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Microalgae Based Wastewater Treatment: A Sustainable Approach

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Abstract

The global water crisis and strict environmental policies demand advanced wastewater treatment techniques that combine pollution control with resource recovery. Microalgae-based wastewater treatment has emerged as a sustainable biotechnological solution that aligns with circular economy principles by simultaneously eliminating contaminants and producing valuable biomass that can be converted into useful products. This review paper provides an in-depth assessment of the application of microalgae in treating municipal, industrial, and agricultural wastewater streams, outlining the mechanisms of nutrient uptake, organic matter degradation, removal of heavy metals, and pathogen inactivation. A critical evaluation of various cultivation systems is conducted, focusing on open high-rate algal ponds and closed photobioreactors, with particular attention to operational parameters, treatment efficiencies, and scalability. This review evaluates biomass harvesting technologies and valorization strategies aimed at the production of biofuels, biofertilizers, animal feed, and high-value biochemicals. Techno-economic analysis and life cycle assessment indicate the feasibility of cost-effective and environmentally friendly wastewater treatment. Despite their advantages, microalgae-based systems still face significant challenges such as risk of contamination, seasonal variability, high harvesting costs, and upscaling challenges remain significant barriers to commercial implementation. Recent advances in genetic engineering, development of microbial consortia, and process optimization through artificial intelligence offer promising solutions to these limitations. Case studies of pilot-scale implementations demonstrate practical effectiveness and identifies key factors that determine their success. Overall, the review concludes that microalgae-based systems represent a transformative approach in wastewater management, enabling simultaneous pollution mitigation, carbon sequestration, and resource generation. Broad implementation requires continued innovation in cultivation and harvesting technologies, supportive regulatory frameworks, and integrated biorefinery models that maximize economic returns while minimizing environmental impacts.

Keywords: microalgae; wastewater treatment; phytoremediation; resource recovery; biomass

valorization

1. Introduction

A global freshwater problem has been brought on by the tremendous growth of human activity, and wastewater discharge has emerged as a major factor in the degradation of aquatic ecosystems. Approximately 380 billion m^3 of wastewater is generated annually worldwide, yet over 80% enters natural water bodies without adequate treatment, triggering eutrophication, hypoxic dead zones, and biodiversity loss [1,2]. Traditional wastewater treatment systems, which mainly depend on activated sludge technology and energy-intensive aeration systems, face significant sustainability issues. Conventional plants consume 0.3-0.6 kWh per cubic meter of wastewater, accounting for nearly 3-4% of global electricity consumption, while generating greenhouse gas emissions and producing 50-60 kg of residual sludge per 1000 m^3 treated [1,9]. Despite achieving BOD reduction efficiencies of 85–95% and total nitrogen removal of 70–80%, these systems have intrinsic limits in terms of energy self-sufficiency, phosphorus recovery, and mitigation of new micropollutants including endocrine disruptors and medications [10,17].

The imperative for transformative wastewater management has intensified under the framework of circular bioeconomy and the United Nations Sustainable Development Goals particularly SDGs 6 (Clean Water and Sanitation), SDGs12 (Responsible Consumption and Production), SDGs 13 (Climate Action) [4, 22]. This shift in perspective demands technologies that consider wastewater as a valuable resource reservoir, not as a waste stream. Phytoremediation—the application of microalgae and cyanobacteria for biological pollutant sequestration has attracted a lot of attention as a novel approach that balances environmental remediation with biorefinery economics [2, 13, 17].

Microalgae is a phylogenetically heterogeneous group of photosynthetic microorganisms with extreme metabolic diversification and fast growth dynamics [12, 23]. The unicellular organisms use solar energy to absorb dissolved inorganic carbon, nitrogen (NO3-, NH4+) and phosphorus (PO4 3 -) as well as produce oxygen to fuel aerobic bacterial degradation of organic contaminants [13, 17]. Microalgal systems exhibit a rate of up to 10-30 mg N/L/day of nitrogen assimilation and 1-5 mg P/L/day of phosphorus uptake to levels of less than regulatory levels of TN (<10 mg/L) and TP (<1mg/L) in the effluent [5, 19, 24]. Microalgae with photosynthetic efficiencies of 3-9 promote CO2 bio fixation at 1.5-2.0 kg CO2/kg biomass, which is carbon neutral. [20, 22, 26].

The developed biomass contains lipids (20-50% dry weight), proteins (40-60%), and carbohydrates (10-40%), which allow them to be multifacetedly valorized through the production of biodiesel, fermentation of bioethanol, biogas, high-protein animal feeds, and extraction of high-value compounds (omega-3 fatty acids, carotenoids, phycobiliproteins) [4, 6, 12, 23]. This combination value propensity, wastewater purification and bio-products marketable at the same time, may compensate the operation cost especially when they are structured as cascading biorefineries [4, 9, 27].

Although it has made massive progress, commercial practice is limited by technical and economic constraints such as biological pollution, grazing by predators, seasonal variations in productivity, and harvest expenses (20-30% of operating costs) [10, 14, 16,]. Hydraulic retention time (3-10 days), photosynthetically active radiation (100-400 μ mol photons/m^2/s), temperature (20-35°C), pH (7.0-9.0) and nutrient stoichiometry are parameters that are carefully calibrated with optimum variation occurring at specific sites [1, 19, 24].

This is an extensive review of the existing knowledge about the microalgae-based wastewater treatment that critically analyzes cultivation technologies, the mechanisms of pollutants removal, methods of harvesting, and the valorization of biomass (Figure 1). We perform techno-economic analysis by the use of life cycle assessment and cost-benefit analysis, finding out the key success factors and the recurring knowledge gaps [9, 14]. The focus is placed on such new innovations as synthetic biology to improve the strains, engineered microbial consortia, novel photobioreactor designs, and machine learning-based process optimization [10, 14, 27]. This review presents practical information to researchers, engineers, and managers in a quest to establish economically viable and environmentally sustainable phytoremediation infrastructure to promote water security and the management of resources in a circular manner.

Figure 1: Conceptual Framework

1.1 Biology and Metabolic Capacities of Microalgae

Microalgae is a polyphyletic group of photosynthetic organisms that includes the prokaryotic cyanobacteria and eukaryotic algae [2, 12]. Their metabolic plasticity, doubling time (0.5-4 days), and environmental adaptability make them outstanding biodiversity in wastewater bioremediation. [15, 23].

Microalgae are the most efficient biological catalysts to transform waste into value and they have very high surface area-to-volume ratios (104-106 m2/m3) which enable rapid uptake of nutrients and absorption of light, which is much higher in microalgae than in terrestrial plants [4, 19]. They have a near-theoretical quantum efficiency in their photosynthetic machinery, which fixes CO2 and produces oxygen stoichiometrically coupled to biomass production, thus removing the need to use energy-intensive mechanical aeration in wastewater treatment [18, 20, 26]. In comparison with traditional crops, which use considerable resources to support non-productive structural tissues, microalgae channel 95-98% of the energy used to grow them [4, 27]. This single cell structure facilitates immediate nutrient uptake of local media with no vascular transport constraints and complex regulatory systems in response to environmental disturbances in a few minutes via transcriptional and metabolic reprogramming [14, 15]. Most importantly, microalgae are highly stress-adaptive, storing lipids in periods of nitrogen deficiency, producing protective carotenoids in periods of ultra-violet sunlight, and extracellular polymers in periods of phosphorus crisis, and converting wastewater contaminants to useful biochemicals [2, 21, 23]. It is a combination of high growth rates, efficient pollutant uptake, oxygen generation and bio mass valorization potential that makes microalgae, transformative agents at the interface between environmental remediation and the concept of a circular bioeconomy [1, 2, 27].

1.2 Taxonomic Diversity and Species Selection

In Table 1, Some genera that have been studied widely to treat waste water include Chlorella, Scenedesmus, Spirulina, and Desmodesmus in eukaryotes and Synechocystis, Anabaena and Oscillatoria in cyanobacteria [2, 12, 23]. The criteria used in species selection include; growth rate, ability to withstand stress, efficiency in removing nutrients and biomass composition [15]. Chlorella vulgaris demonstrates an outstanding versatility in the removal of nitrogen (more than 90%) and lipid retention (25-40%) in the face of a nutrient limitation [4, 6, 21]. Scenedesmus obliquus can withstand high ammonia levels (as high as 300mg NH4+ per liter) [2, 28], whereas Spirulina platensis, with a protein content of 60-70%, can withstand a high pH (9-11) typical of industrial effluents [23]. Environmental pre-adaptation and syntrophic interactions between indigenous microalgal communities and axenic cultures can make indigenous microalgal consortia superior to axenic cultures in terms of robustness and treatment effectiveness. [10, 17].

Table 1: Characteristics of selected microalgae species for wastewater treatment

Species	Optimal PH	Optimal Temp.	N Removal (%)	P Removal (%)	Special Characteristics	References
Chlorella vulgaris	6.5-8.0	25-30	94-99	95-98	High adaptability, tolerates varied wastewater, excellent nutrient removal, mixotrophic capability	[29-32]
Spirulina platensis (Arthrospira)	9.0-11.0	30-38	75-89	65-80	Alkaline preference, high protein, GRAS status, easy harvesting, no cellulosic cell wall	[15, 23]
Scenedesmus obliquus	7.0-8.5	25-35	85-100	65-99	High ammonia tolerance (up to 312mg/L), rapid growth, mixotrophic capable, robust in various wastewaters	[33-36]
Desmodesmus sp.	7.0-8.5	25-32	80-90	67-80	Forms colonies facilitating settling, biofilm formation, cost effective harvesting	[10, 15]
Chlorella sorokiniana	6.5-8.0	30-38	88-95	72-89	Thermotolerant (up to 38°C), fast growth, high biomass	[2, 15]

					productivity, industrial effluent tolerance	
Scenedesmus dimorphus	6.8-8.5	25-30	82-90	70-85	Municipal wastewater specialist, high CO_2 tolerance, good lipid profile	[2, 19]

1.3 Photosynthetic Metabolism and Carbon Fixation

Oxygenic photosynthesis is used by microalgae with photosystem II and photosystem I to produce ATP and NADPH, which leads to CO2 fixation via the Calvin-Benson-Bassham cycle by the use of the Calvin-Benson-Bassham carboxylase/oxygenase (RuBisCO) [18, 20, 26]. Mechanisms of carbon concentration increase photosynthetic effectiveness by controlling high CO2 at locations of carboxylation [22, 26]. This process produces oxygen with a rate of about 1.2-1.5 g O2 /g biomass and it establishes an aerobic environment that facilitates oxidation of organic contaminants by bacteria without mechanical aeration thus consuming 60-90 % less energy than the conventional activated sludge systems. [1, 7, 13].

1.4 Nitrogen Metabolism and Assimilation

There are two different pathways of assimilation of inorganic nitrogen (nitrate, nitrite, ammonia) and organic forms (urea, amino acids) by microalgae [2, 5]. The energetically favored source, Ammonia, is directly incorporated into glutamate via the glutamine synthetase-glutamate synthase pathway [15]. Sequential reduction to nitrite and then ammonia by nitrate assimilation takes eight electrons per nitrogen atom [5, 21]. Rates of ammonia removal are 5-25 mg NH 4 +-N /L/day, often with removal efficiencies of greater than 95% in optimized systems [2, 19, 24]. The treatment dynamics of the mixed nitrogen species in wastewaters is determined by the superiority pyramid of preference (NH4 + > NO2- > NO3-) [5, 21]. The high levels of ammonia (>100mg/L) are likely to suppress photosynthesis, so high-strength effluents require acclimatization or dilution measures [21, 28].

1.5 Heavy Metals Extraction and Phosphorus Adsorption

Phosphorus, which is mainly obtained as orthophosphate (H2PO4-, HPO4 2-), is vital in the nucleic acids, membrane phospholipids and ATP metabolism [2, 5]. Microalgae were shown to uptake phosphorus in a luxurious manner, storing surplus phosphorus in the form of polyphosphate granules, thus enabled to remove phosphorus in excess of the stoichiometric need at uptake rates of 1-5 mg P/L/day and an effluent concentration of less than 0.5mg/L [5, 19, 24]. Its uptake is optimized between pH 7-8 but becomes induced by alkaline conditions (>9) resulting in calcium phosphate precipitation, and synergic removal [1, 7].

The process of heavy metal remediation is through biosorption (binding heavy metal on its surface) and bioaccumulation (active intracellular binding) [2, 8]. Cationic metals (Cd2 +, Pb2 +, Cu2 +, Zn2 +) are bound by cell wall functional groups (carboxyl, hydroxyl, sulfhydryl) which can sorb in the rapid sorption regime with a capacity of 50-500 mg/g dry biomass [8]. Second is active bioaccumulation which includes membrane transport and intracellular chelation using pyochelin's and metallothionein; reaching 70-99% removal of different metals at 1-100 mg/L [2, 8]. Specifically, Chlorella and Scenedesmus possess quite high metal tolerance and metal accumulation capacities, which allows prospective metal valorization using contaminated biomass [8, 17].

2. Cultivation Systems for Microalgae-Based Wastewater Treatment

The choice and development of cultivation systems are very important in determining the efficacy of treatment, biomass productivity, cost of operation and scalability [6, 38]. The existing systems vary in their complexity between the basic open pond and the advanced closed photobioreactor with its own set of benefits and drawbacks. [37, 38].

2.1 Open Pond Systems

The open ponds are the most economically available cultivation technology that includes natural lagoons, high-rate algal ponds (HRAPs), and raceway ponds [7, 19]. Commercial applications are dominated by the HRAPs which have low capital costs (0.2-0.5 m), paddle wheel circulation (0.15-0.3 m/s), and high surface areas leading to low operating complexities [24, 37]. At optimal conditions these systems have biomass productivities of 10-30 g/m2/day and have hydraulic retention times of 3-10 days [19, 24, 37]. The shallow depth maximizes the light penetration and ensures sufficient mixing to avoid cell sedimentation and to ensure a uniform distribution of nutrients [24].

Though economically advantageous, open systems are characterized by a number of limitations such as low ability to control temperature, pH and dissolved oxygen, excessive evaporative water losses (3-5 mm/day in arid environments) and parasitism by invasive species, zooplankton and protozoa, and low volumetric productivities (0.05-0.15 g/L/day) because of dilute biomass concentrations (0.3-0.8 g/L) [15, 37, 38]. Seasonal changes have a significant influence on performance with productivity reducing by 40-60 percent during winter season in temperate regions [24, 37]. However, open ponds are still favored in large municipal wastewater treatment because they have good cost-benefit ratio [37].

2.2 Closed Photobioreactor Systems

The closed photobioreactors (PBRs) offer controlled conditions, which reduce the risk of contamination and allow the optimization of the cultivation parameters [38, 40]. Tubular PBRs, which consist of transparent tubes (diameter of 0.05-0.1 m, length 50-200 m, horizontal, vertical and helical configurations) are characterized by volumetric productivities of 0.5-1.5 g/L/day and biomass concentrations of 2-5 g/L [4, 6, 40]. Flat-panel PBRs are made using clear materials with short light paths (0.01-0.05 m), and their light utilization efficiency and productivities are 1.0-3.0 g/L/day [39, 40]. Airlift column PBRs are mixed and gas sparged to supply CO2 and are applicable in heavy cultures with low shear stress [4, 6, 40].

The benefits of PBR are high biomass productivity (2-5 times more than open ponds), low risk of contamination, low water loss, effective temperature regulation, and high use of CO 2 (>80% vs. 20-40% in open systems) [38, 40, 42]. Nevertheless, capital is expensive (200-500/m2), needs a lot of energy to pump and regulate temperature, fouls requiring a regular cleaning process, and scalability limits its wide usage [11, 40, 42]. PBR implementation should be cost-effective and should be combined with wastewater treatment in which the nutrient-rich medium lowers the operations cost [4, 38].

2.3 Hybrid and Integrated Systems

Hybrid arrangements of open ponds and PBRs take advantage of the benefits of each and address the weaknesses [10, 38]. The two-stage systems utilize PBRs to obtain inoculums and accumulate high-value metabolites and then open ponds to produce biomass at low costs [4, 38]. The combination of membrane photobioreactor with cultivation and membrane filtration allows the treatment and separation of biomass, and this provides high-quality effluent (BOD <10 mg/L, suspended solid <5 mg/L) that can be directly used in water reuse systems [11, 41].

Microalgae systems that have been immobilized, i.e. entrapment in polymeric matrices or sticking to solid support, exhibit increased resistance to toxic substances, reduced harvesting effort, and sustained functionality without triggering biomass pollution [8, 10]. The algal biofilms grown on rotating biological contactors or submerged media have high cell density (10-20 g/L) and treatment efficiencies and occupy small land area [10, 49]. Other recent developments are photobioreactor-membrane bioreactor systems and algal turf scrubber systems that are promising in the application of decentralized treatment as shown in Figure 2. [41- 48].

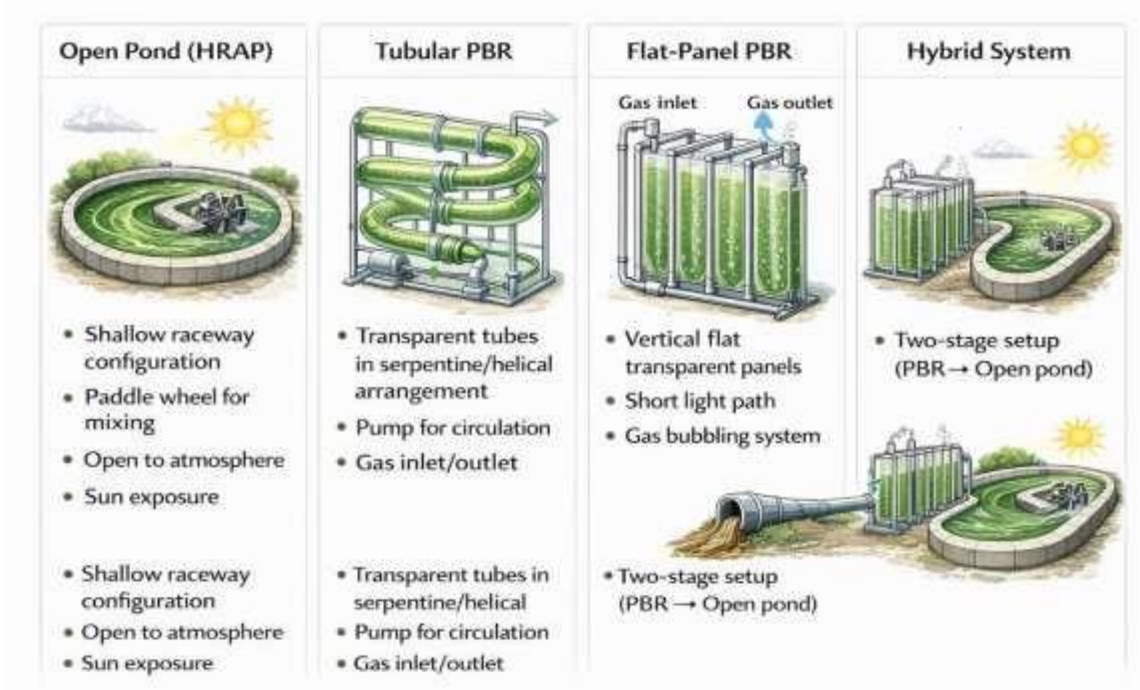

Figure 2: Different Cultivation Systems for Microalgae-Based Wastewater Treatment

2.4 Operational Parameter Optimization

Whether the system is configured in a specific way or not, performance is highly dependent on operational parameters [19, 37]. Light Intensity Optimization Compromise Photosynthetic saturation (200-400 µ mol photons/m 2/s) and photo inhibition at unrealistic irradiance (>1000 µ mol/m 2/s) [19, 40]. The maintenance of temperatures within optimum (20-35C) and pH (7.0- 9.0) maintains efficiency of metabolism and CO2 solubility, and bioavailability of heavy metals respectively [19, 24, 37].

Optimization of hydraulic retention time is a trade off between treatment efficiency and land/reactor volume needed, typically between 3-7 days of secondary treatment, and 7-15 days of nutrient polishing [7, 19]. CO 2 supplementation, especially flue gas or biogas, improves productivity and has pH buffering effects with the optimal levels of 2-5% (v/v) [26, 42]. The rate of nutrient loading should correspond to the capacity of algae assimilation in order to avoid non-compliance of effluent [5, 37].

Table 2: Comparison of Microalgae Cultivation Systems for wastewater Treatment

Parameter	**Open Pond (HRAP)**	**Tubular PBR**	**Flat-Panel PBR**	**Hybrid System**
Capital Cost ($\$/m^3$)	10-50	200-400	300-600	100-300
Biomass Concentration (g/L)	0.3-0.9	2-5	3-6	1-5
Energy Consumption (kWh/kg)	0.5-2.0	5-15	8-20	3-10
Areal Productivity ($g/m^2/day$)	10-30	20-50	30-80	25-60
N Removal Efficiency (%)	70-85	80-90	85-95	75-90
P Removal Efficiency (%)	55-75	70-90	75-88	60-85
Scalability	Excellent	Good	Fair	Good

3. Mechanisms of Pollutant Removal in Microalgal Systems

The effectiveness of microalgae-based treatment is based on the combination of physicochemical and biological processes that work in synergy [13,17]. Mechanistic knowledge forms the basis of optimization of the system and prediction of performance in a wide range of wastewater compositions [2, 15].

Microalgal wastewater treatment is not a mere bio accumulation but is a complex set of metabolic pathways and biochemical changes and ecological interactions that are coordinately able to accomplish multi-pollutant removal [1, 13, 17]. At the core of this process is the photosynthetically-driven increase in dissolved oxygen levels to levels of supersaturation (150-300/sat) which form aerobic micro-environment where organic pollutants are totally mineralized and, at the same time, cause an increase in pH due to the depletion of CO2 and the consumption of bicarbonates, thereby inducing chemical precipitation of phosphates and heavy metals [7, 13, 19]. This is self-regulating biogeochemical cycles between the production of oxygen by algae by photosynthesis and respiration coupled with heterotrophic bacteria and provides nutrient recovery and oxidation of organic matter by bacteria, and in turn, additional algal growth as the production of oxygen by algae supplies the energy and economic basis of the mechanism of self-regulation of biogeochemical cycles [7, 13, 17]. Moreover, microalgae show adaptive metabolic responses to stress needs pollutants, activating particular transport systems, synthesizing metal-chelating peptides, and adjusting enzymatic pathways which not only contribute to tolerance, but also actively convert recalcitrant compounds to less toxic metabolites or in cellular compartments sequester contaminants [2, 8, 17]. Combined with these, the direct assimilation, chemical precipitation, biosorption, biotransformation, and microbial synergism, the application of microalgal systems has placed them as versatile, multi-mechanism treatment systems with the ability to manage complex, variable wastewater streams that are inaccessible to traditional single-mechanism technologies [1, 15, 17].

3.1 Nutrient Removal: Nitrogen and Phosphorus

In Figure 3, Nitrogen and phosphorus removal is a solution to eutrophication issues based on assimilatory incorporation of biomass at N:P ratios ranging between 7:1 and 16:1 (mass basis) [5, 19]. Complete elimination of nitrogen includes organic mineralization, nitrification-denitrification in algal-bacterial consortia, ammonia volatilization at high PH (>9), and direct assimilation [7, 13, 17]. Photosynthetically-produced oxygen is utilized in the oxidation of ammonia to nitrate by nitrifying bacteria (Nitrosomonas, Nitrobacter), whereas anoxic sub-populations within the algal flocs oxidize nitrate to gaseous nitrogen [13, 17]. This combined process gets 70-90% total nitrogen removal with 5-10 day hydraulic retention times [7, 19, 24].

The phosphorus is removed by biological assimilation (60-80%) complemented by chemical precipitation as struvite (MgNH4PO46H2O) or hydroxyapatite, when the pH is higher than 9 [1, 5, 7]. Improved phosphorus removal in biologically active species with the ability to take luxury phosphorus builds up phosphorus to 3-5 percent dry weight [5]. Sustainable phosphorus is obtained through harvested biomass to resolve world phosphorus deficiency [21, 22].

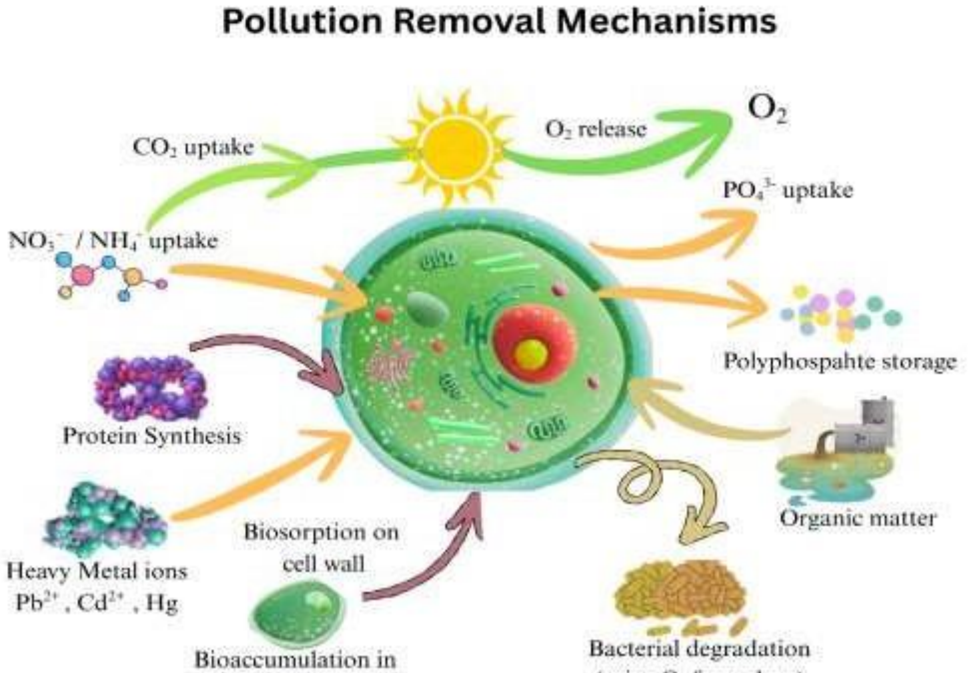

Figure 3: Pollution Removal Mechanism

3.2 Pathogen Inactivation and Organic Matter Degradation

The mechanism behind chemical oxygen demand (COD) and biochemical oxygen demand (BOD) reduction is through the algal-bacteria symbiosis, in which photosynthetic oxygen facilitates aerobic bacterial respiration and the bacteria produces CO2 and nutrients to the algae, thus removing the process of mechanical aeration [7, 13]. The efficiencies of COD removal are between 60-85 percent based on biodegradability [19]. Some of the microalgae are mixotrophic, taking up organic compounds (glucose, acetate, glycerol) in direct proportion to photosynthesis, especially in low-light conditions, which increases the organic removal and biomass productivity [15, 17].

The pathogen reduction occurs in several ways: using pH elevation (9-11) to disrupt membranes, the formation of photosynthetic oxygen radical to cause oxidative stress, nutrient competition and photodynamic inactivation using light-activated chlorophyll [13]. Reductions of bacterial pathogens of 2-4 log units (99-99.99%) are typical of secondary treatment requirements [7, 19]. The 90-99 percent removal of viruses takes a duration of 8-12 day retention times [1]. Scenedesmus and Chlorella release antimicrobial fatty acids and phenolics that increase the pathogen control, and better performance in subtropical/tropical climates because of high temperatures and the sun irradiation [19, 24].

3.3 Removal of Micropollutants and Emerging Contaminants

Pharmaceuticals, personal care products, endocrine disruptors and pesticides are removed by microalgae by biosorption, bioaccumulation and biodegradation with efficiencies ranging widely (20-95%) depending on compound hydrophobicity and molecular structure [17]. Lipophilic compounds exhibit preferential biosorption and membrane partitioning with 60-90% removal being achieved [17]. Biodegradation is achieved through an enzymatic conversion through cytochrome P450 monooxygenases, peroxidases and laccases, to less toxic metabolites [17]. Microalgal laccases are effective in the breakdown of phenolic compounds, pharmaceuticals (diclofenac, ibuprofen) and synthetic dyes [17]. Environmentally relevant levels of hormones (17α-ethinyl estradiol, 17β-estradiol) are removed (70-95) through biodegradation and sorption [17]. Nevertheless, a thorough knowledge of the degradation pathways, metabolite toxicity, and stability in the short term requires studies to understand the mitigation of micropollutants with certain confidence [1, 14].

4. Biomass Harvesting and Processing Technologies

Biomass harvesting is a significant bottleneck in the microalgae-based wastewater treatment, and it usually contributes 20-30 percent of the overall costs of operation because it dilutes cell suspensions (0.3-0.8 g/L) and has a small cell size [16, 25]. The choice of suitable harvesting techniques is based on the nature of the species, down-stream usage and financial limitations.- expand this.

The fact that these organisms are both, paradoxically, microscopic and negatively charged on their surface which does not allow them to form aggregates spontaneously, and, at the same time, is what makes them effective in their nutrient uptake, and, thus, requires energy The inherent dilemma of the microalgal systems as a harvesting system is rooted in -consuming solid-liquid separation [3, 11, 16, 25]. This financial obstacle: in which cost of harvesting may be higher than cost of cultivation is the major impediment to commercial feasibility, especially of low-value applications like wastewater treatment in which revenue generation is heavily reliant on keeping operational costs low [9, 16, 25]. Optimization of harvesting strategies must therefore be done in a holistic approach taking into account the whole process chain balancing recovery efficiency, energy consumption, preservation of biomass quality and compatibility with downstream valorization pathways [3, 11, 16]. The new paradigms promote multi-step strategies that incorporate low-cost bulk dewatering (volume down to 95-99 percent) with selective use of secondary concentration, thus dispersing the energy inputs in a strategic manner as well as keeping the process economical [11, 16, 25]. Also new biological strategies that can use natural flocculation mechanisms, such as biofilm growth, auto-flocculation by manipulation of the pH, and bio-flocculation by co-cultivation of bacteria, provide potentially radical solutions that can dispense with the use of chemicals, and can be used to achieve passive settling, radically reorganizing the harvesting cost equation [8, 10, 38]. The current establishment of energy-saving and cost-effective harvesting technologies is in the centre of making microalgal wastewater treatment not a concept, but a large scale industrial practice [16, 25, 41].

4.1 Flocculation and Sedimentation

Flocculation clumps dispersed cells into larger flocs which can be separated by gravity. The rapid aggregation is attained through chemical flocculation by using multivalent cations (Al3+, Fe3+), cationic polymers, which add contaminants restricting the use of biomass as a bio-resource and generates reagent expenses ($0.10-0.50/m3) [3, 16]. The calcium and magnesium ions precipitate the cells during intensive photosynthesis induced by increasing pH (>10) without the addition of chemical agents [11]. Alternatives that can be made sustainable and that need optimization of the species include bioflocculation with bacterial exopolysaccharides or biopolymers of some microalgae [8, 10].

With 60-80% recovery, gravity sedimentation concentrates the suspension to 1-3% solids over 12-24 hours which is suitable when operating on large scale but consumes large land area [25]. DAF (dissolved air flotation) has better recovery (>90% in 20-30 minutes) at lower energy cost (0.1-0.3 kWh/m3) in order to produce thicker slurries (2-6% solids) [3, 16].

4.2 Filtration, Centrifugation, and Integrated Strategies

Membrane filtration (microfiltration, ultrafiltration) is an option with >95% recovery to produce clarified effluent to be used again but capital and fouling are limiting factors to extensive use [11, 25]. With centrifugation (3,000-10,000 g) the concentrated paste (15-25% solids) is obtained within minutes with >95% efficiency, however, at high cost in terms of energy (0.5-1.5 kWh/m3) limits its use to high value products [4, 11].

The economic optimization requires multi-stage harvesting, which involves low-cost bulk separation (flocculation/sedimentation to 1-3% solids) and secondary dewatering (centrifugation/filtration to 15-25% solids) [16, 25]. In the use of biofuels, additional drying can be done using solar dehydration or filter press, to obtain 80-90 percent solids prior to processing [4, 11].

5. Value-Added Products and Biomass Valorization

The core of economic viability is that the biomass valorization creates revenue streams to mitigate the cost of operation. Multi-product configurations of cascading biorefinery achieve maximum resource extraction [12, 23].-expand this.

The novel economic paradigm of waste treatment as a cost center to integrated biorefinery as a profit center is critically dependent on maximizing the biomass value by optimization of strategic product portfolio [12, 23, 27]. Microalgal biomass is a biochemical treasure trove with concomitantly extractable lipids, proteins, carbohydrates, pigments, and functional metabolites, which makes possible cascading valorization, in which high-value products are sequentially extracted by biomass before energy recovery is done on residual biomass [12, 27]. This hierarchical processing, which can be compared to the petroleum refining, converts one feedstock into one or more revenue streams with significantly different market values of biofuels (commodity) at \$0.5-2/kg or bioactives (pharmaceutical) at \$5,000-50,000/kg that can fundamentally change project economics [23, 27]. The sequential order of the extraction process, maintenance of bioactivity throughout the processing and corresponding quality of the biomass to the final application demand a complex design of the biorefinery that compromises the technical feasibility with the economic effectiveness [4, 27]. Finally, effective commercialization requires the establishment of value-maximizing product mixes based on local market conditions, regulatory policies and wastewater properties which in combination identify the best biorefinery mixes [9, 27].

5.1 Biofuel Production

Biodiesel production through transesterification of algal lipids (20-50% dry weight) represents extensively studied valorization option, demonstrating similar fuel properties to petroleum diesel with 60-80% lifecycle reduction in greenhouse gas [4, 6, 12]. Carbohydrates (10-40% dry weight) are converted in fermentation of bioethanol with yields of 0.3-0.5 g ethanol/g substrate, but cell wall recalcitrance requires pretreatment [4, 15].

An anaerobic digestion provides the most cost-effective route and transforms whole biomass to biogas (55-65% methane) with 0.2-0.4 L CH_4/g volatile solids without the need to extract it [15, 21]. The co-digestion with organic wastes promotes production of methane whereas digestate is used as nutrient-rich manure, which is one of the examples of the principles of the circular economy [28].

5.2 Agricultural Applications and Animal Feed

Biomass of microalgae at 5-10% nitrogen and 1-3% phosphorus is considered as organic fertilizer, and field experiments reveal that increased crop yield of 10-30% can be attributed to biostimulant action of phytohormones and polysaccharides [21]. Cyanobacterial biofertilizers trap atmospheric nitrogen (20-40 kg N/ha/year) which is especially efficient in rice-cultivation [22].

The microalgae have a high protein content (40-60% dry weight), which places this food as alternative feeds [12, 23]. GRAS defined spirulina and Chlorella have a digestibility of above 80% and pigments improve the quality of animal products [15, 23]. Economic analysis shows that there are competitive costs of protein of wastewater-cultivated algae with low prices ranging between \$2-5/kg, but the quality control is necessary in relation to any possible contaminants [17, 21].

5.3 High-Value Biochemicals

The specialized metabolites have high prices that would allow their production to be economically viable. Dunaliella and Haematococcus carotenoids (β-carotene, astaxanthin, lutein), have a nutraceutical market value of \$300-2,000/kg [12, 23]. Cyanobacteria phycobiliproteins are also used as natural colorants and fluorescent markers which are being sold at prices of \$5,000-50,000/kg [23]. Omega-3 fatty acids (EPA, DHA) produced by Nannochloropsis and Schizochytrium appeal to the sustainable fish oil products at \$30-100/kg

[12, 27]. Such co-products are of great value and contribute towards the overall process economics when combined with wastewater treatment [23, 27].

6. Types of Wastewaters Treated with Microalgae

Microalgae are highly adaptive to a wide range of wastewater streams, the treatment efficacy of which is determined by the composition of pollutants, stoichiometry of nutrients, and the presence of inhibitory substances [17].-expand this.

The versatility of microalgae-based treatment systems both indicates the flexibility of metabolism of particular species and the ability to selectively strain-based on specifics of effluent properties [1, 2, 15, 17]. The overall compositions of wastewater are regarded as core determinants of treatment performance due to multiple factors that cannot occur independently of each other: nutrient ratios (especially N:P) that determine biomass stoichiometry and growth dynamics and to a larger extent organic carbon availability promoting mixotrophic metabolism that not only is more productive but also increases the rate at which pollutants are degraded, presence of micronutrients (Fe, Mg, Mn, Zn) promoting enzyme functions, and toxic compounds (heavy metals, xenobiotics, extreme The concentration gradient between the dilute municipal effluents and the concentrated agricultural wastewaters have three orders of magnitude so adaptive strategies such as dilution protocol, sequential treatment phases, or acclimatization of high-strength streams are required [1, 21, 28]. Moreover, temporal variability of wastewater properties, including its diurnal flow variation, seasonal agricultural discharge, and episodic releases of industries, poses an issue to the stability of the system, and the robust microalgal consortia tend to exhibit better resilience than a monoculture due to functional redundancy and metabolic complementarity [10, 17]. The knowledge of these wastewater-specific parameters can facilitate a reasonable design of the system, the right choice of species, and optimization of operations that can bring the maximum efficiency to the treatment process and allow the production of biomass that can be used in the desired valorization routes [1, 15, 38].

6.1 Municipal Wastewater

The wastewater of municipalities is the most studied source, whose characteristics are medium nutrient levels (TN: 20-85 mg/L, TP: 4-15 mg/L), biodegradable organic matter (COD: 250-800 mg/L) [2]. Primary and secondary effluents offer N:P ratios (5:1-10:1) that is close to the needs of microalgae allowing the efficient assimilation without supplementation [15]. The high-rate algal ponds are able to attain 70-90% removal of nitrogen, 50-80% removal of phosphorus, and 60-80% removal of COD in 4-10 days retention times [7,24]. Large-scale operations are made possible by predictable composition and large volumes (150-400 L/capita/day) [15].

6.2 Agricultural and Livestock Wastewater

The livestock effluents have high nutrient loads (TN: 500-3000 mg/L, TP: 50-500 mg/L) and organic matter (COD: 5,000-50,000 mg/L), which are subject to dilution, or anaerobic pretreatment [21, 28]. Anaerobe digestion yields digestate that contains mineralized nutrients (mainly NH4+) that are conducive to algal uptake [28]. Chlorella and Scenedesmus can withstand ammonia to 100-300mg/L and both can remove ammonia greater than 90% with productivities of 0.5-1.0 g/L/day when acclimated [21, 28]. Dark color and the presence of pathogens demand proper system design [17, 21].

6.3 Industrial Wastewater

Municipal effluents have unstable compositions that need individual assessment. The wastewaters of food processing facilitate the use of mixotrophic cultivation which yields more [2, 17]. Textile effluents show 60-90% removal of dyes through biosorption whereas pharmaceutical wastewaters have an active compound removal 40-80% [17]. Effluents contaminated with metals take advantage of the biosorption capacity and the effluents contain 70-95% Cd, Pb, Cu, and Zn [2, 8]. Toxicity screening and nutrient balancing are normally required in the industrial applications [1, 17].

7. Challenges and Limitations

Commercial implementation is subjected to complex impediments that require methodical allocation [14].-expand this

Although there has been significant scientific progress and technical feasibility at pilot scales, the development of the gap between laboratory innovation and commercial scale implementation has consistently been challenged at the biological, engineering, economic, and regulatory levels [1, 4, 14]. These hindrances are not solitary issues but rather sequential limitations where the solution to one problem enhances another- e.g. the removal of contamination using closed photobioreactors raises capital expenses, whereas open ponds which cost less to maintain means sacrificing control of the process [4, 6, 14]. All features of system design are permeated by the underlying conflict between the goal of treating water and reducing minimally the operational costs per unit of geographic area, wastewater attributes, and local market dynamics where biomass products are sold [9, 14, 27]. Also, the lack of performance metrics that are standardized, inconsistent regulatory frameworks in different jurisdictions, and the lack of long-term operational data at full-scale facilities create uncertainty, which suppresses capital investment and technological adoption [1, 14]. These multidimensional challenges can only be dealt with in a coordinated manner that involves technological innovation, optimization of processes, enabling policy frameworks and proving economic feasibility by carrying out comprehensive techno-economic evaluations [9, 14, 27].

7.1 Technical Challenges

Bacteria, fungi and invasive algae also cause biological contamination which interferes with the stability of cultures in open systems [1, 10, 15]. The impact of zooplankton predation may destroy a population in several days, necessitating the control of pH or selective screening [10, 15]. Productivity variation (45-70%) seasonally poses a challenge to year-round stability in temperate latitudes [7, 19, 24]. Scale-up creates challenges in terms of light distribution, mixing homogeneity, and contamination control and dilute suspension (0.3-0.8 g/L) imposes harvesting expenses [4, 11, 16, 25].

7.2 Economic and Regulatory Barriers

Capital costs are \$10-50/m2 (open ponds) to \$200-500/m2 (photobioreactors), with biomass production costs of \$3-30/kg dry weight [4, 6, 9]. Modern economics prefer high value co-product integration as compared to commodity applications [6, 9, 27]. The absence of proper regulatory frameworks brings about confusion over effluent standards and use of biomass [1, 14]. Feed biomass produced using wastewater needs to be shown to be safe in terms of accumulating contaminants [17, 21, 23].

8. Recent Advances and Future Perspectives

New technologies tackle existing constraints and are able to extend their application opportunities due to the combined technological and biological developments [10, 14, 27]. Genome editing with CRISPR-Cas9 allows to boost the growth rate, stress resistance, and product concentration in a specific direction, even though regulators might restrict the use of genetically modified organisms in open systems [14, 27]. Redundant metabolic complementarity is optimized by rationally engineered algal-bacterial consortia, which improves the stability and treatment with respect to performance [10, 13, 17]. Synthetic ecology and metagenomics methods can be used to build unstable communities that are adapted to particular wastewater communities [10, 17].

Advanced photobioreactors with enhanced light distribution and membrane integration have attained a high quality of effluent that is suitable for direct reuse [6, 11]. The algorithms of artificial intelligence and machine learning allow real-time optimization, predictive maintenance, and automated control, and technologies of digital twins allow testing of ideas in the virtual world before their implementation [14]. The cascading biorefinery designs are designed to maximize value by extracting high-value compounds followed by production of biofuels using remaining materials [23, 27]. Coupling with industrial sources of CO2 and anaerobic digestion defines closed-loop systems that are nearly energy-positive, and are examples of the principles of the circular economy [21, 22].

9. Conclusions

Wastewater treatment based on microalgae represents a radically new treatment model that will combine pollution reduction with resource recovery, which is essentially in line with the principles of a circular bioeconomy and sustainable development requirements [4, 22]. This review sums up to the clear conclusion that phycoremediation systems can successfully remediate an eclectic range of pollutants classes -removing nitrogen (70-95%), phosphorus (50-90%), COD (60-85%), heavy metal (70-99%), and emerging contaminants (20-95%) and, at the same time, produce biomass that can be valorized as biofuels, biofertilizers, animal feed, high-value biochemicals [23, 24].

The choice of cultivation system is one of the most crucial factors to consider in terms of techno-economic performance: the open high-rate algal ponds are economically viable and effective in large, municipal scale applications in well-favored climates, and closed photobioreactors are more appropriate in the high-value processes highly sensitive to contamination [6, 7]. In-between options like hybrid systems and immobilized systems are also possible and should be developed further [11]. The technologies of harvesting are one of the key cost determinants in which there is a need to have integrated multi-stage strategies to optimize the economy [16].

Despite the significant advances in science, commercialization faces an overarching challenge such as contamination susceptibility, seasonal fluctuation in productivity, burden of scale-up, high production expenses and regulating ambiguity [15]. Existing biomass prices (\$3-30/kg) are above commodity biofuel application prices, forcing the use of high value co-products to be economically viable [4, 6, 27]. New innovations- including genetic engineering, synthetic consortium design, process optimization via artificial intelligence, and cascading biorefinery designs- provide promising ways out of these barriers [10, 14].

The priority research needs that could be used to speed up commercial-scale implementation are: (i) creation of strong, contamination-resistant strains, using advanced breeding or targeted genome editing [27]; (ii) innovations in energy-efficient and cost-effective harvesting technologies [3, 16]; (iii) development of harmonized regulatory frameworks that can allow safe biomass valorization [23]; (iv) validation of integrated biorefinery platforms that can optimize resource recovery and economic profits [4,27]; and (v) development of demonstration-scale facilities generating long term performance data for techno-economic validation [19].

The combination of the increasing water shortage, strict environmental policies, the requirements of about the circular economy, and the technological maturity forms an unprecedented opportunity of microalgae-based wastewater treatment [22]. An effective translation between research innovation and commercial infrastructure will see phycoremediation becoming one of the foundation technologies of twenty-first century sustainable water management- both sustainable water security, carbon neutrality, nutrient circularity and renewable resource production as an integrated aspect of bio economics [20].

References

1. Acién, F.G., Gómez-Serrano, C., Morales-Amaral, M.M., Fernández-Sevilla, J.M., & Molina-Grima, E. (2016). Wastewater treatment using microalgae: how realistic a contribution might it be to significant urban wastewater treatment? Applied Microbiology and Biotechnology, 100(21), 9013-9022.
2. Abdel-Raouf, N., Al-Homaidan, A.A., & Ibraheem, I.B.M. (2012). Microalgae and wastewater treatment. Saudi Journal of Biological Sciences, 19(3), 257-275.
3. Barros, A.I., Gonçalves, A.L., Simões, M., & Pires, J.C.M. (2015). Harvesting techniques applied to microalgae: A review. Renewable and Sustainable Energy Reviews, 41, 1489-1500.
4. Brennan, L., & Owende, P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. Renewable and Sustainable Energy Reviews, 14(2), 557-577.
5. Cai, T., Park, S.Y., & Li, Y. (2013). Nutrient recovery from wastewater streams by microalgae: Status and prospects. Renewable and Sustainable Energy Reviews, 19, 360-369.
6. Chisti, Y. (2007). Biodiesel from microalgae. Biotechnology Advances, 25(3), 294-306.
7. Craggs, R.J., Heubeck, S., Lundquist, T.J., & Benemann, J.R. (2011). Algal biofuels from wastewater treatment high rate algal ponds. Water Science and Technology, 63(4), 660-665.
8. De-Bashan, L. E., & Bashan, Y. (2010). Immobilized microalgae for removing pollutants: review of practical aspects. *Bioresource technology*, *101*(6), 1611-1627.
9. Delrue, F., Setier, P.A., Sahut, C., Cournac, L., Roubaud, A., Peltier, G., & Froment, A.K. (2012). An economic, sustainability, and energetic model of biodiesel production from microalgae. Bioresource Technology, 111, 191-200.
10. Gonçalves, A.L., Pires, J.C.M., & Simões, M. (2017). A review on the use of microalgal consortia for wastewater treatment. Algal Research, 24, 403-415.
11. Grima, E.M., Belarbi, E.H., Fernández, F.A., Medina, A.R., & Chisti, Y. (2003). Recovery of microalgal biomass and metabolites: process options and economics. Biotechnology Advances, 20(7-8), 491-515.
12. Guiry, M.D. (2012). How many species of algae are there? Journal of Phycology, 48(5), 1057-1063.
13. Hoffmann, J.P. (1998). Wastewater treatment with suspended and nonsuspended algae. Journal of Phycology, 34(5), 757-763.
14. Lam, M.K., & Lee, K.T. (2012). Microalgae biofuels: A critical review of issues, problems and the way forward. Biotechnology Advances, 30(3), 673-690.
15. Mata, T.M., Martins, A.A., & Caetano, N.S. (2010). Microalgae for biodiesel production and other applications: A review. Renewable and Sustainable Energy Reviews, 14(1), 217-232.
16. Milledge, J.J., & Heaven, S. (2013). A review of the harvesting of micro-algae for biofuel production. Reviews in Environmental Science and Bio/Technology, 12(2), 165-178.
17. Muñoz, R., & Guieysse, B. (2006). Algal-bacterial processes for the treatment of hazardous contaminants: A review. Water Research, 40(15), 2799-2815.
18. Oswald, W.J. (1988). Micro-algae and waste-water treatment. In: Microalgal Biotechnology (Borowitzka, M.A., & Borowitzka, L.J., Eds.), pp. 305-328, Cambridge University Press.

19. Park, J.B.K., Craggs, R.J., & Shilton, A.N. (2011). Wastewater treatment high rate algal ponds for biofuel production. Bioresource Technology, 102(1), 35-42.
20. Pittman, J.K., Dean, A.P., & Osundeko, O. (2011). The potential of sustainable algal biofuel production using wastewater resources. Bioresource Technology, 102(1), 17-25.
21. Rawat, I., Ranjith Kumar, R., Mutanda, T., & Bux, F. (2011). Dual role of microalgae: Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. Applied Energy, 88(10), 3411-3424.
22. Singh, U.B., & Ahluwalia, A.S. (2013). Microalgae: A promising tool for carbon sequestration. Mitigation and Adaptation Strategies for Global Change, 18(1), 73-95.
23. Spolaore, P., Joannis-Cassan, C., Duran, E., & Isambert, A. (2006). Commercial applications of microalgae. Journal of Bioscience and Bioengineering, 101(2), 87-96.
24. Sutherland, D.L., Turnbull, M.H., & Craggs, R.J. (2014). Increased pond depth improves algal productivity and nutrient removal in wastewater treatment high rate algal ponds. Water Research, 53, 271-281.
25. Uduman, N., Qi, Y., Danquah, M.K., Forde, G.M., & Hoadley, A. (2010). Dewatering of microalgal cultures: A major bottleneck to algae-based fuels. Journal of Renewable and Sustainable Energy, 2(1), 012701.
26. Wang, B., Li, Y., Wu, N., & Lan, C.Q. (2008). CO_2 bio-mitigation using microalgae. Applied Microbiology and Biotechnology, 79(5), 707-718.
27. Wijffels, R.H., & Barbosa, M.J. (2010). An outlook on microalgal biofuels. Science, 329(5993), 796-799.
28. Zhu, L., Wang, Z., Shu, Q., Takala, J., Hiltunen, E., Feng, P., & Yuan, Z. (2013). Nutrient removal and biodiesel production by integration of freshwater algae cultivation with piggery wastewater treatment. Water Research, 47(13), 4294-4302
29. Mayhead, E., Silkina, A., Llewellyn, C.A., & Fuentes-Grünewald, C. (2018). Comparing nutrient removal from membrane filtered and unfiltered domestic wastewater using Chlorella vulgaris. Biology, 7(1), 12.
30. Ge, S., Qiu, S., Tremblay, D., Viner, K., Champagne, P., & Jessop, P.G. (2018). Centrate wastewater treatment with Chlorella vulgaris: Simultaneous enhancement of nutrient removal, biomass and lipid production. Chemical Engineering Journal, 342, 310-320.
31. Yousif, Y.I.D., Mohamed, E.Sh., & El-Gendy, A.S. (2022). Using Chlorella vulgaris for nutrient removal from hydroponic wastewater: experimental investigation and economic assessment. Water Science and Technology, 85(11), 3240-3258.
32. Li, F., Amenorfenyo, D. K., Zhang, Y., Zhang, N., Li, C., & Huang, X. (2021). Cultivation of Chlorella vulgaris in membrane-treated industrial distillery wastewater: growth and wastewater treatment. *Frontiers in Environmental Science*, *9*, 770633.
33. Martínez, M.E., Sánchez, S., Jiménez, J.M., El Yousfi, F., & Muñoz, L. (2000). Nitrogen and phosphorus removal from urban wastewater by the microalga Scenedesmus obliquus. Bioresource Technology, 73(3), 263-272.
34. Duan, Y., Guo, X., Yang, J., Zhang, M., & Li, Y. (2020). Nutrients recycle and the growth of Scenedesmus obliquus in synthetic wastewater under different sodium carbonate concentrations. *Royal Society open science*, *7*(1). doi: 10.1098/rsos.191214
35. Su, Y., Song, K., Zhang, P., Su, Y., Cheng, J., & Chen, X. (2017). Progress of microalgae biofuel's commercialization. Renewable and Sustainable Energy Reviews, 74, 402-411.
36. Liu, J., Yin, J., Ge, Y., Han, H., Liu, M., & Gao, F. (2021). Improved lipid productivity of Scenedesmus obliquus with high nutrient removal efficiency by mixotrophic cultivation in actual municipal wastewater. *Chemosphere*, *285*, 131475.
37. Sutherland, D. L., Park, J., Heubeck, S., Ralph, P. J., & Craggs, R. J. (2020). Size matters–Microalgae production and nutrient removal in wastewater treatment high rate algal ponds of three different sizes. *Algal Research*, *45*, 101734.
38. Narala, R. R., Garg, S., Sharma, K. K., Thomas-Hall, S. R., Deme, M., Li, Y., &

Schenk, P. M. (2016). Comparison of microalgae cultivation in photobioreactor, open raceway pond, and a two-stage hybrid system. *Frontiers in Energy Research*, *4*, 29.

39. Slegers, P.M., Wijffels, R.H., van Straten, G., & van Boxtel, A.J.B. (2011). Design scenarios for flat panel photobioreactors. Applied Energy, 88(10), 3342-3353.
40. Huang, Q., Jiang, F., Wang, L., & Yang, C. (2017). Design of photobioreactors for mass cultivation of photosynthetic organisms. *Engineering*, *3*(3), 318-329.
41. Bilad, M.R., Arafat, H.A., & Vankelecom, I.F.J. (2014). Membrane technology in microalgae cultivation and harvesting: A review. Biotechnology Advances, 32(7), 1283-1300.
42. Tredici, M. R., Bassi, N., Prussi, M., Biondi, N., Rodolfi, L., Zittelli, G. C., & Sampietro, G. (2015). Energy balance of algal biomass production in a 1-ha "Green Wall Panel" plant: How to produce algal biomass in a closed reactor achieving a high Net Energy Ratio. *Applied Energy*, *154*, 1103-1111.
43. El-Sheekh, M. M., El-Kassas, H. Y., & Ali, S. S. (2025). Microalgae-based bioremediation of refractory pollutants: an approach towards environmental sustainability. *Microbial Cell Factories*, *24*(1), 19.
44. Yang, K., Wang, J., Zheng, J., & Cai, W. (2025). Microalgae-based wastewater treatment: Advances and challenges in membrane harvesting technologies. Separation and Purification Technology, 360, 130805.
45. Kundu, P., Dutta, N., & Bhattacharya, S. (2024). Application of microalgae in wastewater treatment with special reference to emerging contaminants: a step towards sustainability. *Frontiers in Analytical Science*, *4*, 1513153.
46. Calatrava, V., Gonzalez-Ballester, D., & Dubini, A. (2024). Microalgae for bioremediation: Advances, challenges, and public perception on genetic engineering. BMC Plant Biology, 24, 1261.
47. Li, P., Luo, Y., Tian, J., Cheng, Y., Wang, S., An, X., ... & Li, X. (2024). Outdoor tubular photobioreactor microalgae-microorganisms biofilm treatment of municipal wastewater: Enhanced heterotrophic assimilation and synergistic aerobic denitrogenation. *Bioresource Technology*, *408*, 131151.
48. Gupta, R., Mishra, N., Singh, G., Mishra, S., & Lodhiyal, N. (2024). Microalgae cultivation and value-based products from wastewater: Insights and applications. *Blue Biotechnology*, *1*(1), 20.