, **4**(4); 195–204
- Ting, H., L. Haifeng, M. Shanshan, Y. Zhang, L. Zhidan, and N. Dong (2017). Progress in Microalgae Cultivation Photobioreactors and Applications in Wastewater Treatment: A Review. *International Journal of Agricultural and Biological Engineering*, **10**(1); 1–29
- Touliabah, H. E. S., M. M. El-Sheekh, M. M. Ismail, and H. El-Kassas (2022). A Review of Microalgae-and Cyanobacteria-Based Biodegradation of Organic Pollutants. *Molecules*, **27**(3); 1141
- Wang, L., H. Xiao, N. He, D. Sun, and S. Duan (2019). Biosorption and Biodegradation of the Environmental Hormone Nonylphenol By Four Marine Microalgae. *Scientific Reports*, **9**(1); 1–11
- Wang, M., H. Yang, S. J. Ergas, and P. Van Der Steen (2015). A Novel Shortcut Nitrogen Removal Process Using an Algal-Bacterial Consortium in a Photo-Sequencing Batch Reactor (PSBR). *Water Research*, **87**; 38–48
- Wang, Y., S. Wang, L. Sun, Z. Sun, and D. Li (2020). Screening of a Chlorella-Bacteria Consortium and Research on Piggery Wastewater Purification. *Algal Research*, **47**; 101840
- Wirth, R., B. Pap, T. Böjti, P. Shetty, G. Lakatos, Z. Bagi, K. L. Kovács, and G. Maróti (2020). *Chlorella vulgaris* and Its Phycosphere in Wastewater: Microalgae-Bacteria Interactions During Nutrient Removal. *Frontiers in Bioengineering and Biotechnology*, **8**; 557572
- Wollmann, F., T. Walther, S. Dietze, J. Ackermann, F. Kruczatz, T. Bley, and J. Steingroewer (2019). Microalgae Wastewater Treatment: Biological and Technological Approaches. *Engineering in Life Sciences*; 860–871
- Xiao, Y. and Y. Luo (2022). Research Progress and Application of Photobioreactor in Wastewater Treatment. In *E3S Web of Conferences*, volume 352. pages 2022–2025
- Xiarchis, H., Y. J. Stephanedes, P.-G. Saranti, K. P. Marousi, and C. Panayiotou (2024). Development of a Green Procurement Method for Eutrophic and Anoxic Coastal Areas. *Journal of Civil Engineering and Construction*, **13**(2); 76–87
- Xu, M., Q. Zeng, H. Li, Y. Zhong, L. Tong, R. Ruan, and H. Liu (2020). Contribution of Glycerol Addition and Algal-Bacterial Cooperation to Nutrients Recovery: A Study on the Mechanisms of Microalgae-Based Wastewater Remediation. *Journal of Chemical Technology and Biotechnology*, **95**(6); 1717–1728.
- Yu, H., J. Kim, C. Rhee, J. Shin, S. G. Shin, and C. Lee (2022). Effects of Different pH Control Strategies on Microalgae Cultivation and Nutrient Removal from Anaerobic Digestion Effluent. *Microorganisms*, **10**(2); 357
- Zhang, Q., Y. Guan, Z. Zhang, S. Dong, T. Yuan, Z. Ruan, and M. Chen (2024). Sustainable Microalgae Cultivation: A Comprehensive Review of Open and Enclosed Systems for Biofuel and High Value Compound Production. In *E3S Web of Conferences*, volume 577. page 01008
- Zhao, F., Z. Li, X. Han, Z. Shao, and Z. Li (2022). Optimization of Air Flotation and the Combination of Air Flotation and Membrane Filtration in Microalgae Harvesting. *Processes*, **10**(8); 1594