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Review

Microalgae from the Extremes: Unlocking Their Potential for Emerging Pollutant Removal and Sustainable Water Remediation

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Abstract

Anthropogenic pollution of aquatic ecosystems presents a significant global challenge, underscoring the urgent need for resilient, biologically mediated remediation strategies. In this context, microalgae have emerged as a compelling solution, owing to their inherent adaptability to diverse environments and their capacity for efficient contaminant mitigation through bioremediation. These organisms possess the potential to sequester and remove a broad spectrum of pollutants from wastewater streams, including excess nutrients, organic substrates, heavy metals, and various emerging contaminants. Specifically, their metabolic versatility allows these microorganisms to tolerate and degrade complex substances such as recalcitrant micropollutants and hydrocarbons even under fluctuating environmental conditions. This review evaluates extremophilic microalgae as specialized biological agents capable of functioning under harsh anthropogenic stressors that may constrain the performance of microalgal strains commonly investigated for wastewater treatment. Their distinctive stress tolerance may provide advantages for treating wastewater characterized by extreme physicochemical conditions. By examining the unique metabolic pathways of these extremophiles, this analysis addresses critical gaps in the current bioremediation literature regarding the practical scalability and economic viability of integrating such specialized biomass into large-scale treatment infrastructure.

Keywords: emerging contaminants; extremophiles; microalgae; wastewater treatment; nature-based solution

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1. Introduction

1.1. Background

The escalating global water crisis exacerbated by rapid population growth and industrial expansion necessitates the development of cost-effective and sustainable remediation strategies for emerging contaminants [1]. These contaminants, encompassing pharmaceuticals, personal care products, endocrine-disrupting chemicals, heavy metals, forever

chemicals, pesticides and others, present substantial threats to ecological systems and human well-being, largely because of their resistance to traditional wastewater treatment processes [2,3]. Consequently, microalgae have emerged as a viable biological remediation option, utilizing their diverse metabolic capabilities to either sequester or degrade intricate organic and inorganic pollutants [4]. Microalgae-based wastewater treatment has attracted considerable attention as a sustainable alternative to conventional physicochemical and biological processes because they simultaneously remove nutrients, sequester carbon dioxide, produce oxygen, and generate valuable biomass. To date, most wastewater treatment studies have focused on freshwater chlorophytes, cyanobacteria, and diatoms, owing to their rapid growth, ease of cultivation, and relatively high nutrient removal efficiencies. Among chlorophytes, *Chlorella vulgaris*, *Chlorella sorokiniana*, *Scenedesmus obliquus*, *Desmodesmus* spp., and *Coelastrella* spp. are the most extensively investigated for municipal, agricultural, textile, and food-processing wastewaters because of their high nitrogen and phosphorus assimilation rates and tolerance to moderate organic loading. Other genera such as *Euglena*, *Chlamydomonas*, *Botryococcus*, and *Haematococcus* have also been investigated for specific applications, including heavy metal removal and pharmaceutical degradation. Despite these advances, the practical application of these commonly investigated microalgae remains constrained because most species perform optimally only under relatively narrow environmental conditions. Industrial wastewaters often exhibit characteristics such as high salinity, extreme pH, elevated temperatures, heavy metal contamination, toxic organic compounds, high ammonia concentrations, and fluctuating hydraulic and organic loading rates that substantially inhibit the growth and metabolic activity of conventional freshwater microalgae. Specifically, extremophilic microalgal strains demonstrate considerable tolerance to fluctuating salinity, pH levels, and temperatures, allowing their proliferation in varied and demanding industrial wastewater settings [5,6]. The exploitation of these distinct metabolic pathways by extremophilic microalgae provides a robust foundation for advanced tertiary and quaternary wastewater treatment, thereby reducing high levels of contamination and concurrently enabling the production of valuable biomolecules [7,8]. Moreover, incorporating these microorganisms into bioremediation systems facilitates the transformation of assimilated contaminants into biomass, which can then be valorized as biofuels or biofertilizers, thus fostering a circular economy approach in wastewater management [9]. These microalgal species possess an extensive array of enzymes capable of breaking down persistent compounds that typically resist conventional biodegradation methods [10]. However, despite their considerable promise, studies on extremophilic candidates are still sparse, indicating that precise strain selection and metabolic pathway engineering are crucial areas for future biotechnological development [11]. Present challenges in this domain involve the intrinsic variability of wastewater components and the requirement for improved bioremediation efficiencies to achieve industrial-scale implementation [12]. Overcoming these limitations necessitates a thorough elucidation of the fundamental mechanisms governing pollutant removal, such as bioaccumulation, biosorption, and enzymatic degradation [13].

1.2. Knowledge Gap

While conventional treatment systems are well-established, there is a paucity of literature evaluating the specific efficacy of microalgae-based technologies in degrading organic microcontaminants, such as polycyclic aromatic hydrocarbons and biocides [14]. Furthermore, as existing studies disproportionately emphasize the removal of basic nutrients and heavy metals, a significant knowledge gap persists regarding the co-metabolic pathways required to neutralize recalcitrant emerging contaminants, including antibiotics and complex personal care products [15,16]. The synergistic potential of coupling microalgal bioremediation with industrial flue gas utilization for the targeted degradation of

these persistent pollutants remains under-researched [17]. The transition from controlled laboratory environments to large-scale operational settings is further impeded by a lack of standardized protocols for optimizing the metabolic flux of extremophilic strains in continuous-flow treatment systems [18,19]. Consequently, advancing the scalability of these biological reactors requires deeper investigation into the design of non-assisted systems capable of functioning under variable environmental conditions [20]. Establishing reliable operational frameworks also necessitates addressing current technical limitations regarding degradation rates and the susceptibility of microbial consortia to the inconsistent compositions inherent in industrial wastewater [21]. Achieving the economic viability of these processes requires a shift from current laboratory-scale models toward high-throughput, cost-effective bioreactor designs that leverage native, resilient species [22].

1.3. Scope of Review

This review systematically evaluates the current state of microalgal applications in the remediation of emerging contaminants, specifically focusing on the physiological and biochemical adaptations of extremophilic species in complex industrial effluents. It further examines the critical transition from laboratory-scale studies to field-ready configurations, assessing their largely unaddressed capacity to remove recalcitrant organic microcontaminants.

2. Global Freshwater Pollution Crisis

The proliferation of trace-level contaminants ranging from pharmaceuticals to endocrine-disrupting chemicals in domestic and industrial wastewater has reached concentrations that existing treatment infrastructure is inadequately equipped to mitigate [23,24]. These substances, encompassing antibiotic residues and resistant genetic material, often bypass conventional wastewater treatment plants, thereby facilitating their entry into receiving water bodies [24]. Such widespread dissemination complicates the degradation of low-concentration substrates, which frequently remain recalcitrant to standard microbial metabolism due to the thermodynamic constraints of oligotrophic carbon cycling [25]. Consequently, there is an urgent need for innovative technological solutions, such as the implementation of bacterial-microalgal consortia, which have shown considerable potential in enhancing the metabolic degradation of diverse organic pollutants [26,27]. By leveraging cross-feeding interactions, these consortia overcome the inhibitory effects of residual antibiotics that might otherwise impair the metabolic performance of individual species [28]. Furthermore, the strategic utilization of algal-bacterial consortia addresses the global freshwater crisis by offering a synergistic approach that relates high rates of atmospheric carbon fixation with the intensified removal of complex organic and inorganic pollutants [6,17]. These systems exhibit greater operational resilience compared to monocultures, effectively remediating wastewater streams that evade conventional technologies and facilitating the recovery of high-quality water resources essential for environmental and human health.

2.1. What Are Emerging Pollutants (EPs)?

Emerging pollutants comprise a diverse class of unregulated synthetic or naturally occurring substances, including pharmaceuticals, personal care products, endocrine-disrupting chemicals, and illicit drugs, that are increasingly detected in aquatic environments [29]. These compounds are often characterized by their persistence and their capacity to induce significant ecological disruption at trace concentrations, particularly through the promotion of antimicrobial resistance [30,31]. The pervasive discharge of such hazardous constituents from industrial and municipal sources necessitates the implementation of advanced mitigation strategies to counteract their long-term deleterious impact on natural habitats and public health [32]. Furthermore, many of these compounds

exhibit pseudo-persistence whereby their high transformation and removal rates are continuously offset by uninterrupted introduction from diffuse and point-source emissions and frequently occur as complex mixtures whose combined ecotoxicological effects substantially exceed those predicted for individual constituents [33,34]. These complex mixtures also challenge traditional remediation metrics, as their synergistic interaction with heavy metals and other inorganic contaminants complicates the selection of suitable microbial candidates for efficient bio-removal [35]. Integrating such multispecies consortia allows for the strategic exploitation of specific niche ecological interactions that can significantly increase organic removal [36]. The integrated yield of algal-bacterial consortia enhances the technical feasibility of addressing complex emerging pollutant mixtures, as the inherent metabolic processes for contaminant removal also yield recoverable biomass that supports the development of sustainable, large-scale treatment frameworks.

2.1.1. Pharmaceuticals and Personal Care Products

These compounds represent a significant class of contaminants, encompassing substances ranging from lipid regulators and analgesics to fragrances and sunscreen agents, which are continuously discharged into aquatic systems via domestic and industrial effluents [37,38]. Unlike conventional contaminants, these bioactive agents are specifically engineered for biological efficacy, a trait that inherently contributes to their recalcitrance and potential for adverse effects within aquatic ecosystems [39,40]. The perpetual introduction of these pseudo-persistent compounds, most notably antibiotics, exerts selective pressure on indigenous microbial communities, thereby fostering the proliferation of antibiotic-resistant bacteria and associated genetic elements within wastewater treatment infrastructure [41,42]. Consequently, the presence of these residues in aquatic systems presents a substantial risk to both human health and biota, underscoring the critical need for the development of innovative treatment strategies to ensure their efficient degradation [43,44]. The challenge is further compounded by the accumulation of metabolites, which often retain or even enhance the toxicity of their parent compounds, posing long-term risks through bioaccumulation and interference with normal endocrine functions in non-target organisms [45,46]. The incomplete metabolism of these pharmaceuticals during standard treatment processes results in their frequent detection throughout the broader ecosystem, underscoring the limitations of current plant configurations. Microalgae have emerged as a compelling alternative for wastewater remediation, demonstrating a capacity to sequester pharmaceutical residues through intricate mechanisms, including bio-adsorption, bioaccumulation, and enzymatic degradation [47,48]. The functional diversity inherent in bacterial-microalgal symbioses facilitates the simultaneous degradation of complex micropollutants, heavy metals, and residual nutrients, which often remain recalcitrant to conventional activated sludge treatment processes [49]. Microalgal cells facilitate the rapid passive sequestration of various pharmaceuticals through electrostatic interactions with their cell wall components and extracellular polymeric substances [50]. These complex structures serve as a protective matrix that not only stabilizes the microalgal cells under severe environmental stress but also functions as an active site for the extracellular enzymatic transformation of recalcitrant antibiotics [51].

2.1.2. Per and Polyfluoroalkyl Substances (PFAS)

Per- and polyfluoroalkyl substances constitute a class of synthetic organofluorine compounds characterized by extreme environmental stability due to the strength of their carbon-fluorine bonds, rendering them largely refractory to conventional biological degradation pathways [52]. The inherent recalcitrance of these compounds necessitates the integration of specialized biotechnological approaches, as their resistance to standard

microbial mineralization requires advanced catalytic pathways that remain largely underexplored in conventional wastewater treatment systems [53]. Current research suggests that incorporating specialized microalgal strains may improve the transformation of complex organic molecules through targeted biotransformation pathways [54]. For instance, certain cyanobacteria integrated into hybrid photocatalyst systems have demonstrated the ability to mineralize persistent organic pollutants into carbon dioxide and water, offering a potential breakthrough for recalcitrant fluorine-containing structures [55]. Such advancements reflect the growing potential of phycoremediation to transcend traditional biodegradation by leveraging the diverse metabolic capabilities of algae in engineered systems [56]. Furthermore, the integration of microalgal-bacterial consortia within these engineered configurations offers a promising strategy for enhancing the metabolic versatility required to degrade the robust carbon-fluorine bonds inherent in PFAS, potentially overcoming the limitations of conventional biological treatments. Emerging research indicates that microalgae can supplement this degradation through intracellular metabolism and the secretion of extracellular enzymes, such as cytochrome P450, which aid in the breakdown of synthetic organic chemicals [57]. Additionally, the utilization of microalgae in tandem with specific defluorination microbial strains within constructed wetlands may facilitate the targeted breakdown of these persistent molecules by providing necessary electron donors [58].

2.1.3. Endocrine-Disrupting Compounds

These substances, which include synthetic hormones and plasticizers, are characterized by their ability to interfere with hormonal signaling pathways even at low concentrations [59]. Such chemicals often exhibit high resistance to standard wastewater treatment protocols, leading to their persistence in receiving water bodies where they may induce significant physiological disruptions in aquatic wildlife [60]. The transformation of these pollutants into more harmful intermediate by-products often occurs during incomplete degradation, further complicating their long-term impact on the mutagenicity and teratogenicity of non-target organisms [61]. To address this, phycoremediation leverages estrogen-degrading metabolic pathways, where microalgal enzymes catalyze the cleavage of core structural rings, effectively neutralizing their hormonal activity [62]. Moreover, the integration of these systems with advanced oxidation processes has demonstrated success in enhancing the mineralization of such endocrine-disrupting contaminants [63]. Continuous-flow systems utilizing species such as *Scenedesmus* and *Chlamydomonas* have shown significant efficacy in removing synthetic hormones like E1, E2, and EE2 even at trace concentrations, with biodegradation pathways accounting for over half of the total removal [64]. This efficacy is largely attributed to the robust enzymatic systems of these species, which actively cleave complex endocrine-disrupting molecules that remain unaffected by conventional physical-chemical treatment methods [65,66].

2.1.4. Pesticides

The persistence of hydrophobic pesticides in aquatic environments remains a critical challenge due to their toxicity and low solubility, which often limits their accessibility to conventional treatment technologies [67]. Microalgae-based systems address this limitation by providing specialized surface environments that facilitate the biosorption and subsequent enzymatic conversion of these recalcitrant compounds into less toxic metabolites [68]. This dual-action approach relies on both active bioaccumulation, where organisms metabolize the pollutants, and passive biosorption, which engages both living and dead biomass to trap contaminants from the surrounding water [69]. Furthermore, these microalgal systems function as effective biocatalysts, transforming recalcitrant pesticides into less toxic

metabolites while simultaneously enabling nutrient recovery from wastewater to bolster biomass production [68,69]. Through these complementary metabolic and surface-based mechanisms, microalgae and cyanobacteria effectively reduce pesticide toxicity by converting persistent hazardous compounds into less harmful metabolites, thereby enhancing the overall performance of these bioremediation systems. The cultivation of these photoautotrophic microorganisms in wastewater treatment plants allows for the simultaneous recycling of nutrients such as phosphorus and ammonium, which further supports the generation of value-added biomass alongside pollutant degradation [70,71].

2.1.5. Microplastics

The accumulation of these non-biodegradable synthetic polymers poses a severe environmental risk, as they persist in aqueous matrices for centuries [72]. Microalgae mitigate this threat through the formation of biofilms on plastic surfaces, which can facilitate microbial colonization and potentially accelerate the fragmentation and biotic degradation of polymers [73]. The functional groups present within the microalgal cell wall, including carboxyl and hydroxyl moieties, can chemically alter the surface properties of these polymers, thereby increasing their susceptibility to subsequent enzymatic cleavage by associated microbial communities [74,75]. Despite these benefits, the large-scale application of this technique remains constrained by long retention times and the complex variability of wastewater characteristics such as fluctuating concentrations of co-occurring pharmaceuticals and heavy metals that fundamentally alter the physical and chemical properties of microplastics [76]. Consequently, effective remediation strategies require a deeper understanding of how these co-contaminants influence the binding affinity of algae toward microplastic surfaces, particularly as different functional groups like thiol and acyl moieties may be inhibited by high heavy metal concentrations [77].

2.1.6. Nanomaterials

The release of engineered nanoparticles into aquatic ecosystems introduces distinct toxicological profiles, as their high surface-to-volume ratio facilitates unintended interactions with microalgal cell walls and membranes [78,79]. These interactions often trigger the secretion of extracellular polymeric substances, which serve as a protective barrier by sequestering metal ions and preventing oxidative damage [80,81]. This protective response, however, may conversely limit the bioavailability of nutrients essential for cellular growth, thereby necessitating a precise balance between remediation capacity and biomass productivity [82,83].

2.1.7. Disinfection By-Products

These compounds, formed during the water treatment process through the reaction of disinfectants with natural organic matter, pose persistent toxicological risks due to their potential carcinogenicity and mutagenicity. Microalgal species demonstrate a capacity to mitigate these risks by metabolizing halogenated disinfection by-products into inorganic halides and simpler organic fragments through specialized oxidative and reductive enzymatic processes [84]. These organisms effectively incorporate released halide ions into their metabolic cycles, preventing the accumulation of toxic intermediates that typically inhibit growth in conventional water reclamation systems [85]. However, the efficacy of these biological processes is frequently challenged by the complex chemical composition of actual wastewater, where the presence of diverse pollutants like heavy metals and pathogenic microorganisms can disrupt microbial activity and modify the overall removal efficiency [86]. Such synergistic impacts are further complicated by the presence of inorganic and biological contaminants, such as heavy metals or pathogenic bacteria, which can inhibit microalgae growth and impede the stability of the entire treatment consortium [87].

2.2. Limitations of Conventional Treatment Technologies

Conventional methods, including chemical oxidation and mechanical filtration, often incur prohibitive costs due to high energy demands and the continuous requirement for hazardous reagents [88]. These conventional processes also frequently generate significant volumes of secondary waste, which complicates disposal and risks introducing new environmental pollutants into the ecosystem. In contrast, microalgae-based phytoremediation presents a more sustainable and energy-efficient alternative that eliminates the production of problematic secondary sludge while simultaneously enabling nutrient recovery and the generation of value-added biomass [73,80,88]. Despite these advantages, the commercial scalability of such systems is frequently constrained by technical hurdles, including the need to manage the presence of pathogens and hazardous contaminants within the harvested biomass [89,90].

2.3. Why Extremophilic Microalgae?

Extremophilic microalgae, such as *Dunaliella salina*, offer significant operational advantages by thriving in high-salinity environments that inherently suppress the proliferation of invasive, non-target microbial species and pathogenic contaminants [91]. This unique physiological adaptation allows for the sustainable treatment of hypersaline wastewater, where *D. salina* effectively removes up to 88% of nitrogen and phosphorus while concurrently producing high-value bioproducts like beta-carotene [92]. By utilizing saline environments, these systems circumvent the challenges associated with competition from freshwater-adapted contaminants, facilitating a more robust and selective remediation process [93]. Moreover, the inherent halophilic nature of these organisms facilitates direct wastewater remediation in industrial sectors such as food processing and desalination, where high salinity traditionally disrupts conventional biological treatment [94]. Other extremophiles like thermophiles, barophiles, and polyextremophiles are excellently adopted in adverse conditions and can be used as an excellent treatment option for pollutant removal, as they exhibit high removal efficiencies for nitrogen, phosphorus, and heavy metals across a variety of industrial and municipal streams [1,95]. These microorganisms leverage specialized enzymatic pathways to maintain structural integrity and metabolic activity, effectively sequestering contaminants even in environments characterized by extreme thermal or barometric stress [96]. However, the practical implementation of these organisms requires careful consideration, as the slower growth kinetics typical of many extremophiles necessitate a balance between pollutant remediation capacity and the need to maintain sufficient biomass productivity [97]. To optimize these systems, researchers are increasingly investigating mixotrophic cultivation strategies, such as the use of *Galdieria sulphuraria*, which can mitigate metabolic limitations while ensuring high pollutant removal efficiency [98]. Furthermore, the metabolic versatility of such extremophilic species enables the simultaneous sequestration of contaminants and the synthesis of bioactive compounds, which significantly enhances the economic viability of integrated treatment systems [7]. Beyond these metabolic advantages, the inherent resilience of these extremophilic communities to fluctuating pollutant profiles allows for more stable operation in diverse industrial wastewater applications compared to conventional microbial consortia [9]. These extremophilic communities produce a diverse array of specialized enzymes and exopolysaccharides that remain stable and functional under harsh conditions, thereby providing a robust mechanism for the degradation of recalcitrant toxic pollutants [10,99]. These organisms can also catabolize persistent organic pollutants like phenolic compounds and polycyclic aromatic hydrocarbons, transforming hazardous chemicals into inert metabolites or harvestable biomass [9].

2.4. Bibliographic Data

The primary research themes and their interconnections were delineated through keyword co-occurrence analysis conducted with VOSviewer software (Version 1.6.20). For bibliographic analysis, Data from 1990 to 2025 were taken from ScienceDirect. Terms used for visual analysis were: "Emerging Pollutant removal", "Extremophile Microalgae", and "Wastewater Treatment Using Microalgae" (Figure 1).

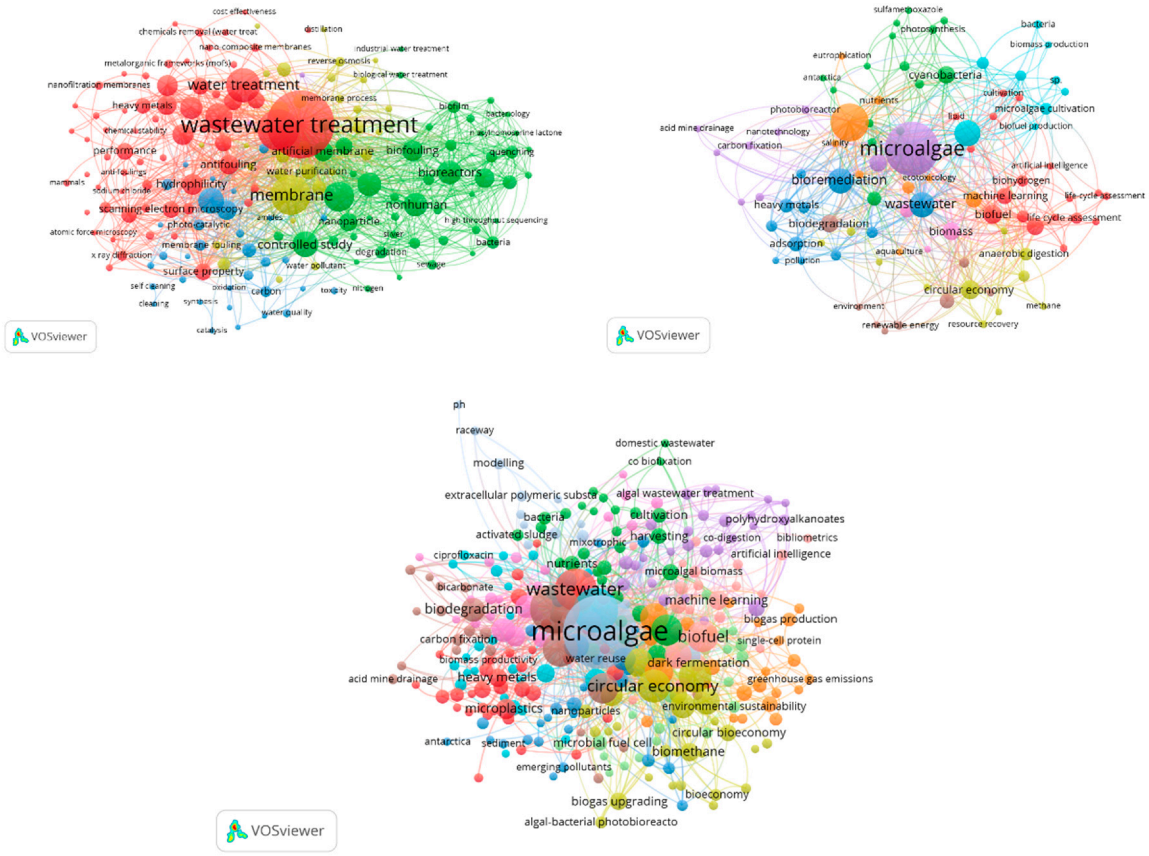

Figure 1. Co-occurrence network map for extremophilic microalgal emerging contaminant (ECs) removal (different colors represent distinct keywords co-occurrence clusters).

3. Classification of Extremophilic Algae and Their Habitats

3.1. Thermophiles

These organisms are defined by their ability to thrive in geothermal springs and industrial effluents characterized by high temperatures and acidic pH levels [100]. Species such as *Chlamydomonas acidophila* and *Euglena mutabilis* are frequently identified in these environments, particularly within acidic mine drainage sites where they maintain metabolic homeostasis despite high heavy metal concentrations. Furthermore, the red alga *Galdieria sulphuraria* represents a prominent example of an extremophile that thrives in such niches, demonstrating a remarkable capacity to lower organic carbon, ammonium, and phosphate levels in primary-settled wastewater [101]. These strains inherently benefit from reduced resource competition and contamination risks, providing a unique resilience against climate-driven environmental fluctuations during large-scale cultivation [102]. The red alga *Galdieria sulphuraria* acts as a versatile polyextremophile capable of mixotrophic growth on numerous carbon sources while enduring both acidic conditions and elevated temperatures up to 56 °C [103,104]. Additionally, these organisms possess the potential for biotechnological exploitation, as their specialized enzymes often remain functional under physicochemical pressures that would denature conventional proteins [105]. *Cyani-*

dium caldarium exhibits a high tolerance for metallic elements and can be utilized in the reclamation of acidic wastewater streams through the bioaccumulation of toxic ions [106]. Specifically, the thermo-acidophilic nature of *Cyanidium caldarium* enables cultivation at elevated temperatures that inherently restrict the proliferation of competing pathogenic microorganisms, thereby simplifying sterilization requirements in industrial wastewater systems. *Coelastrella thermophila* is another highly stable algal strain that can withstand up to 63 °C and demonstrates significant potential for the reclamation of geothermal industrial effluents [107]. *Thermosynechococcus elongatus* a unicellular cyanobacterium that thrives at 50–60 °C. It features highly stable proteins that efficiently fix heavy metals and capture high concentrations of industrial carbon dioxide (CO_2). Similarly, *acidothermophilic cyanidiophytes* demonstrate an impressive capacity for the remediation of hexavalent chromium in both acidic and neutral conditions, highlighting their industrial utility [108]. *Mastigocladus laminosus* is a filamentous, heat-loving cyanobacterium found in hot springs (growing optimally around 45–55 °C). Its filamentous structure makes it highly advantageous because it is far easier to harvest (via filtration) compared to unicellular strains. *Fischerella thermalis* is another filamentous cyanobacterium well-adapted to high-temperature environments, which facilitates efficient biomass recovery processes in large-scale wastewater treatment facilities. Furthermore, the Cyanidiophyceae class, including species like *Cyanidioschyzon merolae*, has emerged as a robust model for high-cell density cultivation, leveraging its ability to thrive on pure CO_2 and produce valuable bioproducts such as heat-stable phycocyanin and starch under elevated thermal conditions [109].

3.2. Psychrophiles

These microorganisms demonstrate optimal metabolic activity in environments where temperatures consistently remain below 5 °C, representing habitats that encompass the majority of Earth's biomass. These psychrophilic organisms have evolved specific structural adaptations to maintain membrane fluidity and functional enzyme activity despite the challenges posed by extreme cold [110]. Such adaptive mechanisms, which include the synthesis of polyunsaturated fatty acids and cold-active proteins, facilitate their survival in glacial regions and permafrost, potentially offering unique enzymes for low-temperature industrial biocatalysis [111]. These specialized enzymes, known as psychrophilic enzymes, exhibit high catalytic efficiency in cold-adapted environments, rendering them valuable for energy-intensive biotechnological processes that require lower thermal inputs [112,113]. *Koliella antarctica* and *Chloromonas* sp. are notable examples of cold-adapted algae that produce cryoprotectants, such as mannitol, to mitigate cellular damage from ice crystal formation in sub-zero environments [114]. *Koliella antarctica* is a strict psychrophile and has a growth optimum below 10 °C. It is uniquely utilized for the energy-efficient biological treatment of cold-temperature wastewater generated by the fresh fruit processing industry. The harvested biomass accumulates valuable bioproducts like astaxanthin, lutein, and essential polyunsaturated fatty acids (EPA/DHA). *Chlamydomonas* sp. *KNM0029C*, isolated from polar environments, this Arctic green microalga that functions smoothly under low-temperature conditions. It is used in bioremediation to assimilate high levels of dissolved inorganic nutrients (nitrogen and phosphorus) while simultaneously synthesizing massive amounts of starches and lipids, which are processed into bioethanol and biodiesel [80]. *Monoraphidium* sp. *Dek19* is native to colder, upper Midwestern climates. This species is highly cold-tolerant and maintains dense growth in winter environments. It is deployed in large-scale mesocosm pools using treated municipal effluent, achieving rapid nitrate and phosphate removal under low-light intensities. Its robust structure makes it easy to separate using standard flocculants (like $FeCl_3$) [115]. Pseudopleurochloris antarctica is an Antarctic microalga engineered for combined cold-weather remediation and biomass

valorization. It absorbs nitrogenous compounds from cold agricultural runoff and excels at accumulating highly valuable eicosapentaenoic acid (EPA), creating a lucrative secondary stream for animal feed additives [116].

3.3. Halophiles

These microorganisms have evolved specialized osmotic balance mechanisms to thrive in high-salinity environments, such as hypersaline lakes, salterns, and deep-sea brine pools [117]. These organisms, particularly Haloarchaea, utilize complex genetic plasticity and metabolic adaptations to maintain homeostasis in these extreme ecosystems, rendering them promising agents for bioremediation in challenging industrial settings [118]. *Dunaliella salina* is a halotolerant microalga that accumulates high concentrations of β-carotene to protect against the oxidative stress typically encountered in hypersaline habitats [119]. This physiological resilience allows it to efficiently extract heavy metals and remove excess nutrients from saline industrial effluents, where conventional wastewater treatment microbes would fail [6,120]. This ultra-halophilic green microalga thrives in extreme salinity ranges, spanning from 35 g/L up to saturation (>300 g/L). It is deployed in high-rate algal ponds to treat saline food processing wastewater and aquaculture effluent. *D. salina* rapidly removes nitrates, phosphates, and sulfates while accumulating massive amounts of beta-carotene, creating a highly profitable secondary stream for the nutraceutical market [94,121]. Additionally, research indicates that the cultivation of *D. salina* in controlled municipal wastewater environments can achieve nutrient removal efficiencies for nitrate, ammonia, and phosphorus ranging from 45% to 88% [122,123]. Another marine green microalga, *Tetraselmis suecica*, tolerates fluctuating salinities up to 50 g/L. It is heavily used in recirculating aquaculture systems (RAS) and fish farm drainage to strip over 90% of inorganic nitrogen and ammonia within 48 h. The harvested nitrogen-rich biomass is recycled directly back into the loop as premium live feed for shrimp and bivalve hatcheries [124]. Beyond inorganic nutrient removal, *Tetraselmis* species exhibit significant capabilities in degrading complex organic pollutants, including phenol and various hydrocarbons, which are prevalent in saline industrial process waters [125]. *Chlorella MEM25* a highly specialized halophilic industrial strain capable of treating seafood processing wastewater. It exhibits a unique biodesalination effect via biosorption while actively removing up to 98% of phosphates. The resulting biomass yields up to 52% essential proteins, making it an excellent resource for functional animal feeds [126]. These halophilic strains demonstrate that transitioning toward non-conventional microalgae can effectively bridge the gap between waste remediation and the production of sustainable, high-value biochemicals [5].

3.4. Acidophiles

These microorganisms thrive in environments with low pH levels, often found in acid mine drainage and industrial waste streams where conventional species cannot survive. *Galdieria sulphuraria*, for example, maintains metabolic stability at pH values as low as 0.5, allowing it to efficiently assimilate heavy metals and neutralize acidic effluents through proton consumption mechanisms [127]. This resilience to extreme acidity is complemented by its heterotrophic capacity to utilize diverse carbon sources, such as sugar and polyols, which enhances biomass productivity in industrial sites contaminated with organic pollutants [3,17]. Additionally, enzymatic hydrolysis of fishery side streams has been successfully utilized to support the growth of *G. sulphuraria*, demonstrating that non-sterile conditions do not compromise the safety or pathogen-free status of the resulting biomass [128]. *Chlamydomonas acidophila*, which grows optimally between pH 2.0 and 4.0, is extensively used for the biosorption and bioaccumulation of toxic heavy metals such as copper, cadmium, nickel, and lead from active mining runoffs. It utilizes a highly negative

cell surface charge to rapidly capture and lock down dissolved metal ions. *Galdieria maxima* is a true thermoacidophilic red microalga found in volcanic sulfur springs that grows at a pH of 1.0 to 3.0 and temperatures up to 56 °C. It is deployed to treat rare earth element (REE) mining runoff and electronic waste shredding effluents. It uses a thick cell wall to lock down and recover highly valuable, toxic heavy metals via surface biosorption [103]. *Klebsormidium acidophilum* a filamentous acidophilic green alga that grows vigorously in metal-dense mine waters at a pH below 3.0. It is engineered for low-cost passive treatment systems like algal turf scrubbers (ATS). Because it forms long, interconnected filaments, the biomass can be harvested easily using basic mechanical screens, eliminating expensive centrifugation steps [129].

3.5. Barophiles

These microorganisms inhabit deep-sea environments characterized by high hydrostatic pressure, which often correlates with low temperatures and limited nutrient availability. Barophilic (also known as piezophilic) microalgae are pressure-loving or pressure-tolerant organisms. In standard municipal treatment setups, hydrostatic pressure is negligible, but barophilic microalgae are engineered for highly specialized, niche applications like deep-sea waste dump bioremediation, deep-well industrial injection line treatment, and high-pressure photobioreactors (HP-PBRs). To thrive under such intense conditions, barophilic algae have evolved unique lipid compositions that maintain membrane fluidity and functional protein stability against extreme compression. Research into these extremophiles remains critical, as their specialized metabolic pathways for carbon fixation under pressure may offer novel insights for synthesizing biopolymers in high-pressure industrial bioreactors. While *Chlorella* is traditionally a surface organism, specific mutated strains such as *Chlorella pyrenoidosa* (High-Pressure Adapted Strains) are engineered for high-pressure industrial bioreactors working up to 20–30 MPa. These are used to treat highly concentrated volatile organic compounds (VOCs) and chemical oxygen demand (COD) in sealed systems. Operating under pressure prevents the outgassing of volatile toxins and captures 100% of injected CO_2 gas without bubble escape. *Halochlorella rubescens* (Deep-Shelf Isolates), discovered in deeper marine environments, this robust, halotolerant, and barotolerant microalga that can operate under moderate pressure loads. It is heavily investigated for treating deep-well-injected oil and gas produced water. It metabolizes polycyclic aromatic hydrocarbons (PAHs) and toxic heavy metals before the liquid settles into underground storage strata [9]. *Porphyridium purpureum* is a barotolerant morphotype. This red microalga is capable of handling fluctuating pressure gradients up to 15 MPa in pressurized processing loops. It is used to clear high concentrations of nitrogen and phosphorus from industrial runoff. Under high pressure, it triggers a defensive mechanism that secretes massive volumes of extracellular sulfated polysaccharides (EPS), which act as natural bio-flocculants to trap suspended toxic heavy metals.

3.6. Metal-Tolerant Microalgae

Metal-tolerant microalgae exhibit exceptional physiological resilience, employing highly evolved micronutrient transporters and complex extracellular ultrastructures to selectively sequester heavy metals from low-concentration industrial wastewater [19]. Beyond simple uptake, these species often utilize a dual-mechanism approach-combining passive biosorption at the cell surface with active intracellular bioaccumulation to effectively detoxify effluents. This versatility renders them superior candidates for remediating hazardous mining and industrial runoffs where conventional biological treatment systems fail.

3.7. Radiation-Resistant Species

These extremophiles thrive in environments exposed to high levels of ionizing radiation, effectively maintaining cellular integrity and metabolic function through robust DNA repair mechanisms. By upregulating specific antioxidant enzymes and non-enzymatic scavengers, these organisms prevent the accumulation of reactive oxygen species that typically arise under high-intensity ultraviolet or ionizing exposure [130]. Such molecular shielding, coupled with an inherent ability to distinguish between essential and non-essential heavy metals, facilitates the effective detoxification of radioactive liquid waste streams [131]. These species demonstrate a remarkable capacity to metabolize radionuclides alongside heavy metals, suggesting their utility in treating effluents from nuclear research facilities [12,132]. The deployment of these radio-tolerant populations for environmental recovery has gained momentum, particularly following catastrophic nuclear events that necessitate the remediation of large-scale radionuclide contamination [133]. While ionizing radiation damages cellular DNA and triggers catastrophic oxidative stress, these species survive by deploying hyper-efficient DNA double-strand break repair networks and thick cell walls loaded with protective carotenoid antioxidants that stabilize cellular membranes against radiological degradation [134]. Recent investigations have identified specific green microalgae strains that not only withstand these extreme radiological conditions but also demonstrate a significant capacity to strongly accumulate radionuclides like 14C. *Coccomyxa actinabiotis* is a premier, ultra-radiotolerant green microalga originally isolated from the cooling pools of active nuclear facilities. It survives extreme ionizing radiation doses up to 20,000 Grays (Gy), a threshold thousands of times higher than the lethal human dose. It is used to decontaminate industrial nuclear effluents by extracting over 85% of dissolved radionuclides (including Uranium-238, Cesium-137, Cobalt-60, and Carbon-14) within a single 24-h cycle, performing as efficiently as expensive synthetic chemical ion-exchange resins [135]. Another radiation-tolerant species is *Haematococcus lacustris* (formerly *Haematococcus pluvialis*), which is a green microalga that exhibits high resilience to harsh ambient UV-C radiation and ionizing stress. Under intense radiation or environmental pressure, it accumulates massive pools of the powerful antioxidant pigment astaxanthin to shield its core nucleic acids. It is utilized to treat low-level radioactive wastewater, capturing up to 88% of dangerous Cobalt-60 and Cesium-137 isotopes over a 48-h exposure window [136].

4. Methodology for Isolation and Cultivation of Extremophilic Microalgal Species

The successful identification of these microorganisms requires rigorous screening protocols involving controlled exposure to environmental stressors, such as high-intensity UV radiation or heavy metal contamination, to isolate strains with specific metabolic adaptations [137,138]. These protocols often utilize flow cytometry and fluorescence-activated cell sorting to quantify physiological responses under acute metallic or radiative stress [139]. Following the isolation of robust candidates, engineering growth systems must then be tailored to maintain these stress-induced phenotypes, optimizing variables such as salinity, nutrient profiles, and irradiance levels to maximize biomass yield and bioactive accumulation [140]. These cultivation strategies often rely on bioreactor configurations that mimic the complex physicochemical parameters of volcanic hot springs or radioactive cooling ponds to ensure the stability of extreme-condition phenotypes [135]. Moreover, shifting from laboratory-scale isolation to commercial production necessitates the implementation of a biorefinery framework that integrates biomass generation with the extraction of high-value metabolites [141]. This integrated approach leverages the metabolic versatility of microalgae, enabling the simultaneous production of nutraceutical pigments like astaxanthin and

biofuels while providing effective biological systems for CO_2 sequestration and wastewater treatment [142,143].

Although collecting microalgae from salt pans aligns with standard protocols for marine or freshwater ecosystems, the extreme physicochemical gradients inherent to solar salterns and hypersaline environments necessitate significant procedural adaptations. Consequently, rigorous screening and customized collection strategies are essential to isolate viable extremophilic strains, as standard approaches often fail to address the specific environmental stressors present in these niche habitats [137,138]:

- Hydrological conditions at sampling sites: Water levels in crystallization basins are frequently minimal or absent, especially during summer months. Furthermore, the entrapment of microorganisms within developing halite crystals during brine crystallization offers novel avenues for specimen collection.
- Salinity fluctuations: Given the drastic annual salinity gradients inherent to hypersaline environments, precise in situ measurement is critical to determining the osmotic threshold for laboratory cultivation. Failure to accurately replicate these native environmental conditions often results in the loss of stress-adapted metabolic phenotypes, thereby diminishing the biomass productivity and biotechnological potential of isolated strains [140].
- Soil sediments: Microbial mat samples are frequently densely embedded in complex matrices of mud and detritus. This extraneous material creates xenic confounding factors that significantly impede the establishment of stable, axenic cultures [144]. Mitigating this requires rigorous separation techniques-such as multi-stage washing or density-based fractionation to ensure the effective recovery of targeted extremophilic cells without compromising their structural integrity.
- Diversity of sample types: The isolation of photosynthetic microorganisms from aqueous versus benthic microbial mat samples necessitates distinct procedural approaches to ensure the effective recovery of specific microbial subsets. Furthermore, laboratory cultivation parameters must be adjusted in response to factors such as the seasonal timing of collection and relevant environmental variables. Establishing axenic laboratory cultures remains a primary bottleneck, as standardized protocols for hypersaline isolates are currently lacking in the broader scientific literature [145]. To address this challenge, researchers are increasingly employing advanced techniques such as single-cell isolation via fluorescence-activated cell sorting and specialized aerosol-based methodologies to enhance recovery rates from these complex, multi-phasic environments [144].

4.1. Factors Influencing Cultivation

4.1.1. Growth Medium

The formulation of these media must account for the specific ionic composition and pH requirements of extremophilic microalgae, as high salinity can dramatically alter nutrient bioavailability [146]. For instance, recent research on cultivating microorganisms from hypersaline lakes identifies various suitable growth media, while a comprehensive review further elucidates the functional roles of specific media constituents for halophilic and halotolerant prokaryotes. Standardized media for photoautotrophic cultivation generally consist of salts, nitrogen and phosphorus sources, and essential trace elements. Boric acid is frequently incorporated as a boron source, given its essential role in cyanobacterial heterocyst development. However, careful selection is required, as certain trace metal ions, such as copper, may prove inhibitory to specific cyanobacterial strains, necessitating their substitution. Liquid growth media are frequently fortified with vitamins including thiamine, biotin, and cobalamin to optimize biomass productivity [140]. Beyond these

standard supplements, using suspension buffers that are geochemically analogous to the native sampling site rather than standard distilled water can prevent osmotic shock and significantly increase microbial culturability [147].

4.1.2. Light Intensity and Quality

Extremophilic microalgae often possess specialized photosynthetic apparatuses. While certain taxa necessitate high irradiance for optimal growth, such as Nannochloropsis species, others are notably susceptible to photoinhibition. Modulating the light spectrum and implementing precise light/dark cycles are, therefore, essential for optimizing both growth kinetics and metabolite accumulation. It is imperative to maintain a critical balance between photon flux density and nutrient availability to mitigate oxidative stress; although elevated irradiance can stimulate carotenoid synthesis, it often results in a concomitant decline in biomass productivity [148,149].

4.1.3. Temperature

Temperature acts as a primary determinant of enzymatic activity and metabolic flux, governing the kinetics of essential biochemical pathways. For extremophilic microalgae, precise thermal regulation is paramount; deviations from the species-specific metabolic optimum frequently induce profound cellular stress, manifesting as protein denaturation, membrane destabilization, and reduced biomass productivity [150]. Beyond maintaining cellular homeostasis, targeted thermal modulation is frequently employed in industrial bioprocessing as a potent stress-induction strategy. Specifically, thermal downshifting can be utilized to trigger adaptive physiological responses, forcing a metabolic redirection that prioritizes the accumulation of high-value compounds such as specific polyunsaturated fatty acids at the expense of rapid biomass proliferation. While such stress-based induction strategies effectively enhance secondary metabolite synthesis, they remain highly species-specific and pose substantial scalability challenges for industrial bioreactor configurations [148].

4.1.4. Salinity Stress

For halophilic and salt-tolerant microorganisms, the rigorous regulation of salinity serves as a primary operational lever for adjusting metabolic flux. Targeted elevation of salt concentrations acts as a significant abiotic stressor; this induced osmotic imbalance triggers the synthesis and accumulation of compatible solutes and value-added secondary metabolites, including various lipids and pigments, as an adaptive mechanism to preserve cellular homeostasis [140,148,150]. Nevertheless, excessive salinity stress may inadvertently impair primary metabolic functions, such as CO_2 fixation, necessitating precise regulatory control to optimize the balance between intracellular metabolite yields and overall biomass viability [151,152].

4.1.5. Nutrient Availability

Macronutrient ratios exert a profound influence on microalgal growth. In two-stage cultivation systems, cultures are initially developed to high densities under nutrient-replete conditions before being subjected to nutrient deprivation to stimulate the biosynthesis of lipids and high-value pigments. This approach effectively decouples the inherent trade-off between rapid cellular proliferation and targeted product accumulation, allowing for the strategic modulation of nutritional inputs to maximize the economic output of the bioprocess [153]. Specifically, nitrogen depletion is widely implemented as the primary stimulus during the second stage to redirect carbon flux toward the synthesis of triacylglycerols and carotenoids [154,155]. Similarly, phosphorus starvation serves as a potent metabolic trigger, and the systematic deprivation of both nitrogen and phosphorus represents a

well-established strategy for directing carbon flow toward lipid storage in diverse genera, such as *Chlorella* and *Neochloris* [156].

5. Application and Mechanism for Emerging Pollutant Removal

Current research focuses on characterizing the metabolic flexibility of extremophilic strains when exposed to diverse industrial wastewater profiles, emphasizing their capacity for bioaccumulation and biosorption of heavy metals [22]. These investigations often utilize strategies such as nutrient supplementation, including nitrates and phosphates, to optimize biomass productivity when treating nutrient-deficient industrial effluents [18]. The utilization of these extremophiles in phycoremediation leverages their robustness to successfully remove potentially toxic elements from discharges without succumbing to the inhibitory effects typically associated with high-contaminant loads [157]. *Scenedesmus almeriensis (CCAP 276/24)*, which is susceptible to temperatures up to 45 °C, was used in a study to remove sulfamethoxazole, trimethoprim, metronidazole, ofloxacin, and ciprofloxacin in a thin-layered photobioreactor [158]. Sulfamethoxazole showed the highest removal rate of about 91%, trimethoprim 44%, metronidazole 99%, Trimethoprim 50% and Ofloxacin reached 86%. An open-pond-shaped 650 L pilot-scale reactor was used to treat several pharmaceutical products. *Tetradesmus dimorphus* was used to quantify the removal efficiency of 52 pharmaceuticals resulted in variable efficiencies with very high (>90%), moderate (50–90%), low (10–50%), and very low or non-quantifiable (<10%) for 9, 14, 11, and 18 pharmaceuticals, respectively [159]. Three Nordic subarctic algal species namely *Chlorella vulgaris (13-1)*, *Scenedesmus* sp. *(B2-2)* and *Desmodesmus* sp. *(RUC-2)*, were applied at 5–15 °C to treat high-strength urban wastewater. *Scenedesmus* sp. showed a removal rate of 90% TN and 100% P, followed by *S. obliquus* (85% TN, 82% P) and *Desmodesmus* sp. (83% TN, 73% P), respectively. *C. vulgaris* showed the highest removal potential with 97% TN and 99% P at 15 °C [160]. Another study showed that *Chaetoceros calcitrans MZB-1*, a marine microalga, significantly removed PFOA and PFAS. Removal efficiencies of PFOA and PFOS were 24.41% and 29.16%, respectively [161]. Another class of emerging contaminants, endocrine-disrupting chemicals (EDCs), was studied extensively. Methylparaben (MeP), propylparaben (PrP), butylparaben (BuP), benzophenone (BP), bisphenol A (BPA), and estrone (E), in the presence of the microalgae *Scenedesmus* sp. or *Chlorella vulgaris*, were removed in a batch reactor. *Scenedesmus* sp. achieved 67 to 100%, whereas *Chlorella* sp. ranged from 62.1 to 100% removal efficiency for these EDCs [162]. Enzymatic biotransformation of heavy metals involves the oxidative or reductive conversion of hazardous metals into less toxic forms, a process facilitated by oxidoreductase enzymes produced by microalgae [163]. These enzymes, such as arsenate, chromate, and mercuric reductases, specifically target the conversion of arsenic, chromium, and mercury, respectively. Although the complete elimination of heavy metals is often difficult, altering their oxidation states can mitigate their toxicity by converting them into less harmful inorganic substances [163]. For example, *Chlorella vulgaris* produces chromate reductase to reduce Cr^{6+} to Cr, while *Galdiera sulphuraria, Selenastrum minutum*, and *Chlorella fusca* utilize mercuric reductase to biotransform Hg^{2+} into elemental mercury and metacinnabar. Additionally, arsenate biotransformation has been observed in *Chlamydomonas reinhardtii* via the activity of arsenate reductase [164–166] (Figure 2). Table 1 shows the potential extremophiles for the emerging and harsh pollutant treatment capabilities.

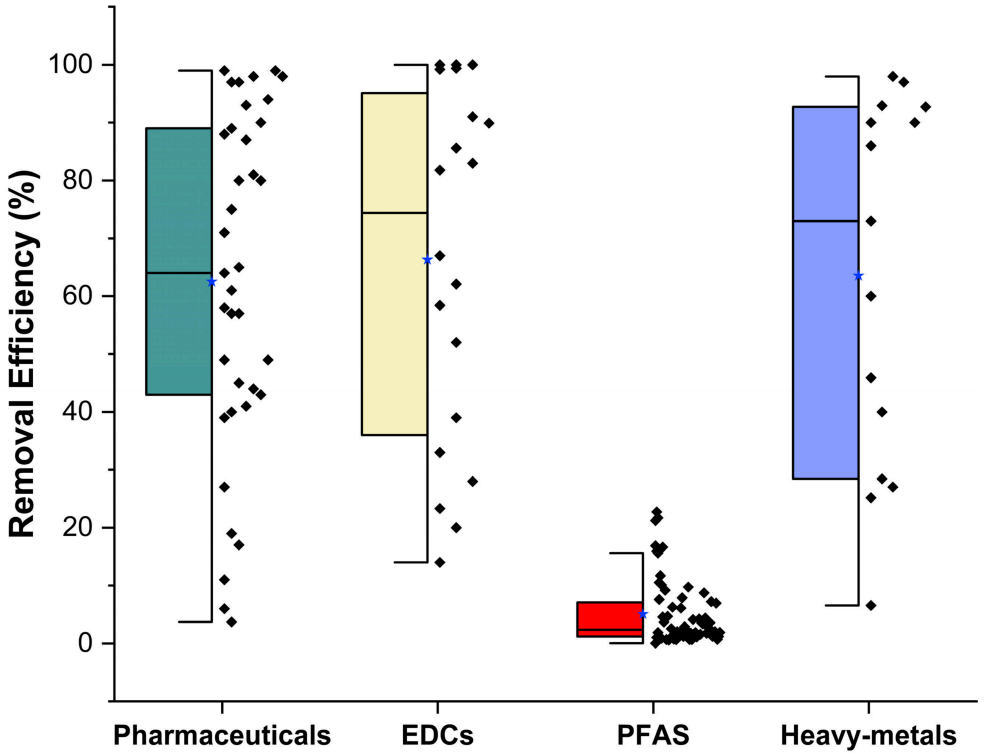

Figure 2. Box plot showing removal efficiency of various ECs by extremophilic microalage. (n = No. of ECs treated). Pharmaceuticals (n_{pharm} = 37), Endocrine-disrupting compounds (n_{EDCS} = 20), Per and Polyfluoroalkyl Substances (n_{pfas} = 64), Heavy-metals (n_{HM} = 15). (Diamond symbol (⧫) shows the number of studies considered and Blue star (★) shows the mean value for each box plot).

Table 1. Studies comprising emerging contaminants and their removal effieciency by extremophilic microalgae.

Emerging Pollutant Type	Subtype	Microalgal Species	Temperature Range	pH Range	Removal Efficiency (%)	References
Pharmaceutical wastewater	Naproxen	*Cymbella* sp.	15–22	7–8	97.1	[167]
	Nonylphenol	*Lessonia nigrescens (L13)*	12–15	7.8–8.2	100	[167]
	Clofibric acid	*P. capillaceae*	10–22	6.5–8.5	97.7	[167]
	Atenolol	*Chlorella-Scenedesmus consortium*			80	[49]
	Diltiazem				75	
	Azithromycin and Erythromycin				80	
Heavy metal wastewater	Cd	*G. sulphuraria*	>56	1.5–2.5	45.90	[168]
	Pb				25.15	
	Ni				6.56	
	Zn				28.44	
	Cd	*Chlamydomonas acidophila RT46*		2.3–3.4	Adaptability under high Cd stress up to 40 mg/L	[169]
	Cd	*Euglena gracilis*	22–28	3.0–4.0	90	[170]
	Cu	*Desmodesmus* sp. *MAS1*	23–26	3.5–6.7	27	[171]
	Fe				86	
	Zn				60	
Acid mine drainage	Zn	*Stigeoclonium* sp.	20–25	5.5–7.5	10 µM	[172]
	Fe	*Fucus serratus*	10–15	2.0–4.0	250 mg/g	[173]
	Cu	*Fucus vesiculosus*	20–25	5.0–8.0	6 mg/g	[173]
	Zn				2 mg/g	
	Ar				190 µg/g	

Table 1. *Cont.*

Emerging Pollutant Type	Subtype	Microalgal Species	Temperature Range	pH Range	Removal Efficiency (%)	References
Microplastic	Polystyrene Polymethyl Methacrylate Polylactic Acid	*Scenedesmus abundans*	25–45	6.5–7.5	84	[174]
	Mixed polymers	*Ulva prolifera* *Sargassum horneri*	3–28	8.0–8.2	0.10 ± 0.05 items/g (fresh weight) 0.03 ± 0.02 items/g (fresh weight)	[175]
	Fiber, Film, Fragment, Microbead fiber	*Pyropia yezoensis*	5–15	7.8–8.5	0.11–0.31 items/g (fresh weight)	[176]
Dyes	Methylene blue	*Sargassum muticum*	15–20	7.5–8.5	93	[177]
	Reactive red 195	*Pterocladia capillacea*	17–25	6.5–8.5	91.1	[178]
	Azo dye	*Chlorella sorokiniana (ASK25)*	25–42	5–11	99.71	[179]

5.1. Mechanisms of Emerging Pollutant Removal

5.1.1. Biosorption

Biosorption operates as a passive immobilization mechanism wherein pollutants are sequestered via binding to cell wall surface functional groups, including carboxyl, hydroxyl, and phosphate moieties, which exhibit a strong affinity for heavy metal ions and organic micropollutants [150] (Figure 3). This process facilitates the rapid removal of contaminants from dilute solutions, acting as a critical preliminary defense before any intracellular uptake occurs. Diverse structural components within the cell wall-notably polysaccharides, proteins, and lipids provide a varied array of binding sites that enable the effective sequestration of heavy metals and organic molecules through complexation and electrostatic interactions [180]. Moreover, the formation of extracellular polymeric substance matrices further enhances this surface-level adsorption, acting to both sequester pollutants and shield algal cells from systemic toxicity [26]. Biosorption is a non-metabolic process that can be facilitated by both live and dead microalgal cells. Studies have indicated that cell surface receptors in microalgae remain capable of interacting with pollutants even in non-viable biomass. The use of dead microalgae as bioadsorbents presents several distinct advantages: it circumvents the toxic effects of contaminants on the cells, allows for the potential reuse of biomass following treatment with a desorbing agent, and reduces operational costs by eliminating the necessity of maintaining viable cultures. Complete bioadsorption efficiency of 100% for 7-amino cephalosporanic acid has been documented using the microalgal species *Chlorella*, *Mychonastes*, and *Chamydomonas* [181]. Three cultivars of *Aphanothece* sp. (A0, A8, and A15) were used to remove Cd2+ from aqueous solution. A15 exhibited the highest sorption of Cd2+, with qmax values of 12.24, 36.90, and 60.24 mg/g for A0, A8, and A15, respectively [182]. Another similar study reveals that in a batch reactor, Cd2+ biosorption reaches up to 90% [183]. Microalgal cell surfaces facilitate the efficient sequestration of positively charged antibiotics through the formation of electrostatic bonds. Non-viable *Chlorella* biomass demonstrated the capacity to sequester cefalexin through bioadsorption, achieving removal capacities of 129 and 63 mg g^{-1} [184]. Low concentrations of heavy metals have been observed to stimulate microalgal growth, a phenomenon attributed to hormesis. Furthermore, species such as *Anabaena*, *Spirogyra*, *Phormidium*, and *Oscillatoria* exhibit notable tolerance to heavy metal stress within natural aquatic environments [185]. Documented research indicates that *Chlorella vulgaris* exhibits an enhanced capacity for Pb bioadsorption when treating industrial wastewater (89.26–93.2%).

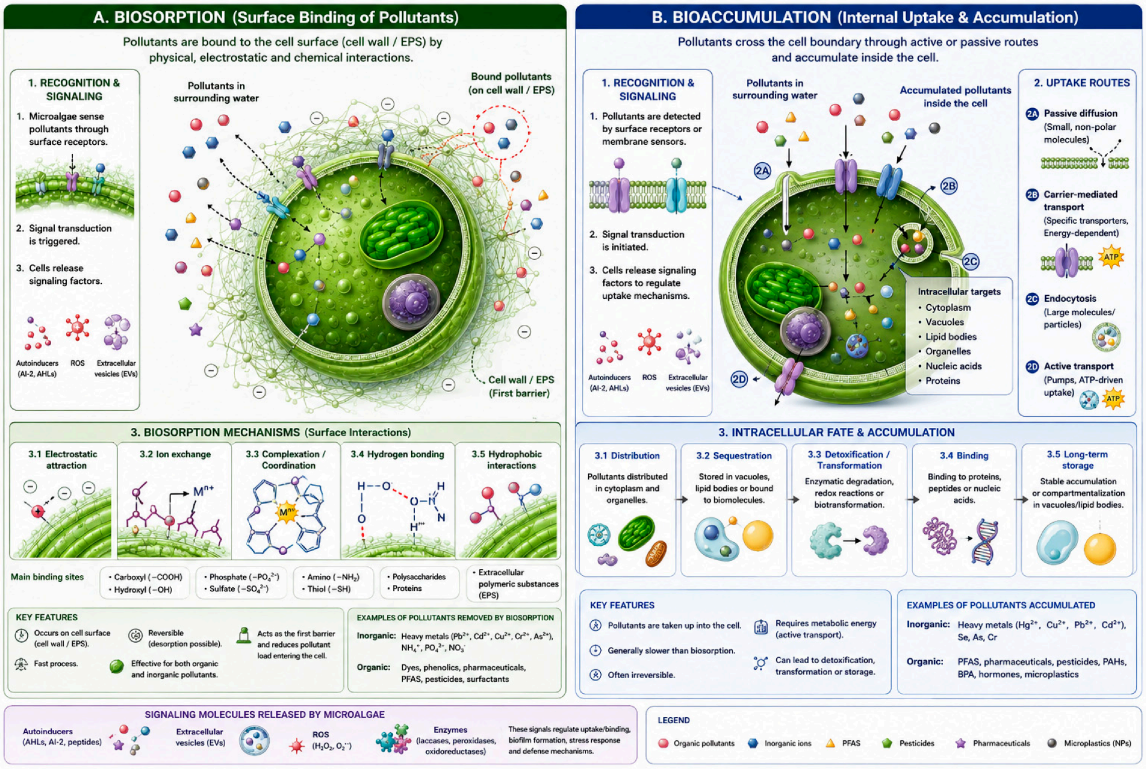

Figure 3. Mechenism of Bioadsorption and Bioaccumulation of pollutants in microalgal cell.

5.1.2. Bioaccumulation

Unlike the passive mechanism of biosorption, bioaccumulation functions as an active, metabolism-dependent process that entails the transport of pollutants across cell membranes into the cytoplasm [163,186]. This intracellular uptake is mediated by the cell's metabolic cycle, where heavy metal ions undergo positive diffusion to penetrate the membrane and accumulate within the cellular matrix. This energy-intensive phase relies on the physiological activity of living cells, where internalized substances are frequently sequestered by specialized proteins or stored within vacuoles to mitigate cytotoxicity (Figure 3) [8,187]. The bio-concentration factor (BCF) serves as a key indicator of bioaccumulation. BCF values are influenced by a multitude of factors, including pollutant bioavailability and ionization state, the presence of dissolved organic matter, physical barriers, the specific analytical methods employed, microalgal metabolic activity, interspecies variability, and various environmental parameters. Unlike biosorption, bio-uptake occurs in living microalgal cells, which sequester contaminants through three primary pathways: passive transport, passive-facilitated transport, and active transport [188]. Upon internalization, these contaminants often undergo intracellular metabolic transformation, including enzymatic degradation via cytochrome P450 complexes or are sequestered within specific organelles to mitigate systemic cellular damage [57,189]. *Chlorella sorokiniana* facilitates the removal of the antiviral drug oseltamivir from wastewater through a process of bioaccumulation followed by degradation [190]. The bioaccumulation of various heavy metals, including zinc, aluminum, iron, cadmium, and copper, has been documented in *Chlorella vulgaris*, *Oscillatoria bornettia*, *Euglena acus*, and *Pratylenchus curvicauda* [191].

5.1.3. Biodegradation

Biodegradation is a metabolic process that involves the enzymatic catabolism of complex organic pollutants, including emerging contaminants, dyes, and antibiotics, into simpler, less toxic compounds through intracellular oxidation and reduction pathways. Unlike passive sequestration mechanisms, biodegradation relies on active microbial enzymatic activity, often mediated by complexes such as cytochrome P450, to break down recalcitrant compounds that are otherwise resistant to removal [48,57] (Figure 4). Microalgae-mediated pollutant degradation is typically characterized as a two-stage enzymatic catalytic process. The initial phase involves functionalization through metabolic reactions such as carboxylation, hydroxylation, decarboxylation, hydrogenation, methylation, demethylation, ring cleavage, and oxidation-reduction, which are catalyzed by complexes like cytochrome P450, cytochrome b5, monooxygenase, and mixed-function oxidases. The subsequent phase typically involves the conjugation of these modified metabolites with endogenous molecules, thereby enhancing their polarity and water solubility to facilitate further transformation or final detoxification [192,193]. The degradation of sulfamethoxazole by *Chlorella pyrenoidosa* proceeds through a two-phase reaction process. Phase I involves the oxidation and hydroxylation of the amine group, while phase II encompasses formylation and pterin-related conjugation. Biodegradation mediated by *Chlorella* has demonstrated significant efficacy in the removal of florfenicol, achieving a degradation efficiency of 72%. This pathway exhibited superior performance when compared to passive bioadsorption and intracellular bioaccumulation mechanisms [194,195]. Microalgae-bacteria consortia have demonstrated significant efficacy in wastewater treatment and resource recovery, often offering a more energy-efficient approach. In these systems, microalgae produce oxygen that supports the metabolic activity of associated microorganisms. Reciprocally, these microbes contribute essential nutrients such as fixed nitrogen, siderophores, and vitamin B12 to the microalgae as a symbiotic exchange that results in improved bioremediation of xenobiotic compounds [196,197].

5.1.4. Photodegradation Enhancement

Photodegradation serves as an auxiliary process that harnesses solar radiation to facilitate the abiotic degradation of complex organic micropollutants, functioning synergistically with enzymatic catabolic pathways. This modality demonstrates particular efficacy in the treatment of large, hydrophobic compounds, where photon-induced cleavage of molecular bonds sensitizes recalcitrant substrates for subsequent intracellular metabolic transformation by the microalgae [67] (Figure 5). Only a limited number of EC compounds, such as ciprofloxacin and triclosan, exhibit photosensitivity. Photodegradation proceeds via either direct or indirect pathways, depending on the nature of the compound involved [185]. Direct photo-transformation is initiated by the interaction of photons with the contaminant, resulting in structural alterations such as bond cleavage, photoionization, or the formation of reactive excited states [184]. Pollutants possessing specific structural characteristics, namely aromatic rings, heteroatoms, or conjugated π-systems, are particularly susceptible to direct photolysis [198]. Fluorescent substances, including various antibiotics, undergo degradation through direct photolysis, where light-induced covalent modification and chemical damage occur, known as photo-bleaching. Consequently, antibiotics such as tetracycline, cefazolin, ciprofloxacin, and cephapirin are highly susceptible to photolysis within microalgal-based wastewater treatment systems. Conversely, indirect photolysis utilizes dissolved organic matter present in wastewater as photosensitizers to harvest light energy and produce reactive oxygen species, which subsequently facilitate the degradation of pollutants that exhibit limited susceptibility to direct solar irradiation [64]. During indirect photo-transformation, photons interact with photosensitizers such as nitrates, nitrites,

humic substances, iron, and dissolved organic matter to generate reactive transient species, often in the form of radicals [64]. These reactive intermediates subsequently interact with and degrade target contaminants. Furthermore, reactive oxygen species are endogenously generated by algae during respiration and photosynthesis.

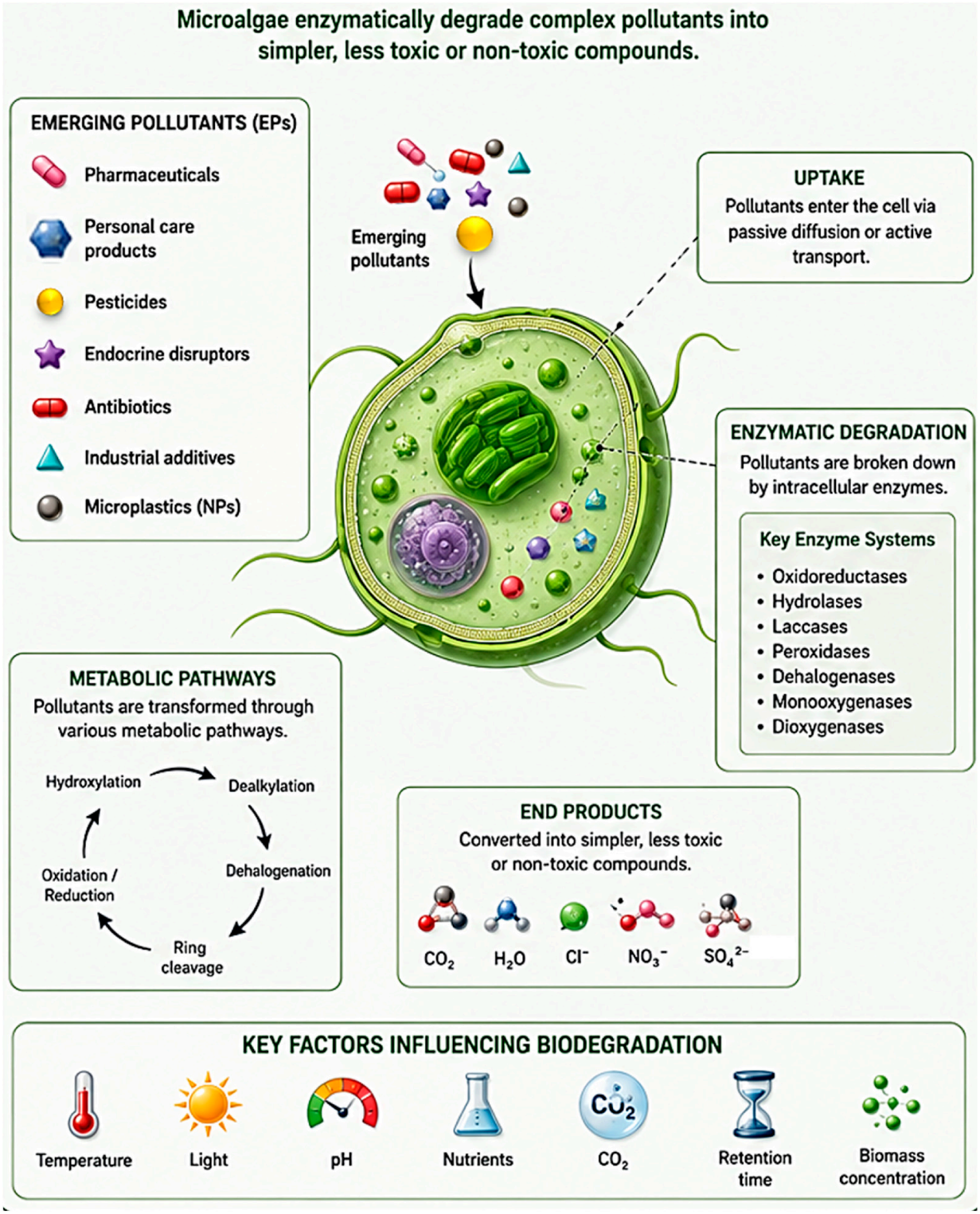

Figure 4. Mechanism of Biodegradation of pollutants in microalgal cells.

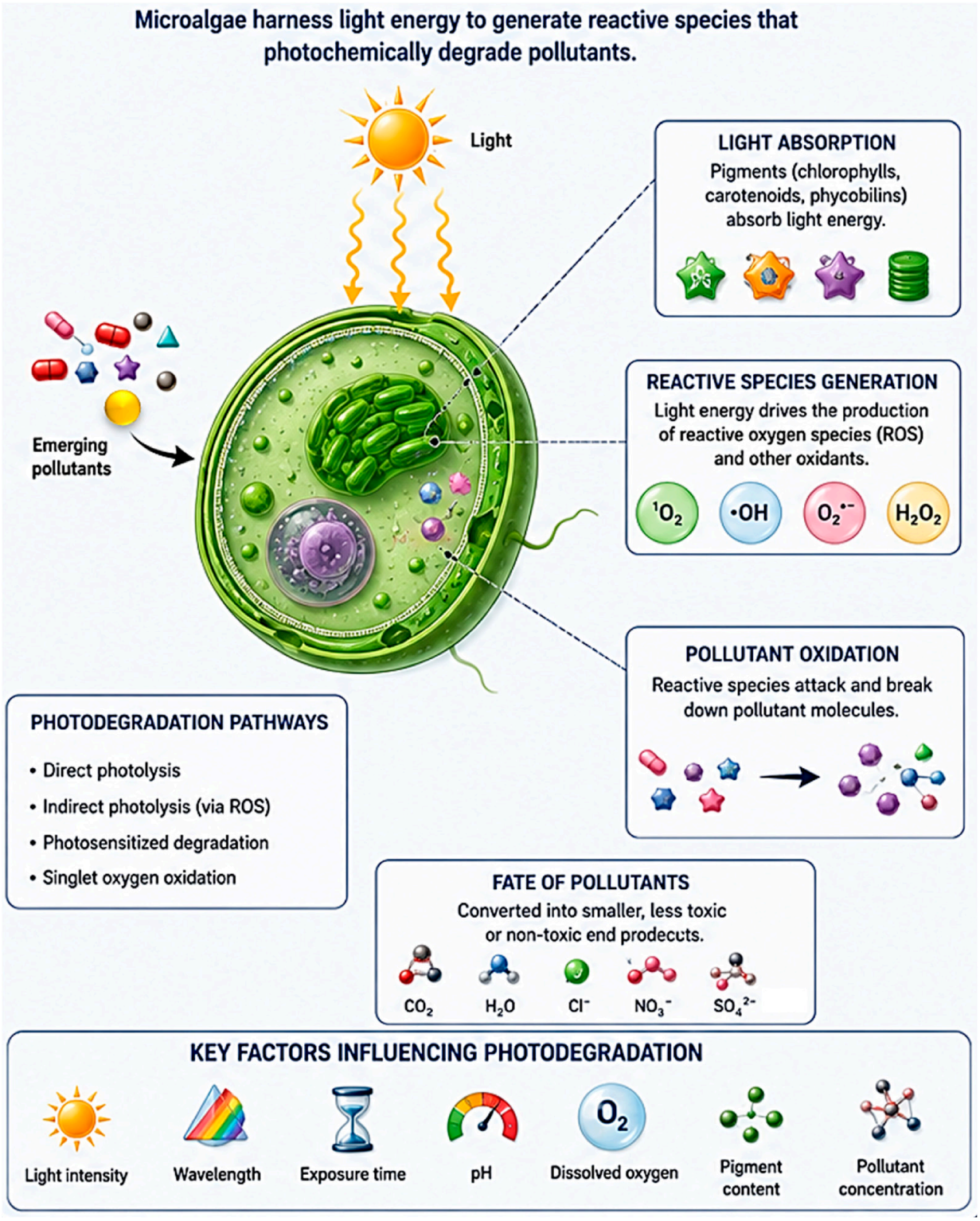

Figure 5. Mechanism of Photodegradation of pollutants in microalgal cells.

An important but frequently overlooked issue in the application of extremophilic microalgae is the distinction between true microalgae-mediated pollutant removal and abiotic photolytic degradation. Most extremophilic microalgae, including halophilic (*Dunaliella* spp.), alkaliphilic (*Arthrospira* spp.), acidophilic, and thermotolerant species, are cultivated under conditions of intense illumination, elevated dissolved oxygen, extreme pH, and prolonged hydraulic retention times. These conditions are inherently favorable for both direct photolysis and indirect photolysis. Consequently, pollutant disappearance observed

in illuminated extremophilic photobioreactors cannot automatically be attributed to algal metabolism. Instead, the measured removal generally represents the combined effects of biosorption, bioaccumulation, biodegradation, photolysis, hydrolysis, volatilization, and precipitation, the relative importance of which depends on contaminant chemistry, wastewater composition, and reactor operating conditions. Norvill et al. (2016) highlighted that photodegradation is potentially important in algal wastewater treatment ponds and argued that, because of the high dissolved-organic-matter concentrations normally present in such systems, indirect photodegradation may be more relevant than direct photolysis [199]. Another study specifically investigated the mechanisms responsible for removing caffeine, ibuprofen, galaxolide, tributyl phosphate, 4-octylphenol, tris(2-chloroethyl) phosphate and carbamazepine using algal batch reactors dominated by *Chlorella* and *Scenedesmus* [14]. The study incorporated non-aerated and dark controls to distinguish biological processes from abiotic effects. Importantly, up to 99% removal of relatively volatile compounds such as 4-octylphenol, galaxolide and tributyl phosphate was attributed primarily to volatilization/air stripping rather than to microalgal degradation. Dark/light controls are essential for assigning removal mechanisms. In experiments with *Chlorella sorokiniana*, ibuprofen and diclofenac were predominantly removed through photolytic processes, whereas metoprolol and paracetamol were influenced by a combination of photolysis and biodegradation [200]. Reymann et al. (2020) separately evaluated photolysis, sorption, and microalgal-mediated elimination of five micropollutants during cultivation of *Acutodesmus obliquus*. Sulfamethoxazole removal reached 43% and was primarily associated with biotic processes, whereas ciprofloxacin removal reached 86% but was predominantly attributed to photolysis, with microalgal activity contributing only approximately 10%. For quetiapine, both photolysis and microalgal activity contributed to the observed 99% removal [201]. Similarly, another investigation reveals the apparent phytodegradation of pentachlorophenol by *Chlorella pyrenoidosa* under controlled conditions, separating photolysis, bacterial degradation, and direct algal degradation. Although pentachlorophenol degradation occurred both in the presence and absence of algae, overall degradation was primarily governed by photolysis. These findings demonstrate that high removal efficiencies observed under illuminated microalgal cultivation cannot necessarily be attributed entirely to biological activity and emphasize the importance of appropriate algae-free and dark controls [202].

Biological transformation by extremophilic microalgae can be demonstrated when pollutant removal is accompanied by physiological responses or identifiable transformation products. The alkaliphilic extremophilic microalga *Picocystis* sp. achieved up to 72% removal of bisphenol A and 73% of diclofenac, where removal was attributed mainly to biodegradation/biotransformation [203,204].

6. Challenges and Gaps

Although microalgal bioremediation exhibits significant promise, current research is constrained by a limited fundamental understanding of autotrophic metabolic pathways. Furthermore, while cometabolism facilitates partial pollutant removal, the underlying enzymatic mechanisms and specific transformation routes in complex wastewater matrices remain insufficiently characterized [15]. Additionally, the operational instability of microalgae-bacteria consortia in large-scale applications poses a significant hurdle, as dynamic intraspecies relationships within these systems complicate the maintenance of consistent remediation performance [13]. The lack of standardized protocols for scaling laboratory-scale photobioreactors to real-world municipal and industrial wastewater treatment plants impedes the transition from controlled experimental environments to full-scale implementation [29,205].

6.1. Growth Rate

Growth rates in many algal strains limit the speed of nutrient uptake and biomass accumulation, often necessitating prolonged cultivation periods that reduce overall process productivity [77,206]. High-density cultivation often encounters mass transfer limitations and light attenuation, which frequently compromise the metabolic efficiency of both microalgae and their bacterial partners in large-scale reactors [207]. Moreover, competition for inorganic carbon becomes pronounced under high-density conditions, as excessive aeration can deplete CO_2 levels and inadvertently trigger photorespiration, which suppresses biomass productivity [28,208]. Psychrophilic glacier algae such as *Mesotaenium berggrenii* represent promising candidates for cold wastewater treatment in alpine and polar regions. However, their extremely low growth rates at moderate temperatures make reactor productivity very poor, greatly increasing HRT and reactor footprint [209].

6.2. Biomass Harvesting

The recovery of microalgal biomass remains a major economic bottleneck, as conventional methods such as centrifugation or chemical flocculation are highly energy-intensive and often increase the total cost of the bioremediation process [210]. Alternatively, utilizing industrial-scale hybrid cultivation systems may mitigate these financial burdens by optimizing productivity through integrated nutrient recovery and atmospheric carbon capture [83,211]. Researchers must address the current lack of infrastructure compatibility and the variability of influent characteristics across different industrial sectors to achieve reliable, long-term operational success [212]. *Coccomyxa melkonianii* is an acidophilic, metal-tolerant green alga that survives in acid mine drainage containing extremely high concentrations of Zn, Cd and Cu. However, its biomass productivity remains relatively low because a considerable proportion of assimilated energy is diverted to metal detoxification, vacuolar sequestration and antioxidant defence [7]. Like *D. salina*, *Dunaliella bardawil* species lacks a rigid cell wall, making centrifugation and membrane filtration difficult because cells rupture easily under shear stress. Harvesting therefore remains considerably more expensive than for thick-walled chlorophytes [213].

6.3. Genetic Instability

The risk of horizontal gene transfer and potential escapes from open cultivation systems necessitate rigorous environmental risk assessments, especially when employing genetically engineered strains [54]. Furthermore, the inherent sensitivity of these co-cultures to environmental fluctuations, including shifts in temperature, pH, and light intensity, requires the development of more robust microbial associations to maintain consistent community composition and metabolic performance [205]. To bridge this gap, future investigations must prioritize the development of advanced reactor configurations, such as membrane bioreactors and biofilm photobioreactors, which facilitate the retention of specialized microbial populations and simplify downstream biomass harvesting [214]. The remarkable adaptability of *G. sulphuraria* results partly from extensive horizontal gene transfer from bacteria and archaea. While this provides exceptional metabolic versatility, it also raises questions regarding long-term phenotypic stability under continuous industrial cultivation and repeated wastewater exposure, which remain poorly investigated [100].

6.4. Scale-Up

The transition from pilot-scale operations to full-scale industrial facilities remains impeded by technical irregularities, such as sludge deposition and insufficient mixing, which underscore the necessity for advanced, automated remote monitoring systems to ensure operational reliability [73]. Furthermore, the design of large-scale systems must account for

inherent constraints in CO_2 mass transfer and solubility within standard photobioreactor configurations, which frequently result in significant gas losses and inefficient carbon utilization [215]. Consequently, future developmental strategies should prioritize optimizing reactor architecture to ensure uniform light and nutrient distribution at scale, while concurrently exploring the integration of microalgal cultivation with established power generation infrastructures to enhance economic sustainability [216,217]. Comprehensive life cycle assessments are essential to validate the economic feasibility and net energy balance of these integrated systems prior to their full-scale deployment [218]. *Cyanidioschyzon merolae* is a unicellular thermoacidophilic red alga with one of the smallest known eukaryotic genomes and is widely used as a model for organelle biology and stress adaptation. While it survives highly acidic, metal-rich environments, practical wastewater applications remain scarce. Its relatively low biomass productivity and the lack of pilot-scale cultivation studies currently limit its translation from laboratory research to environmental biotechnology [219]. *Dactylococcus dissociatus* MT1, an inhabitant of deserts, is an extremophile that exhibits exceptional tolerance to desiccation, high irradiance and temperature fluctuations. Despite its ecological importance, research has focused primarily on stress physiology rather than wastewater treatment. At present, cultivation protocols, growth kinetics, pollutant-removal capacity and scale-up strategies remain largely unexplored, making it one of the least characterized extremophilic microalgae [220,221].

6.5. Trade-Off Between Stress-Induced Pollutant Removal and Productivity

Extremophilic microalgae offer an important biological advantage for treating harsh wastewaters under extreme environmental stresses, but their practical implementation requires simultaneous consideration of pollutant removal capacity, growth kinetics, biomass productivity and process stability. The assumption that extremophilic microalgae are inherently slow-growing should, however, be treated cautiously. Growth performance is highly species- and condition-dependent, and some extremophilic or stress-tolerant strains can exhibit rapid growth under appropriately selected conditions. For example, *Desmodesmus* sp. *MAS1* and *Heterochlorella* sp. *MAS3*, originally characterized from acidic environments, exhibited specific growth rates of 1.10–1.30 d^{-1} during mixotrophic cultivation in highly alkaline winery wastewater and simultaneously achieved up to 80% carbon and 90% nitrogen and phosphate removal, respectively [222]. Thus, the central challenge is not simply that extremophiles grow slowly, but rather that the environmental conditions required for maximum pollutant resistance may not coincide with those required for maximum biomass productivity. This trade-off represents an important knowledge gap for the scale-up of extremophilic microalgae-based wastewater treatment. Liu and Yildiz [223] demonstrated that *D. salina* could remove 45–88% of nitrate, ammonia and phosphorus from municipal wastewater, with optimum growth occurring at approximately 30% salinity. These results demonstrate that pollutant removal and biomass generation can be simultaneously achieved, but also indicate the importance of identifying an organism-specific salinity optimum rather than assuming that higher salinity necessarily provides better treatment performance. An additional complication is that stress can simultaneously decrease growth while increasing the synthesis of compounds associated with pollutant tolerance and biomass value. For example, saline stress in *D. salina* can stimulate accumulation of carotenoids and other protective metabolites. From a biorefinery perspective, this may partially compensate for reduced biomass productivity because the value of the biomass is determined not only by its quantity but also by its biochemical composition.

7. Future Directions

7.1. Metabolic Engineering

This approach aims to enhance the inherent biosorption capacity of extremophilic strains by overexpressing specific genes responsible for the synthesis of extracellular polymeric substances or high-affinity metal-binding proteins [166]. Furthermore, integrating CRISPR-Cas9 technologies allows for the precise modification of cell wall composition to increase the density of carboxyl and sulfate groups, thereby optimizing electrostatic attraction for targeted cationic contaminants [163]. By modulating the expression of metallothioneins and phytochelatins, these engineered strains can further improve the intracellular sequestration efficiency of heavy metals, effectively mitigating toxicity during long-term wastewater treatment operations [224].

7.2. AI-Guided Strain Selection

Leveraging machine learning algorithms allows for the predictive modeling of microbial performance under fluctuating environmental conditions, identifying optimal species based on their tolerance to complex salinity profiles and pollutant toxicity [23]. These computational frameworks facilitate the identification of robust extremophilic microalgal consortia capable of maintaining steady-state growth in environments where standard analytical methods fail to predict synergistic interactions between environmental stressors and wastewater chemistry. Additionally, the integration of omics approaches, such as transcriptomics and proteomics, provides a comprehensive understanding of the genes and transcription factors involved in these removal processes, enabling the development of more effective and targeted bioremediation solutions [8]. Furthermore, the deployment of AI-driven digital twins and predictive analytics enables real-time optimization of culture conditions, ensuring early detection of process instability while simultaneously maximizing the synthesis of target metabolites [205].

7.3. Multi-Omics Integration

The integration of transcriptomic, proteomic, and metabolomic datasets allows researchers to decipher the regulatory networks that dictate microalgal molecular responses to pollutant exposure [225]. This systems-level understanding illuminates key bottlenecks in metabolic fluxes, thereby facilitating the targeted modification of lipid biosynthesis and stress response pathways to enhance overall microbial performance. Furthermore, the utilization of these high-throughput analytical techniques supports the identification of synergistic gene expression patterns that augment microbial activity and environmental resilience within complex consortia [226]. Ultimately, this integrated framework enables the systematic mapping of metabolic pathways, optimizing the synthesis of high-value bioproducts concurrently with the remediation of diverse industrial pollutants [179].

7.4. Climate-Resilient Microalgae

Cultivating thermally tolerant and light-adaptive strains is imperative for sustaining metabolic productivity against the backdrop of escalating extreme weather events and temperature variability [227]. Contemporary research underscores the capacity of these resilient phenotypes to flourish in diverse, non-arable environments, which is essential for ensuring consistent yields despite unpredictable climatic stressors [228]. Furthermore, the deployment of such robust strains facilitates the concurrent recovery of resources from wastewater, effectively transitioning climate-vulnerable remediation systems into reliable hubs for the production of biofuels and biochemicals [20]. Finally, the integrated synthesis of high-value byproducts alongside lipid-derived fuels constitutes a pivotal approach to

mitigating the inherent economic barriers currently impeding the commercial viability of microalgal technologies [148,229].

7.5. Nature-Based Solutions

The incorporation of microalgal cultivation into constructed wetlands and decentralized ecological treatment systems constitutes a sustainable, energy-efficient methodology for restoring aquatic integrity while concurrently mitigating nutrient enrichment. These configurations utilize microalgae-microbial consortia to facilitate large-scale bioremediation and the sequestration of toxic metals, effectively repurposing wastewater nutrients to reduce operational expenditures [81,230]. Furthermore, these nature-based interventions harmonize with circular economy paradigms by valorizing waste streams for the production of bio-fertilizers and other high-value biomass commodities [20]. Through the application of process systems engineering and artificial neural networks, these decentralized frameworks can be optimized to maximize nutrient recovery efficiency, thereby securing the economic sustainability of biomass valorization [231]. Additionally, the strategic deployment of these systems in rural and agricultural regions significantly reduces the spatial footprint associated with conventional wastewater treatment infrastructure [81].

7.6. Efficient Strain Selection

Future research should shift from the conventional aim of identifying the "most tolerant" extremophilic species toward identifying the most productive species under the target wastewater conditions. Tolerance should be evaluated together with specific growth rate, biomass productivity, pollutant uptake rate, photosynthetic efficiency and long-term culture stability. For example, a strain capable of surviving at 100 g L^{-1} salinity but growing at only 0.05 d^{-1} may be less useful for continuous treatment than a strain that remains stable at 50 g L^{-1} salinity while growing at 0.5 d^{-1} even if the latter has a narrower tolerance range.

Accordingly, future screening studies should employ a multidimensional performance matrix rather than ranking strains solely according to pollutant removal percentage. At minimum the following parameters should be evaluated simultaneously: (i) specific growth rate; (ii) doubling time; (iii) biomass productivity; (iv) maximum sustainable biomass concentration; (v) pollutant removal efficiency; (vi) volumetric pollutant removal rate; (vii) pollutant removal per unit biomass; (viii) photosynthetic efficiency; (ix) stress tolerance; (x) biomass recoverability; and (xi) biochemical composition and downstream biomass value. Such an approach would help identify strains that provide the best compromise between treatment performance and biomass generation.

7.7. Policy and Regulatory Frameworks

The future development of extremophilic microalgae-based wastewater treatment technologies will be influenced not only by advances in algal physiology and reactor engineering but also by rapidly evolving environmental regulations, water quality standards, and circular bioeconomy policies. A major regulatory milestone is the revised European Union Urban Wastewater Treatment Directive (Directive (EU) 2024/3019), which entered into force in 2025 [232]. Unlike previous regulations that primarily emphasized nutrient removal, the revised directive introduces quaternary treatment for the removal of micropollutants, strengthens the polluter-pays principle through extended producer responsibility for pharmaceutical and cosmetic industries, promotes water reuse and resource recovery, requires improved energy efficiency and climate neutrality of wastewater treatment plants, and expands wastewater monitoring to include pathogens, antimicrobial resistance, PFAS, and other priority contaminants. Water reuse regulations will also become an important driver for extremophilic microalgae. Increasing water scarcity has acceler-

ated global interest in wastewater reclamation for agricultural irrigation, industrial reuse, groundwater recharge, and indirect potable reuse. Regulatory frameworks such as the EU Water Reuse Regulation (EU) 2020/741 establish minimum water-quality requirements and risk-management approaches for reclaimed water used in the agroeconomy [233]. Because many industrial wastewaters exhibit elevated salinity, extremophilic microalgae may provide an attractive biological polishing step prior to reuse, particularly when conventional freshwater microalgae cannot be maintained. Future research should therefore evaluate reclaimed-water quality parameters relevant to regulatory acceptance, including pathogen indicators, residual micropollutants, salinity, nutrient concentrations, and ecotoxicity, rather than focusing exclusively on biomass production.

8. Conclusions

The paradigm of microalgal biotechnology represents a transformative shift toward a circular bioeconomy by bridging the critical gap between environmental remediation and the sustainable production of renewable energy and value-added commodities. The current review highlights the role of extremophilic and extremotolerant microalgae as potential candidates for emerging contaminant treatment and underscores the necessity of refining harvesting techniques and genetic engineering protocols to elevate the cost-effectiveness of these integrated systems. Continued exploration and technological innovation are essential to bridge the gap between experimental laboratory findings and large-scale commercial application.

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Abbreviations

The following abbreviations are used in this manuscript:

BCF	Bio-concentration factor
ECs	Emerging contaminants
EDCs	Endocrine-disrupting compounds
PFAS	Per- and Polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid

References

1. Abdelfattah, A.; Ali, S.S.; Ramadan, H.; El-Aswar, E.I.; Eltawab, R.; Ho, S.; Elsamahy, T.; Li, S.; El-Sheekh, M.M.; Schagerl, M.; et al. Microalgae-Based Wastewater Treatment: Mechanisms, Challenges, Recent Advances, and Future Prospects. *Environ. Sci. Ecotechnology* **2022**, *13*, 100205. [CrossRef] [PubMed]
2. Qin, Y.; Li, T.; Nie, C.; Geng, X.; Sun, X. Microalgae: Promising Solutions Paving the Way toward a Greener and More Sustainable Future. *Front. Fuels* **2025**, *3*, 1643675. [CrossRef]
3. Anand, U.; Dey, S.; Parial, D.; Federici, S.; Ducoli, S.; Bolan, N.; Dey, A.; Bontempi, E. Algae and Bacteria Consortia for Wastewater Decontamination and Transformation into Biodiesel, Bioethanol, Biohydrogen, Biofertilizers and Animal Feed: A Review. *Environ. Chem. Lett.* **2023**, *21*, 1585–1609. [CrossRef]
4. Fabris, M.; Abbriano, R.M.; Pernice, M.; Sutherland, D.L.; Commault, A.S.; Hall, C.; Labeeuw, L.; McCauley, J.I.; Kuzhiuparambil, U.; Ray, P.; et al. Emerging Technologies in Algal Biotechnology: Toward the Establishment of a Sustainable, Algae-Based Bioeconomy. *Front. Plant Sci.* **2020**, *11*, 279. [CrossRef] [PubMed]
5. Wollmann, F.; Dietze, S.; Ackermann, J.; Bley, T.; Walther, T.; Steingroewer, J.; Krujatz, F. Microalgae Wastewater Treatment: Biological and Technological Approaches. *Eng. Life Sci.* **2019**, *19*, 860–871. [CrossRef] [PubMed]
6. Sharma, P.; Gaur, V.K.; Gupta, S.; Varjani, S.; Pandey, A.; Gnansounou, E.; You, S.; Ngo, H.H.; Wong, J.W.C. Trends in Mitigation of Industrial Waste: Global Health Hazards, Environmental Implications and Waste Derived Economy for Environmental Sustainability. *Sci. Total Environ.* **2021**, *811*, 152357. [CrossRef] [PubMed]
7. Rojas-Villalta, D.; Rojas-Rodríguez, D.; Villanueva-Ilama, M.; Guillén-Watson, R.; Murillo-Vega, F.; Gómez-Espinoza, O.; Núñez-Montero, K. Exploring Extremotolerant and Extremophilic Microalgae: New Frontiers in Sustainable Biotechnological Applications. *Biology* **2024**, *13*, 712. [CrossRef] [PubMed]
8. Srimongkol, P.; Sangtanoo, P.; Songserm, P.; Watsuntorn, W.; Karnchanatat, A. Microalgae-Based Wastewater Treatment for Developing Economic and Environmental Sustainability: Current Status and Future Prospects. *Front. Bioeng. Biotechnol.* **2022**, *10*, 904046. [CrossRef] [PubMed]
9. Anabtawi, H.M.; Ikhlaq, A.; Kumar, S.; Rafique, S.; Hassan, A.A. Addressing Challenges for Eco-Friendly and Sustainable Wastewater Treatment Solutions Using Extremophile Microorganisms. *Sustainability* **2025**, *17*, 2339. [CrossRef]
10. Chia, X.K.; Hadibarata, T.; Jusoh, M.N.H.; Sutiknowati, L.I.; Tan, I.S.; Foo, H.C.Y. Role of Extremophiles in Biodegradation of Emerging Pollutants. *Top. Catal.* **2024**, *68*, 965–982. [CrossRef]
11. Hammed, A.; Prajapati, S.K.; Şimşek, Ş.; Şimşek, H. Growth Regime and Environmental Remediation of Microalgae. *ALGAE* **2016**, *31*, 189–204. [CrossRef]
12. Hassanien, A.E.; Saadaoui, I.; Schipper, K.; Al-Marri, S.; Dalgamouni, T.; Aouida, M.; Saeed, S.; Jabri, H.A. Genetic Engineering to Enhance Microalgal-Based Produced Water Treatment with Emphasis on CRISPR/Cas9: A Review. *Front. Bioeng. Biotechnol.* **2023**, *10*, 1104914. [CrossRef] [PubMed]
13. Nguyen, H.T.; Yoon, Y.; Ngo, H.H.; Jang, A. The Application of Microalgae in Removing Organic Micropollutants in Wastewater. *Crit. Rev. Environ. Sci. Technol.* **2020**, *51*, 1187–1220. [CrossRef]
14. Matamoros, V.; Uggetti, E.; García, J.; Bayona, J.M. Assessment of the Mechanisms Involved in the Removal of Emerging Contaminants by Microalgae from Wastewater: A Laboratory Scale Study. *J. Hazard. Mater.* **2015**, *301*, 197–205. [CrossRef] [PubMed]
15. Vo, H.N.P.; Ngo, H.H.; Guo, W.; Nguyen, K.H.; Chang, S.W.; Nguyen, D.D.; Liu, Y.; Liu, Y.; Ding, A.; Bui, X. Micropollutants Cometabolism of Microalgae for Wastewater Remediation: Effect of Carbon Sources to Cometabolism and Degradation Products. *Water Res.* **2020**, *183*, 115974. [CrossRef] [PubMed]
16. Pachouri, V.; Chandramauli, A.; Singh, R.; Gehlot, A.; Priyadarshi, N.; Twala, B. Removal of Contaminants by Chlorella Species: An Effort towards Sustainable Remediation. *Discov. Sustain.* **2024**, *5*, 19. [CrossRef]
17. Parmar, P.; Kumar, R.; Neha, Y.; Srivatsan, V. Microalgae as next Generation Plant Growth Additives: Functions, Applications, Challenges and Circular Bioeconomy Based Solutions. *Front. Plant Sci.* **2023**, *14*, 1073546. [CrossRef] [PubMed]

18. Maurya, R.; Zhu, X.; Valverde-Pérez, B.; Kiran, B.R.; General, T.; Sharma, S.; Sharma, A.K.; Thomsen, M.; Mohan, S.V.; Mohanty, K.; et al. Advances in Microalgal Research for Valorization of Industrial Wastewater. *Bioresour. Technol.* **2021**, *343*, 126128. [CrossRef] [PubMed]
19. de Morais, E.G.; da Silveira, J.T.; Schüler, L.; de Freitas, B.B.; Costa, J.A.V.; de Morais, M.G.; Ferrer, I.; Barreira, L. Biomass Valorization via Pyrolysis in Microalgae-Based Wastewater Treatment: Challenges and Opportunities for a Circular Bioeconomy. *J. Appl. Phycol.* **2023**, *35*, 2689–2708. [CrossRef]
20. Khandelwal, A.; Lens, P.N.L. Algal Systems for Resource Recovery from Waste and Wastewater. In *IWA Publishing eBooks*; UWA Publishing: Perth, Australia, 2023; pp. 3–8.
21. Thirumalaivasan, N.; Gnanasekaran, L.; Kumar, S.; Rajesh, D.; Sundaram, T.; Rajendran, S.; Nangan, S.; Kanagaraj, K. Utilization of Fungal and Bacterial Bioremediation Techniques for the Treatment of Toxic Waste and Biowaste. *Front. Mater.* **2024**, *11*, 1416445. [CrossRef]
22. Brar, A.S.; Kumar, M.; Vivekanand, V.; Pareek, N. Photoautotrophic Microorganisms and Bioremediation of Industrial Effluents: Current Status and Future Prospects. *3 Biotech* **2017**, *7*, 18. [CrossRef] [PubMed]
23. Mehariya, S.; Das, P.; Thaher, M.; Quadir, M.A.; Khan, S.; Sayadi, S.; Hawari, A.H.; Verma, P.; Bhatia, S.K.; Karthikeyan, O.P.; et al. Microalgae: A Potential Bioagent for Treatment of Emerging Contaminants from Domestic Wastewater. *Chemosphere* **2024**, *351*, 141245. [CrossRef] [PubMed]
24. Chandran, P.; Suresh, S.; Balasubramain, B.; Gangwar, J.; Raj, A.S.; Aarathy, U.L.; Meyyazhagan, A.; Pappuswamy, M.; Joseph, K.S. Biological Treatment Solutions Using Bioreactors for Environmental Contaminants from Industrial Waste Water. *J. Umm AI-Qura Univ. Appl. Sci.* **2023**, *11*, 185–207. [CrossRef]
25. Yin, Q.; He, K.; Collins, G.; Vrieze, J.D.; Wu, G. Microbial Strategies Driving Low Concentration Substrate Degradation for Sustainable Remediation Solutions. *npj Clean Water* **2024**, *7*, 52. [CrossRef]
26. Vo, H.N.P.; Ngo, H.H.; Guo, W.; Liu, Y.; Chang, S.W.; Nguyen, D.D.; Nguyen, P.D.; Bui, X.; Ren, J. Identification of the Pollutants' Removal and Mechanism by Microalgae in Saline Wastewater. *Bioresour. Technol.* **2018**, *275*, 44–52. [CrossRef] [PubMed]
27. Matamoros, V.; Gutiérrez, R.; Ferrer, I.; García, J.; Bayona, J.M. Capability of Microalgae-Based Wastewater Treatment Systems to Remove Emerging Organic Contaminants: A Pilot-Scale Study. *J. Hazard. Mater.* **2015**, *288*, 34–42. [CrossRef] [PubMed]
28. Rathour, R.K.; Sharma, D.; Ullah, S.; Mahmoud, E.-H.M.; Sharma, N.; Kumar, P.; Bhatt, A.K.; Ahmad, I.; Bhatia, R.K. Bacterial–Microalgal Consortia for Bioremediation of Textile Industry Wastewater and Resource Recovery for Circular Economy. *Biotechnol. Environ.* **2024**, *1*, 6. [CrossRef]
29. Amaro, H.M.; Salgado, E.M.; Nunes, O.C.; Pires, J.C.M.; Esteves, A.F. Microalgae Systems—Environmental Agents for Wastewater Treatment and Further Potential Biomass Valorisation. *J. Environ. Manag.* **2023**, *337*, 117678. [CrossRef] [PubMed]
30. Frascaroli, G.; Hunter, C.; Roberts, J.; Escudero, A. Antibiotic Removal by Three Promising Microalgae Strains: Biotic, Abiotic Routes, and Response Mechanisms. *Water Air Soil Pollut.* **2024**, *235*, 600. [CrossRef]
31. Danner, M.-C.; Robertson, A.L.; Behrends, V.; Reiss, J. Antibiotic Pollution in Surface Fresh Waters: Occurrence and Effects. *Sci. Total Environ.* **2019**, *664*, 793–804. [CrossRef] [PubMed]
32. Vo, T.P.; Danaee, S.; Chaiwong, C.; Pham, B.T.; Poddar, N.; Kim, M.; Kuzhiumparambil, U.; Songsomboon, C.; Pernice, M.; Ngo, H.H.; et al. Microalgae-Bacteria Consortia for Organic Pollutants Remediation from Wastewater: A Critical Review. *J. Environ. Chem. Eng.* **2024**, *12*, 114213. [CrossRef]
33. Petrović, M. Analysis and Removal of Emerging Contaminants in Wastewater and Drinking Water. *TrAC Trends Anal. Chem.* **2003**, *22*, 685–696. [CrossRef]
34. Gibi, C.; Liu, C.; Anandan, S.; Wu, J.J. Recent Advances on Electrochemical Sensors for Detection of Contaminants of Emerging Concern (CECs). *Molecules* **2023**, *28*, 7916. [CrossRef] [PubMed]
35. Venugopal, E.; Patil, S.J. Microalgae and Bacteria Consortia for the Removal of Emerging Contaminants from Wastewater and Biomass Production. In *Nature-Based Solutions for Remediation of Emerging Pollutants in Wastewater*; CRC Press: Boca Raton, FL, USA, 2026; pp. 178–187.
36. Abate, R.; Oon, Y.-S.; Oon, Y.-L.; Bi, Y. Microalgae-Bacteria Nexus for Environmental Remediation and Renewable Energy Resources: Advances, Mechanisms and Biotechnological Applications. *Heliyon* **2024**, *10*, e31170. [CrossRef] [PubMed]
37. Mishra, R.K.; Mentha, S.S.; Misra, Y.; Dwivedi, N. Emerging Pollutants of Severe Environmental Concern in Water and Wastewater: A Comprehensive Review on Current Developments and Future Research. *Water-Energy Nexus* **2023**, *6*, 74–95. [CrossRef]
38. Ahmed, M.B.; Zhou, J.L.; Ngo, H.H.; Guo, W.; Thomaidis, N.S.; Jiang, X. Progress in the Biological and Chemical Treatment Technologies for Emerging Contaminant Removal from Wastewater: A Critical Review. *J. Hazard. Mater.* **2016**, *323*, 274–298. [CrossRef] [PubMed]
39. Kumar, R.; Qureshi, M.; Vishwakarma, D.K.; Al-Ansari, N.; Kuriqi, A.; Elbeltagi, A.; Saraswat, A. A Review on Emerging Water Contaminants and the Application of Sustainable Removal Technologies. *Case Stud. Chem. Environ. Eng.* **2022**, *6*, 100219. [CrossRef]

40. Mantovani, M.; Rossi, S.; Ficara, E.; Collina, E.; Marazzi, F.; Lasagni, M.; Mezzanotte, V. Removal of Pharmaceutical Compounds from the Liquid Phase of Anaerobic Sludge in a Pilot-Scale High-Rate Algae-Bacteria Pond. *Sci. Total. Environ.* **2023**, *908*, 167881. [CrossRef] [PubMed]
41. Gomes, I.B.; Maillard, J.; Simões, L.C.; Simões, M. Emerging Contaminants Affect the Microbiome of Water Systems—Strategies for Their Mitigation. *npj Clean Water* **2020**, *3*, 39. [CrossRef]
42. Tiwari, B.; Sellamuthu, B.; Ouarda, Y.; Drogui, P.; Tyagi, R.D.; Buelna, G. Review on Fate and Mechanism of Removal of Pharmaceutical Pollutants from Wastewater Using Biological Approach. *Bioresour. Technol.* **2016**, *224*, 1–12. [CrossRef] [PubMed]
43. De Oliveira, F.R.; Lütterbeck, C.A.; Schneider, R.d.C.d.S.; Rodríguez, A.L.; Baggiotto, C.; Kersting, M.; Rieger, A.; Nunes, T.C.; Iepsen, G.L.; Frantz, J.V.; et al. Sequential Use of Microalgae and Constructed Wetlands and Its Potential to Remove Organic Load, Toxicity and Pharmaceuticals from Urban Wastewaters. *Res. Sq.* **2024**. [CrossRef] [PubMed]
44. Rizzo, L.; Malato, S.; Antakyalı, D.; Beretsou, V.G.; Đolić, M.; Gernjak, W.; Heath, E.; Ivančev-Tumbas, I.; Karaolia, P.; Ribeiro, A.R.; et al. Consolidated vs New Advanced Treatment Methods for the Removal of Contaminants of Emerging Concern from Urban Wastewater. *Sci. Total Environ.* **2018**, *655*, 986–1008. [CrossRef] [PubMed]
45. Vaksmaa, A.; Guerrero-Cruz, S.; Ghosh, P.; Zeghal, E.; Hernando-Morales, V.; Niemann, H. Role of Fungi in Bioremediation of Emerging Pollutants. *Front. Mar. Sci.* **2023**, *10*, 1070905. [CrossRef]
46. Vassalle, L.; Sunyer-Caldú, A.; Uggetti, E.; Díez-Montero, R.; Díaz-Cruz, M.S.; García, J.; García-Galán, M.J. Bioremediation of Emerging Micropollutants in Irrigation Water. The Alternative of Microalgae-Based Treatments. *J. Environ. Manag.* **2020**, *274*, 111081. [CrossRef] [PubMed]
47. Lata, S.; Mondal, S.; Mishra, R.; Sinha, S.; Bora, J.; Talukdar, N.; Deshwal, R.K.; Thapliyal, S.; Rustagi, S.; Ramniwas, S.; et al. Technological Potential of Microalgae for Removal of Pharmaceuticals and Personal Care Product's from Waste Water. *Ind. Biotechnol.* **2025**, *22*, 229–246. [CrossRef]
48. Tawfik, A.; Eraky, M.; Alhajeri, N.S.; Osman, A.I.; Rooney, D.W. Cultivation of Microalgae on Liquid Anaerobic Digestate for Depollution, Biofuels and Cosmetics: A Review. *Environ. Chem. Lett.* **2022**, *20*, 3631–3656. [CrossRef]
49. Hom-Díaz, A.; Jaén-Gil, A.; Bello-Laserna, I.; Rodríguez-Mozaz, S.; Vicent, T.; Barceló, D.; Blánquez, P. Performance of a Microalgal Photobioreactor Treating Toilet Wastewater: Pharmaceutically Active Compound Removal and Biomass Harvesting. *Sci. Total Environ.* **2017**, *592*, 1–11. [CrossRef] [PubMed]
50. Bertolini, M.; Conti, F. Algae Culture Conditions and Process Parameters for Phycoremediation and Biomaterials Production. *Environ. Clim. Technol.* **2022**, *26*, 1092–1105. [CrossRef]
51. Xiong, Q.; Hu, L.; Liu, Y.; Zhao, J.; He, L.-Y.; Ying, G. Microalgae-Based Technology for Antibiotics Removal: From Mechanisms to Application of Innovational Hybrid Systems. *Environ. Int.* **2021**, *155*, 106594. [CrossRef] [PubMed]
52. García-Galán, M.J.; Arashiro, L.T.; Santos, L.H.M.L.M.; Insa, S.; Rodríguez-Mozaz, S.; Barceló, D.; Ferrer, I.; Garfí, M. Fate of Priority Pharmaceuticals and Their Main Metabolites and Transformation Products in Microalgae-Based Wastewater Treatment Systems. *J. Hazard. Mater.* **2019**, *390*, 121771. [CrossRef] [PubMed]
53. Požar, A.K.; Atanasova, N.; Bulc, T.G.; Istenič, D. Microalgal Technologies: Treatment Strategy for Contaminants of Emerging Concern. In Proceedings of the Socratic Lectures: 12th International Symposium, Ljubljana, Slovenia, 11 January 2025.
54. Das, B.; Bhattarai, A. The Versatility of Algae in Addressing the Global Sustainability Challenges. *Front. Bioeng. Biotechnol.* **2025**, *13*, 1621817. [CrossRef] [PubMed]
55. Dawiec-Liśniewska, A.; Podstawczyk, D.; Bastrzyk, A.; Czuba, K.; Pacyna-Iwanicka, K.; Okoro, O.V.; Shavandi, A. New Trends in Biotechnological Applications of Photosynthetic Microorganisms. *Biotechnol. Adv.* **2022**, *59*, 107988. [CrossRef] [PubMed]
56. Touliabah, H.E.; El-Sheekh, M.M.; Ismail, M.M.; El-Kassas, H.Y. A Review of Microalgae- and Cyanobacteria-Based Biodegradation of Organic Pollutants. *Molecules* **2022**, *27*, 1141. [CrossRef] [PubMed]
57. Ende, S.; Henjes, J.; Spiller, M.; Elshobary, M.E.; Hanelt, D.; Abomohra, A.E. Recent Advances in Recirculating Aquaculture Systems and Role of Microalgae to Close System Loop. *Bioresour. Technol.* **2024**, *407*, 131107. [CrossRef] [PubMed]
58. Shahsavari, E.; Rouch, D.A.; Khudur, L.S.; Thomas, D.C.; Aburto-Medina, A.; Ball, A.S. Challenges and Current Status of the Biological Treatment of PFAS-Contaminated Soils. *Front. Bioeng. Biotechnol.* **2021**, *8*, 602040. [CrossRef] [PubMed]
59. Boahen, E.; Owusu, L.; Adjei-Anim, S.O. A Comprehensive Review of Emerging Environmental Contaminants of Global Concern. *Discov. Environ.* **2025**, *3*, 144. [CrossRef]
60. Elgallal, M.M.; Fletcher, L.; Evans, B. Assessment of Potential Risks Associated with Chemicals in Wastewater Used for Irrigation in Arid and Semiarid Zones: A Review. *Agric. Water Manag.* **2016**, *177*, 419–431. [CrossRef]
61. Ganthavee, V.; Trzcinski, A.P. Artificial Intelligence and Machine Learning for the Optimization of Pharmaceutical Wastewater Treatment Systems: A Review. *Environ. Chem. Lett.* **2024**, *22*, 2293–2318. [CrossRef]
62. Pârvulescu, V.I.; Epron, F.; García, H.; Granger, P. Recent Progress and Prospects in Catalytic Water Treatment. *Chem. Rev.* **2021**, *122*, 2981–3121. [CrossRef] [PubMed]

63. Narayanan, I.; Rajamanickam, R.; Singh, R.; Singh, P.; Prabhu, A.A.; Pandey, A.K.; Pradhan, N.; Nancharaiah, Y.V.; Kumar, V.; Selvasembian, R.; et al. Microalgae-Based Remediation of Pharmaceutical Contaminants: Emerging Strategies and Technological Synergies. *Discov. Appl. Sci.* **2025**, *7*, 1288. [CrossRef]
64. Cheng, D.L.; Ngo, H.H.; Guo, W.; Chang, S.W.; Nguyen, D.D.; Kumar, S.M. Microalgae Biomass from Swine Wastewater and Its Conversion to Bioenergy. *Bioresour. Technol.* **2018**, *275*, 109–122. [CrossRef] [PubMed]
65. Langbehn, R.K.; Müller, F.M.; Schneider, E.E.; Senna, C.P.; Sanches-Simões, E.; Gutkoski, J.P.; Kelbert, M.; Michels, C.; Soares, H.M. Treatment Approaches for Emerging Contaminants in Sludge and Wastewater. In *IWA Publishing eBooks*; UWA Publishing: Perth, Australia, 2024; pp. 113–134.
66. Tawfik, A.; Mohsen, M.; Ismail, S.; Alhajeri, N.S.; Osman, A.I.; Rooney, D.W. Methods to Alleviate the Inhibition of Sludge Anaerobic Digestion by Emerging Contaminants: A Review. *Environ. Chem. Lett.* **2022**, *20*, 3811–3836. [CrossRef]
67. Avila, R.; Peris, A.; Eljarrat, E.; Vicent, T.; Blánquez, P. Biodegradation of Hydrophobic Pesticides by Microalgae: Transformation Products and Impact on Algae Biochemical Methane Potential. *Sci. Total Environ.* **2020**, *754*, 142114. [CrossRef] [PubMed]
68. Goh, P.S.; Lau, W.J.; Ismail, A.F.; Samawati, Z.; Liang, Y.Y.; Kanakaraju, D. Microalgae-Enabled Wastewater Treatment: A Sustainable Strategy for Bioremediation of Pesticides. *Water* **2022**, *15*, 70. [CrossRef]
69. Pathak, V.M.; Verma, V.; Rawat, B.; Kaur, B.; Babu, N.; Sharma, A.; Dewali, S.; Yadav, M.; Kumari, R.; Singh, S.; et al. Current Status of Pesticide Effects on Environment, Human Health and It's Eco-Friendly Management as Bioremediation: A Comprehensive Review. *Front. Microbiol.* **2022**, *13*, 962619. [CrossRef] [PubMed]
70. Akmukhanova, N.R.; Seiilbek, S.N.; Zayadan, B.K.; Bolatkhan, K.; Bakytzhan, R.A.; Domash, G.S.; Bruce, B.D. Harnessing Microalgae and Cyanobacteria for Sustainable Pesticide Biodegradation: Advances, Challenges, and Ecological Benefits. *Microorganisms* **2025**, *13*, 2404. [CrossRef] [PubMed]
71. García-Galán, M.J.; Monllor-Alcaraz, L.S.; Postigo, C.; Uggetti, E.; de Alda, M.L.; Díez-Montero, R.; García, J. Microalgae-Based Bioremediation of Water Contaminated by Pesticides in Peri-Urban Agricultural Areas. *Environ. Pollut.* **2020**, *265*, 114579. [CrossRef] [PubMed]
72. Webster, L.J.; Villa-Gomez, D.; Brown, R.B.; Clarke, W.; Schenk, P.M. A Synthetic Biology Approach for the Treatment of Pollutants with Microalgae. *Front. Bioeng. Biotechnol.* **2024**, *12*, 1379301. [CrossRef] [PubMed]
73. Mérida, L.G.R.; Padrón, R.A.R. Application of Microalgae in Wastewater: Opportunity for Sustainable Development. *Front. Environ. Sci.* **2023**, *11*, 1238640. [CrossRef]
74. Yu, B.S.; Pyo, S.; Lee, J.; Han, K. Microalgae: A Multifaceted Catalyst for Sustainable Solutions in Renewable Energy, Food Security, and Environmental Management. *Microb. Cell Fact.* **2024**, *23*, 308. [CrossRef] [PubMed]
75. Rotter, A.; Barbier, M.; Bertoni, F.; Bones, A.M.; Cancela, M.L.; Carlsson, J.; Carvalho, M.F.; Cegłowska, M.; Chirivella-Martorell, J.; Dalay, M.C.; et al. The Essentials of Marine Biotechnology. *Front. Mar. Sci.* **2021**, *8*, 629629. [CrossRef]
76. Gao, N.; Ning, R.; Deng, X. Feasibility, Challenges, and Future Prospects of Microalgae-Based Bioremediation Technique for Removing Microplastics from Wastewater. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1288439. [CrossRef] [PubMed]
77. Hasnain, M.; Zainab, R.; Ali, F.; Abideen, Z.; Yong, J.W.H.; El-Keblawy, A.; Hashmi, S.; Radicetti, E. Utilization of Microalgal-Bacterial Energy Nexus Improves CO_2 Sequestration and Remediation of Wastewater Pollutants for Beneficial Environmental Services. *Ecotoxicol. Environ. Saf.* **2023**, *267*, 115646. [CrossRef] [PubMed]
78. Khairuddin, N.F.M.; Khan, N.A.; Sankaran, S.; Farooq, W.; Ahmad, I.; Aljundi, I.H. Produced Water Treatment by Semi-Continuous Sequential Bioreactor and Microalgae Photobioreactor. *Bioresour. Bioprocess.* **2024**, *11*, 56. [CrossRef]
79. Singh, S.; Dwivedi, K.; Mallick, R.; Gupta, S.; Shrestha, K.; Tripathi, V.; Shukla, N. Microalgae-Based Wastewater Treatment and Production of Value Added Products. In *Nature-Based Solutions for Remediation of Emerging Pollutants in Wastewater*; CRC Press: Boca Raton, FL, USA, 2026; pp. 150–177.
80. Bellido-Pedraza, C.M.; Torres, M.J.; Llamas, Á. The Microalgae Chlamydomonas for Bioremediation and Bioproduct Production. *Cells* **2024**, *13*, 1137. [CrossRef]
81. López-Pacheco, I.Y.; Silva-Núñez, A.; García-Pérez, J.S.; Carrillo-Nieves, D.; Salinas-Salazar, C.; Castillo-Zacarías, C.; Afewerki, S.; Barceló, D.; Iqbal, H.M.N.; Parra-Saldívar, R. Phyco-Remediation of Swine Wastewater as a Sustainable Model Based on Circular Economy. *J. Environ. Manag.* **2020**, *278*, 111534. [CrossRef] [PubMed]
82. Mohsenpour, S.F.; Hennige, S.; Willoughby, N.; Adeloye, A.J.; Gutiérrez, T. Integrating Micro-Algae into Wastewater Treatment: A Review. *Sci. Total. Environ.* **2020**, *752*, 142168. [CrossRef] [PubMed]
83. Nguyen, L.T.; Aditya, L.; Vu, H.P.; Johir, A.H.; Bennar, L.; Ralph, P.J.; Hoang, N.B.; Zdarta, J.; Nghiem, L.D. Nutrient Removal by Algae-Based Wastewater Treatment. *Curr. Pollut. Rep.* **2022**, *8*, 369–383. [CrossRef]
84. Refaay, D.A.; Hussein, M.H.; Abdel-Hamid, M.I.; Shabaan, S.A.; Mohammad, D.M. Biopolymer Treatment of Ammonium-Rich Industrial Effluents for the Mass Cultivation of Microalgae. *J. Appl. Phycol.* **2022**, *34*, 1931–1941. [CrossRef]
85. Kholssi, R.; Ramos, P.V.; Marks, E.A.N.; Montero, O.; Rad, C. 2Biotechnological Uses of Microalgae: A Review on the State of the Art and Challenges for the Circular Economy. *Biocatal. Agric. Biotechnol.* **2021**, *36*, 102114. [CrossRef]

86. Huang, Y.; Yu, J.; Huang, X.; Sun, J.; Tang, W.; Wei, M.; Gan, Y.; Fu, Y. Algal-Bacterial Symbiotic System for Treatment of Heavy Metal Containing Wastewater: Performance, Mechanisms and Applications. *npj Clean Water* **2025**, *8*, 86. [CrossRef]
87. Allen, J.D.; Unlu, S.; Demirel, Y.; Black, P.N.; Riekhof, W.R. Integration of Biology, Ecology and Engineering for Sustainable Algal-Based Biofuel and Bioproduct Biorefinery. *Bioresour. Bioprocess.* **2018**, *5*, 47. [CrossRef]
88. Chen, Y.; Xu, C.; Vaidyanathan, S. Microalgae: A Robust "Green Bio-Bridge" between Energy and Environment. *Crit. Rev. Biotechnol.* **2017**, *38*, 351–368. [CrossRef] [PubMed]
89. Zheng, Q.; Ning, R.; Zhang, M.; Deng, X. Biofuel Production as a Promising Way to Utilize Microalgae Biomass Derived from Wastewater: Progress, Technical Barriers, and Potential Solutions. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1250407. [CrossRef] [PubMed]
90. Sarwer, A.; Hamed, S.M.; Osman, A.I.; Jamil, F.; Al-Muhtaseb, A.H.; Alhajeri, N.S.; Rooney, D.W. Algal Biomass Valorization for Biofuel Production and Carbon Sequestration: A Review. *Environ. Chem. Lett.* **2022**, *20*, 2797–2851. [CrossRef]
91. Celente, G.d.S.; Schneider, R.d.C.d.S.; Rizzetti, T.M.; Lobo, E.A.; Sui, Y. Using Wastewater as a Cultivation Alternative for Microalga Dunaliella Salina: Potentials and Challenges. *Sci. Total Environ.* **2023**, *911*, 168812. [CrossRef] [PubMed]
92. Vonshak, A.V.; Borowitzka, M.A.; Borowitzka, L. *Microalgal Biotechnology*; Cambridge University Press: Cambridge, UK, 1988.
93. Vo, H.N.P.; Ngo, H.H.; Guo, W.; Chang, S.W.; Nguyen, D.D.; Chen, Z.; Wang, X.C.; Chen, R.; Zhang, X. Microalgae for Saline Wastewater Treatment: A Critical Review. *Crit. Rev. Environ. Sci. Technol.* **2019**, *50*, 1224–1265. [CrossRef]
94. Elangovan, B.; Detchanamurthy, S.; Raja, V.K.; Vijayakumar, S. Waste to Wealth: Phycoremediation of Saline Wastewater From the Food Processing Industry Using Dunaliella Salina to Produce Beta-Carotene in High Rate Algal Ponds. *Environ. Qual. Manag.* **2025**, *35*, e70112. [CrossRef]
95. Pang, N.; Bergeron, A.D.; Gu, X.; Fu, X.; Dong, T.; Yao, Y.; Chen, S. Recycling of Nutrients from Dairy Wastewater by Extremophilic Microalgae with High Ammonia Tolerance. *Environ. Sci. Technol.* **2020**, *54*, 15366–15375. [CrossRef] [PubMed]
96. Nitsos, C.; Filali, R.; Taidi, B.; Lemaire, J. Current and Novel Approaches to Downstream Processing of Microalgae: A Review. *Biotechnol. Adv.* **2020**, *45*, 107650. [CrossRef] [PubMed]
97. Beacham, T.A.; Sweet, J.; Allen, M.J. Large Scale Cultivation of Genetically Modified Microalgae: A New Era for Environmental Risk Assessment. *Algal Res.* **2017**, *25*, 90–100. [CrossRef]
98. Geremia, E.; Ripa, M.; Catone, C.M.; Ulgiati, S. A Review about Microalgae Wastewater Treatment for Bioremediation and Biomass Production—A New Challenge for Europe. *Environments* **2021**, *8*, 136. [CrossRef]
99. Banerjee, A.; Sarkar, S.; Govil, T.; González-Faune, P.; Cabrera-Barjas, G.; Bandopadhyay, R.; Salem, D.R.; Sani, R.K. Extremophilic Exopolysaccharides: Biotechnologies and Wastewater Remediation. *Front. Microbiol.* **2021**, *12*, 721365. [CrossRef] [PubMed]
100. Retta, B.; Iovinella, M.; Ciniglia, C. Significance and Applications of the Thermo-Acidophilic Microalga Galdieria Sulphuraria (Cyanidiophytina, Rhodophyta). *Plants* **2024**, *13*, 1786. [CrossRef] [PubMed]
101. Soleimani-Sardo, M.; Khanjani, M.H. Utilization of Unconventional Water Resources (UWRs) for Aquaculture Development in Arid and Semi-Arid Regions—A Review. *Ann. Anim. Sci.* **2022**, *23*, 11–23. [CrossRef]
102. Gupta, A.; Kang, K.; Pathania, R.; Saxton, L.; Saucedo, B.; Malik, A.; Torres-Tiji, Y.; Diaz, C.J.; Molino, J.V.D.; Mayfield, S.P. Harnessing Genetic Engineering to Drive Economic Bioproduct Production in Algae. *Front. Bioeng. Biotechnol.* **2024**, *12*, 1350722. [CrossRef] [PubMed]
103. Vítová, M.; Mezricky, D. Microbial Recovery of Rare Earth Elements from Various Waste Sources: A Mini Review with Emphasis on Microalgae. *World J. Microbiol. Biotechnol.* **2024**, *40*, 189. [CrossRef] [PubMed]
104. Puzorjov, A.; McCormick, A.J. Phycobiliproteins from Extreme Environments and Their Potential Applications. *Edinb. Res. Explor.* **2020**, *71*, 3827–3842. [CrossRef] [PubMed]
105. Cadoret, J.; Garnier, M.; Saint-Jean, B. Microalgae, Functional Genomics and Biotechnology. In *Advances in Botanical Research*; Elsevier BV: Amsterdam, The Netherlands, 2012; pp. 285–341.
106. Vadiveloo, A.; Ishika, T.; Chuka-Ogwude, D.; Raeisossadati, M.; Matos, Â.P. Algae from Extremophilic Conditions and Their Potential Applications. In *Algal Biorefineries and the Circular Bioeconomy*; CRC Press: Boca Raton, FL, USA, 2022; pp. 303–339.
107. Bagchi, S.K.; Patnaik, R.; Navneet, S.; Prasad, R. Extremophilic Microalgae. In *Extremophiles*; Springer Science+Business Media: Berlin/Heidelberg, Germany, 2023; pp. 151–166.
108. Fu, H.; Wang, M. Ascorbate Peroxidase Plays an Important Role in Photoacclimation in the Extremophilic Red Alga Cyanidiococcus Yangmingshanensis. *Front. Plant Sci.* **2023**, *14*, 1176985. [CrossRef] [PubMed]
109. Villegas-Valencia, M.; González-Portela, R.E.; de Freitas, B.B.; Jahdali, A.A.; Romero-Villegas, G.I.; Malibari, R.; Kapoore, R.V.; Fuentes-Grünewald, C.; Lauersen, K.J. Cultivation of the Polyextremophile Cyanidioschyzon Merolae 10D during Summer Conditions on the Coast of the Red Sea and Its Adaptation to Hypersaline Sea Water. *Front. Microbiol.* **2023**, *14*, 1157151. [CrossRef] [PubMed]
110. Sarmiento, F.; Peralta, R.; Blamey, J.M. Cold and Hot Extremozymes: Industrial Relevance and Current Trends. *Front. Bioeng. Biotechnol.* **2015**, *3*, 148. [CrossRef] [PubMed]

111. Yadav, A.N.; Kumar, A.; Kumar, S.; Kumar, V.; Sugitha, T.; Singh, B.; Chauahan, V.; Dhaliwal, H.S.; Saxena, A.K. Beneficial Microbiomes: Biodiversity and Potential Biotechnological Applications for Sustainable Agriculture and Human Health. *J. Appl. Biol. Biotechnol.* **2017**, *5*, 45–57. [CrossRef]
112. Julian, G.; Gerhard, D. *Life in Extreme Environments*; Cambridge University Press: Cambridge, UK, 2020.
113. Najjari, A. *Life in Extreme Environments—Diversity, Adaptability and Valuable Resources of Bioactive Molecules*; IntechOpen: London, UK, 2023.
114. Sysoev, M.; Grötzinger, S.W.; Renn, D.; Eppinger, J.; Rueping, M.; Karan, R. Bioprospecting of Novel Extremozymes From Prokaryotes—The Advent of Culture-Independent Methods. *Front. Microbiol.* **2021**, *12*, 630013. [CrossRef] [PubMed]
115. Holbrook, G.P.; Davidson, Z.; Tatara, R.A.; Ziemer, N.; Rosentrater, K.A.; Grayburn, W.S. Use of the Microalga *Monoraphidium* sp. Grown in Wastewater as a Feedstock for Biodiesel: Cultivation and Fuel Characteristics. *Appl. Energy* **2014**, *131*, 386–393. [CrossRef]
116. Schulze, P.S.C.; Hulatt, C.J.; Morales-Sánchez, D.; Wijffels, R.H.; Kiron, V. Fatty Acids and Proteins from Marine Cold Adapted Microalgae for Biotechnology. *Algal Res.* **2019**, *42*, 101604. [CrossRef]
117. Ali, N.; Nughman, M.; Shah, S.M. Extremophiles and Limits of Life in a Cosmic Perspective. In *IntechOpen eBooks*; IntechOpen: London, UK, 2023.
118. Martínez-Espinosa, R.M. Halophilic Archaea as Tools for Bioremediation Technologies. *Appl. Microbiol. Biotechnol.* **2024**, *108*, 401. [CrossRef] [PubMed]
119. Collins, T.; Margesin, R. Psychrophilic Lifestyles: Mechanisms of Adaptation and Biotechnological Tools. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 2857–2871. [CrossRef] [PubMed]
120. Ayilara, M.S.; Babalola, O.O. Bioremediation of Environmental Wastes: The Role of Microorganisms. *Front. Agron.* **2023**, *5*, 1183691. [CrossRef]
121. Chen, D.; Li, Z.; Shi, J.; Suen, H.; Zheng, X.; Zhang, C.; Chen, Y.; Xue, T. Genomics and Transcriptomics Reveal β-Carotene Synthesis Mechanism in Dunaliella Salina. *Front. Microbiol.* **2024**, *15*, 1389224. [CrossRef] [PubMed]
122. Durvasula, R.; Rao, D.V.S.; Rao, V. Microalgal Biotechnology. In *Biotechnological Applications of Microalgae*; CRC Press: Boca Raton, FL, USA, 2013; pp. 201–228.
123. Jacob-Lopes, E.; Zepka, L.Q.; Queiroz, M.I. *Microalgal Biotechnology*; IntechOpen: London, UK, 2018.
124. Sauvage, J.; Wikfors, G.H.; Sabbe, K.; Nevejan, N.; Goderis, S.; Claeys, P.; Li, X.; Joyce, A. Biodegradable, Metal-Chelating Compounds as Alternatives to EDTA for Cultivation of Marine Microalgae. *J. Appl. Phycol.* **2021**, *33*, 3519–3537. [CrossRef]
125. Malekmohammadi, L. Haloculture in a Changing World: A Comprehensive Review on Sustainable Agriculture, Saline Water Resource Management, and Future Prospects under Water Scarcity and Climate Change Conditions. *Appl. Water Sci.* **2025**, *15*, 289. [CrossRef]
126. Chen, Y.; Song, C.; Cui, X.; Han, J.; Paithoonrangsarid, K.; Gan, Q.; Lu, Y. Halophilic Microalga-Based Circular Economy Producing Functional Food by Reclaiming High-Salinity Seafood Processing Sewage. *Biomass Bioenergy* **2023**, *178*, 106952. [CrossRef]
127. Abiusi, F.; Trompetter, E.; Pollio, A.; Wijffels, R.H.; Janssen, M. Acid Tolerant and Acidophilic Microalgae: An Underexplored World of Biotechnological Opportunities. *Front. Microbiol.* **2022**, *13*, 820907. [CrossRef] [PubMed]
128. Venugopal, V.; Sasidharan, A.; Rustad, T. Green Chemistry to Valorize Seafood Side Streams: An Ecofriendly Roadmap toward Sustainability. *J. Agric. Food Chem.* **2023**, *71*, 17494–17509. [CrossRef] [PubMed]
129. Ñancucheo, I.; Johnson, D.B. Acidophilic Algae Isolated from Mine-Impacted Environments and Their Roles in Sustaining Heterotrophic Acidophiles. *Front. Microbiol.* **2012**, *3*, 325. [CrossRef] [PubMed]
130. Paladino, O.; Neviani, M. Interchangeable Modular Design and Operation of Photo-Bioreactors for Chlorella Vulgaris Cultivation towards a Zero-Waste Biorefinery. *Enzym. Microb. Technol.* **2023**, *173*, 110371. [CrossRef] [PubMed]
131. Guihéneuf, F.; Khan, A.A.; Tran, L.P. Genetic Engineering: A Promising Tool to Engender Physiological, Biochemical, and Molecular Stress Resilience in Green Microalgae. *Front. Plant Sci.* **2016**, *7*, 400. [CrossRef] [PubMed]
132. Ogundele, O.D.; Adewumi, A.J.; Oyegoke, D.A. Phycoremediation: Algae as an Effective Agent for Sustainable Remediation and Waste Water Treatment. *Environ. Earth Sci. Res. J.* **2023**, *10*, 7–17. [CrossRef]
133. Janssen, P.; Lambreva, M.D.; Plumer, N.; Bartolucci, C.; Antonacci, A.; Buonasera, K.; Frese, R.N.; Scognamiglio, V.; Rea, G. Photosynthesis at the Forefront of a Sustainable Life. *Front. Chem.* **2014**, *2*, 36. [CrossRef] [PubMed]
134. Beaulier, C.; Dannay, M.; Devime, F.; Baggio, C.; Sakkout, N.E.; Raillon, C.; Courson, O.; Bourguignon, J.; Alban, C.; Ravanel, S. Characterization of a Uranium-Tolerant Green Microalga of the Genus Coelastrella with High Potential for the Remediation of Metal-Polluted Waters. *Sci. Total Environ.* **2023**, *908*, 168195. [CrossRef]
135. Rivasseau, C.; Farhi, E.; Atteia, A.; Couté, A.; Gromova, M.; Cyr, D.d.G.S.; Boisson, A.; Féret, A.-S.; Compagnon, E.; Bligny, R. An Extremely Radioresistant Green Eukaryote for Radionuclide Bio-Decontamination in the Nuclear Industry. *Energy Environ. Sci.* **2012**, *6*, 1230. [CrossRef]
136. Kim, T.-Y.; Hong, J.E.; Park, H.M.; Lee, U.J.; Lee, S.-Y. Decontamination of Low-Level Contaminated Water from Radioactive Cesium and Cobalt Using Microalgae. *J. Radioanal. Nucl. Chem.* **2020**, *323*, 903–908. [CrossRef]

137. Malavasi, V.; Soru, S.; Cao, G. Extremophile Microalgae: The Potential for Biotechnological Application. *J. Phycol.* **2020**, *56*, 559–573. [CrossRef] [PubMed]
138. Kumar, G.; Shekh, A.; Jakhu, S.; Sharma, Y.; Kapoor, R.; Sharma, T.R. Bioengineering of Microalgae: Recent Advances, Perspectives, and Regulatory Challenges for Industrial Application. *Front. Bioeng. Biotechnol.* **2020**, *8*, 914. [CrossRef] [PubMed]
139. Rivasseau, C.; Farhi, E.; Compagnon, E.; Cyr, D.d.G.S.; van Lis, R.; Falconet, D.; Kuntz, M.; Atteia, A.; Couté, A. Coccomyxa Actinabiotis Sp. Nov. (Trebouxiophyceae, Chlorophyta), a New Green Microalga Living in the Spent Fuel Cooling Pool of a Nuclear Reactor. *J. Phycol.* **2016**, *52*, 689–703. [CrossRef] [PubMed]
140. Singh, M.; Trivedi, N.; Mal, N.; Mehariya, S. Extremophilic Microalgae as a Potential Source of High-Value Bioproducts. In *Extremophiles*; Springer Science+Business Media: Berlin/Heidelberg, Germany, 2023; pp. 167–186.
141. Shah, M.M.R.; Liang, Y.; Cheng, J.J.; Daroch, M. Astaxanthin-Producing Green Microalga Haematococcus Pluvialis: From Single Cell to High Value Commercial Products. *Front. Plant Sci.* **2016**, *7*, 531. [CrossRef] [PubMed]
142. Benedetti, M.; Vecchi, V.; Barera, S.; Dall'Osto, L. Biomass from Microalgae: The Potential of Domestication towards Sustainable Biofactories. *Microb. Cell Fact.* **2018**, *17*, 173. [CrossRef] [PubMed]
143. Occhipinti, P.S.; Russo, N.; Foti, P.; Zingale, I.M.; Pino, A.; Romeo, F.V.; Randazzo, C.L.; Caggia, C. Current Challenges of Microalgae Applications: Exploiting the Potential of Non-conventional Microalgae Species. *J. Sci. Food Agric.* **2023**, *104*, 3823–3833. [CrossRef] [PubMed]
144. Alzahmi, A.; Daakour, S.; Nelson, D.R.; Al-Khairy, D.; Twizere, J.; Salehi-Ashtiani, K. Enhancing Algal Production Strategies: Strain Selection, AI-Informed Cultivation, and Mutagenesis. *Front. Sustain. Food Syst.* **2024**, *8*, 1331251. [CrossRef]
145. Verdev, P.T.; Dolinar, M. A Pipeline for the Isolation and Cultivation of Microalgae and Cyanobacteria from Hypersaline Environments. *Microorganisms* **2025**, *13*, 603. [CrossRef] [PubMed]
146. Genuário, D.B.; Vaz, M.G.M.V.; Hentschke, G.S.; Sant'Anna, C.L.; Fiore, M.F. Halotia Gen. Nov., a Phylogenetically and Physiologically Coherent Cyanobacterial Genus Isolated from Marine Coastal Environments. *Int. J. Syst. Evol. Microbiol.* **2014**, *65*, 663–675. [CrossRef] [PubMed]
147. Schultz, J.; Modolon, F.; Peixoto, R.S.; Rosado, A.S. Shedding Light on the Composition of Extreme Microbial Dark Matter: Alternative Approaches for Culturing Extremophiles. *Front. Microbiol.* **2023**, *14*, 1167718. [CrossRef] [PubMed]
148. Wang, M.; Ye, X.; Bi, H.; Shen, Z. Microalgae Biofuels: Illuminating the Path to a Sustainable Future amidst Challenges and Opportunities. *Biotechnol. Biofuels Bioprod.* **2024**, *17*, 10. [CrossRef] [PubMed]
149. Tan, F.H.P.; Nadir, N.; Sudesh, K. Microalgal Biomass as Feedstock for Bacterial Production of PHA: Advances and Future Prospects. *Front. Bioeng. Biotechnol.* **2022**, *10*, 879476. [CrossRef] [PubMed]
150. Esteves, A.F.; Gonçalves, A.L.; Vilar, V.J.P.; Pires, J.C.M. Is It Possible to Shape the Microalgal Biomass Composition with Operational Parameters for Target Compound Accumulation? *Biotechnol. Adv.* **2024**, *79*, 108493. [CrossRef] [PubMed]
151. Yadav, A.; Sharma, S.C.; Nitesh; Meena, R.S.; Bhardwaj, R.; Swapnil, P.; Meena, M. Tapping the Microalgal Potential: Genetic Precision and Stress-Induction for Enhanced Astaxanthin and Biofuel Production. *Biotechnol. Biofuels Bioprod.* **2025**, *18*, 92. [CrossRef] [PubMed]
152. Zhang, S.; Zhang, L.G.; Geng, X.; Li, F.; Li, X. A Review on Biodiesel Production from Microalgae: Influencing Parameters and Recent Advanced Technologies. *Front. Microbiol.* **2022**, *13*, 970028. [CrossRef] [PubMed]
153. El-fayoumy, E.A.; Ali, H.E.A.; Elsaid, K.; Elkhatat, A.M.; Al-Meer, S.; Rozaini, M.Z.H.; Abdullah, M.A. Co-Production of High Density Biomass and High-Value Compounds via Two-Stage Cultivation of Chlorella Vulgaris Using Light Intensity and a Combination of Salt Stressors. *Biomass Convers. Biorefinery* **2023**, *14*, 22673–22686. [CrossRef]
154. Minhas, A.K.; Hodgson, P.; Barrow, C.J.; Adholeya, A. A Review on the Assessment of Stress Conditions for Simultaneous Production of Microalgal Lipids and Carotenoids. *Front. Microbiol.* **2016**, *7*, 546. [CrossRef] [PubMed]
155. Sun, X.; Ren, L.; Zhao, Q.; Ji, X.; Huang, H. Microalgae for the Production of Lipid and Carotenoids: A Review with Focus on Stress Regulation and Adaptation. *Biotechnol. Biofuels* **2018**, *11*, 272. [CrossRef] [PubMed]
156. Narendra, M.V.; Shakti, M.; Amitesh, S.; Mishra, B.N. Prospective of Biodiesel Production Utilizing Microalgae as the Cell Factories: A Comprehensive Discussion. *Afr. J. Biotechnol.* **2010**, *9*, 1402–1411. [CrossRef]
157. Kumar, R.; Kundu, D.; Kormoker, T.; Joshi, S.; Rose, P.K.; Kumar, S.; Sahoo, P.K.; Sharma, P.; Lamba, J. Phycoremediation of Potentially Toxic Elements for Agricultural and Industrial Wastewater Treatment: Recent Advances, Challenges, and Future Prospects. *Desalin. Water Treat.* **2024**, *319*, 100505. [CrossRef]
158. Morillas-España, A.; López-Serna, R.; Chikri, L.Y.R.; Jiménez, J.J.; Lafarga, T.; Uggetti, E.; Acién, F.G.; González–López, C.V. Microalgae Wastewater Treatment: Pharmaceutical Removal and Biomass Valorization. *J. Environ. Manag.* **2025**, *380*, 124942. [CrossRef] [PubMed]
159. Gentili, F.G.; Fick, J. Algal Cultivation in Urban Wastewater: An Efficient Way to Reduce Pharmaceutical Pollutants. *J. Appl. Phycol.* **2016**, *29*, 255–262. [CrossRef] [PubMed]
160. Ferro, L.; Gorzsás, A.; Gentili, F.G.; Funk, C. Subarctic Microalgal Strains Treat Wastewater and Produce Biomass at Low Temperature and Short Photoperiod. *Algal Res.* **2018**, *35*, 160–167. [CrossRef]

161. Leng, Y.; Li, Y.; Meng, F.; Sun, W. Diatom Chaetoceros Calcitarans MZB-1 for Degrading Propylbenzenes in Seawater: Cultivation Conditions, Degradation Kinetics, and Influencing Factors. *Mar. Environ. Res.* **2025**, *208*, 107154. [CrossRef] [PubMed]
162. García, N.E.S.; Rodríguez, R.; Vicente, G.; Espada, J.J.; Bautista, L.F. Comprehensive Study on Endocrine Disruptor Removal from Wastewater Using Different Microalgae Species. *Appl. Sci.* **2024**, *15*, 132. [CrossRef]
163. Sheraz, N.; Shah, A.; Haleem, A.; Iftikhar, F.J. Comprehensive Assessment of Carbon-, Biomaterial- and Inorganic-Based Adsorbents for the Removal of the Most Hazardous Heavy Metal Ions from Wastewater. *RSC Adv.* **2024**, *14*, 11284–11310. [CrossRef] [PubMed]
164. Alabssawy, A.N.; Hashem, A.H. Bioremediation of Hazardous Heavy Metals by Marine Microorganisms: A Recent Review. *Arch. Microbiol.* **2024**, *206*, 103. [CrossRef] [PubMed]
165. Hui, C. From Bioadsorption to Biotransformation: A Hypothesis for Mercury Bioremediation Using Genetically Modified Microalgae. *Front. Microbiol.* **2026**, *17*, 1724533. [CrossRef] [PubMed]
166. Nyika, J.; Dinka, M.O. Factors and Mechanisms Regulating Heavy Metal Phycoremediation in Polluted Water. *Discov. Water* **2023**, *3*, 14. [CrossRef]
167. Mustafa, S.; Bhatti, H.N.; Maqbool, M.; Iqbal, M. Microalgae Biosorption, Bioaccumulation and Biodegradation Efficiency for the Remediation of Wastewater and Carbon Dioxide Mitigation: Prospects, Challenges and Opportunities. *J. Water Process Eng.* **2021**, *41*, 102009. [CrossRef]
168. Kharel, H.L.; Tan, M.; Jha, L.J.; Selvaratnam, T. Removal of Cadmium (II), Lead (II), Nickel (II), and Zinc (II) from Synthetic Medium by Extremophile Red Alga Galdieria Sulphuraria: Investigating Single and Mixed Metal Systems. *Algal Res.* **2024**, *83*, 103699. [CrossRef]
169. Puente-Sánchez, F.; Díaz-Cruz, M.S.; Penacho, V.; Aguilera, Á.; Olsson, S. Basis of Genetic Adaptation to Heavy Metal Stress in the Acidophilic Green Alga Chlamydomonas Acidophila. *Aquat. Toxicol.* **2018**, *200*, 62–72. [CrossRef] [PubMed]
170. Santiago-Martínez, M.G.; Lira-Silva, E.; Encalada, R.; Pineda, E.; Gallardo-Pérez, J.C.; Zepeda-Rodríguez, A.; Moreno-Sánchez, R.; Saavedra, E.; Jasso-Chávez, R. Cadmium Removal by Euglena Gracilis Is Enhanced under Anaerobic Growth Conditions. *J. Hazard. Mater.* **2015**, *288*, 104–112. [CrossRef] [PubMed]
171. Abinandan, S.; Subashchandrabose, S.R.; Panneerselvan, L.; Venkateswarlu, K.; Megharaj, M. Potential of Acid-Tolerant Microalgae, *Desmodesmus* sp. MAS1 and *Heterochlorella* sp. MAS3, in Heavy Metal Removal and Biodiesel Production at Acidic pH. *Bioresour. Technol.* **2019**, *278*, 9–16. [CrossRef] [PubMed]
172. Kandasamy, S.; Narayanan, M.; He, Z.; Liu, G.; Ramakrishnan, M.; Thangavel, P.; Pugazhendhi, A.; Raja, R.; Carvalho, I.S. Current Strategies and Prospects in Algae for Remediation and Biofuels: An Overview. *Biocatal. Agric. Biotechnol.* **2021**, *35*, 102045. [CrossRef]
173. Chalkley, R.; Child, F.; Al-Thaqafi, K.; Dean, A.P.; White, K.N.; Pittman, J.K. Macroalgae as Spatial and Temporal Bioindicators of Coastal Metal Pollution Following Remediation and Diversion of Acid Mine Drainage. *Ecotoxicol. Environ. Saf.* **2019**, *182*, 109458. [CrossRef] [PubMed]
174. Cheng, Y.-R.; Wang, H. Highly Effective Removal of Microplastics by Microalgae Scenedesmus Abundans. *Chem. Eng. J.* **2022**, *435*, 135079. [CrossRef]
175. Zhang, T.; Wang, J.; Liu, D.; Sun, Z.; Tang, R.; Ma, X.; Feng, Z. Loading of Microplastics by Two Related Macroalgae in a Sea Area Where Gold and Green Tides Occur Simultaneously. *Sci. Total Environ.* **2022**, *814*, 152809. [CrossRef] [PubMed]
176. Li, Q.; Feng, Z.; Zhang, T.; Ma, C.; Shi, H. Microplastics in the Commercial Seaweed Nori. *J. Hazard. Mater.* **2020**, *388*, 122060. [CrossRef] [PubMed]
177. Nielsen, B.V.; Maneein, S.; Anghan, J.D.; Anghan, R.M.; Farid, M.M.A.; Milledge, J.J. Biosorption Potential of Sargassum for Removal of Aqueous Dye Solutions. *Appl. Sci.* **2022**, *12*, 4173. [CrossRef]
178. El-Agawany, N.I.; Abdel-Razik, S.A.R.; Abdel-Kareem, M.S.; Kaamoush, M. Environmental Performance of Two Marine Algae Ulva Fasciata and Pterocladia Capillacea in the Biological Treatment of Four Reactive Dyes from Aqueous Solutions Based on Fresh and Dried Biomass. *Appl. Water Sci.* **2023**, *13*, 82. [CrossRef]
179. Pandey, A.; Kant, G.J.; Chaudhary, A.; Amesho, K.T.T.; Reddy, K.L.; Bux, F. Axenic Green Microalgae for the Treatment of Textile Effluent and the Production of Biofuel: A Promising Sustainable Approach. *World J. Microbiol. Biotechnol.* **2024**, *40*, 81. [CrossRef] [PubMed]
180. Zou, Z.; Li, M.; He, S.; Zhou, Z.; Tian, J.; Cai, B.; Lu, Y.; Dai, Z.; Zhu, X.; Han, Z.; et al. Multifunctionalized Immobilized Microalgae Technologies for Application in Advanced Environmental Remediation Systems. *Trans. Tianjin Univ.* **2026**, *32*, 36–63. [CrossRef]
181. Guo, W.-Q.; Zheng, H.-S.; Li, S.; Du, J.-S.; Feng, X.; Yin, R.; Wu, Q.; Ren, N.-Q.; Chang, J. Removal of Cephalosporin Antibiotics 7-ACA from Wastewater during the Cultivation of Lipid-Accumulating Microalgae. *Bioresour. Technol.* **2016**, *221*, 284–290. [CrossRef] [PubMed]
182. Satya, A.; Harimawan, A.; Haryani, G.S.; Johir, M.A.H.; Vigneswaran, S.; Ngo, H.H.; Setiadi, T. Batch Study of Cadmium Biosorption by Carbon Dioxide Enriched *Aphanothece* sp. Dried Biomass. *Water* **2020**, *12*, 264. [CrossRef]

183. Satya, A.; Harimawan, A.; Haryani, G.S.; Setiadi, T. Non-Linear Isotherm Models, Cadmium Kinetics, and Biosorption Thermodynamics of Dried Biomass of Native *Aphanothece* sp. in a Batch System. *J. Eng. Technol. Sci.* **2017**, *49*, 617–638. [CrossRef]
184. Angulo, E.; Bula, L.; Mercado, I.; Montaño, A.M.; Cubillán, N. Bioremediation of Cephalexin with Non-Living *Chlorella* sp., Biomass after Lipid Extraction. *Bioresour. Technol.* **2018**, *257*, 17–22. [CrossRef] [PubMed]
185. Sun, J.Z.; Cheng, J.; Yang, Z.; Li, K.; Zhou, J.; Cen, K. Microstructures and Functional Groups of *Nannochloropsis* sp. Cells with Arsenic Adsorption and Lipid Accumulation. *Bioresour. Technol.* **2015**, *194*, 305–311. [CrossRef] [PubMed]
186. Ortíz-Sánchez, E.; Guillén-Garcés, R.A.; Morales-Arrieta, S.; Okoye, P.U.; Olvera-Vargas, H.; Sebastián, P.J.; Arias, D.M. Cultivation of Carbohydrate-Rich Microalgae with Great Settling Properties Using Cooling Tower Wastewater. *Environ. Sci. Pollut. Res.* **2023**, *31*, 38999–39014. [CrossRef] [PubMed]
187. Saldarriaga-Hernández, S.; Hernández-Vargas, G.; Iqbal, H.M.N.; Barceló, D.; Parra-Saldívar, R. Bioremediation Potential of *Sargassum* sp. Biomass to Tackle Pollution in Coastal Ecosystems: Circular Economy Approach. *Sci. Total Environ.* **2020**, *715*, 136978. [CrossRef] [PubMed]
188. Monteiro, C.M.; Castro, P.M.L.; Malcata, F.X. Metal Uptake by Microalgae: Underlying Mechanisms and Practical Applications. *Biotechnol. Prog.* **2011**, *28*, 299–311. [CrossRef] [PubMed]
189. Crini, G.; Lichtfouse, É.; Wilson, L.D.; Morin-Crini, N. Conventional and Non-Conventional Adsorbents for Wastewater Treatment. *Environ. Chem. Lett.* **2018**, *17*, 195–213. [CrossRef]
190. Zeeshan, Q.M.; Qiu, S.; Jia, G.; Abbew, A.-W.; Wu, Z.; Chen, Z.; Xu, S.; Ge, S. Unravelling Multiple Removal Pathways of Oseltamivir in Wastewater by Microalgae through Experimentation and Computation. *J. Hazard. Mater.* **2021**, *427*, 128139. [CrossRef] [PubMed]
191. Mariano, S.; Panzarini, E.; Inverno, M.D.; Voulvoulis, N.; Dini, L. Toxicity, Bioaccumulation and Biotransformation of Glucose-Capped Silver Nanoparticles in Green Microalgae Chlorella Vulgaris. *Nanomaterials* **2020**, *10*, 1377. [CrossRef] [PubMed]
192. Esteves, F.; Rueff, J.; Kranendonk, M. The Central Role of Cytochrome P450 in Xenobiotic Metabolism—A Brief Review on a Fascinating Enzyme Family. *J. Xenobiotics* **2021**, *11*, 94–114. [CrossRef] [PubMed]
193. Leng, L.; Liang, W.; Xiong, Q.; Xu, S.; Li, W.; Lv, S.; Lu, Q.; Wan, L.; Wen, Z.; Zhou, W. Use of Microalgae Based Technology for the Removal of Antibiotics from Wastewater: A Review. *Chemosphere* **2019**, *238*, 124680. [CrossRef] [PubMed]
194. Oliveira, A.; Alves, M.; Leitão, F.; Tacão, M.; Henriques, I.; Castro, P.M.L.; Amorim, C.L. Bioremediation of Coastal Aquaculture Effluents Spiked with Florfenicol Using Microalgae-Based Granular Sludge—A Promising Solution for Recirculating Aquaculture Systems. *Water Res.* **2023**, *233*, 119733. [CrossRef] [PubMed]
195. Song, C.; Wei, Y.; Qiu, Y.; Yu, Q.; Li, Y.; Kitamura, Y. Biodegradability and Mechanism of Florfenicol via *Chlorella* sp. UTEX1602 and L38: Experimental Study. *Bioresour. Technol.* **2018**, *272*, 529–534. [CrossRef] [PubMed]
196. Gonçalves, A.L.; Pires, J.C.M.; Simões, M. A Review on the Use of Microalgal Consortia for Wastewater Treatment. *Algal Res.* **2016**, *24*, 403–415. [CrossRef]
197. Quijano, G.; Arcila, J.S.; Buitrón, G. Microalgal-Bacterial Aggregates: Applications and Perspectives for Wastewater Treatment. *Biotechnol. Adv.* **2017**, *35*, 772–781. [CrossRef] [PubMed]
198. Li, L.; Gao, K.; Yang, M.; Zheng, Q.; Zhang, M.; Deng, X. Challenges and Potential Solutions of Microalgae-Based Systems for Wastewater Treatment and Resource Recovery. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1210228. [CrossRef] [PubMed]
199. Norvill, Z.N.; Shilton, A.; Guieysse, B. Emerging contaminant degradation and removal in algal wastewater treatment ponds: Identifying the research gaps. *J. Hazard. Mater.* **2016**, *313*, 291–309. [CrossRef] [PubMed]
200. de Wilt, A.; Butkovskyi, A.; Tuantet, K.; Leal, L.H.; Fernandes, T.V.; Langenhoff, A.; Zeeman, G. Micropollutant removal in an algal treatment system fed with source separated wastewater streams. *J. Hazard. Mater.* **2016**, *304*, 84–92. [CrossRef] [PubMed]
201. Reymann, T.; Kerner, M.; Kümmerer, K. Assessment of the Biotic and Abiotic Elimination Processes of Five Micropollutants during Cultivation of the Green Microalgae Acutodesmus obliquus. *Bioresour. Technol. Rep.* **2020**, *11*, 100512. [CrossRef]
202. Headley, J.V.; Peru, K.M.; Du, J.-L.; Gurprasad, N.; McMartin, D.W. Evaluation of the Apparent Phytodegradation of Pentachlorophenol by Chlorella pyrenoidosa. *J. Environ. Sci. Health A* **2008**, *43*, 361–364. [CrossRef] [PubMed]
203. Ben Ouada, S.; Ben Ali, R.; Leboulanger, C.; Ben Ouada, H.; Sayadi, S. Effect of Bisphenol A on the Extremophilic Microalgal Strain Picocystis sp. (Chlorophyta) and Its High BPA Removal Ability. *Ecotoxicol. Environ. Saf.* **2018**, *158*, 1–8. [CrossRef] [PubMed]
204. Ben Ouada, S.; Ben Ali, R.; Cimetière, N.; Leboulanger, C.; Ben Ouada, H.; Sayadi, S. Biodegradation of Diclofenac by Two Green Microalgae: *Picocystis* sp. and *Graesiella* sp. *Ecotoxicol. Environ. Saf.* **2019**, *186*, 109769. [CrossRef] [PubMed]
205. Saini, S.; Tewari, S.; Dwivedi, J.; Sharma, V. Biofilm-Mediated Wastewater Treatment: A Comprehensive Review. *Mater. Adv.* **2023**, *4*, 1415–1443. [CrossRef]
206. Kong, W.; Kong, J.; Feng, S.; Yang, T.; Xu, L.; Shen, B.; Bi, Y.; Lyu, H. Cultivation of Microalgae–Bacteria Consortium by Waste Gas–Waste Water to Achieve CO_2 Fixation, Wastewater Purification and Bioproducts Production. *Biotechnol. Biofuels Bioprod.* **2024**, *17*, 26. [CrossRef] [PubMed]

207. Rasheed, R.N.; Pourbakhtiar, A.; Allaf, M.M.; Baharlooeian, M.; Rafiei, N.; Aratboni, H.A.; Morones-Ramírez, J.R.; Winck, F.V. Microalgal Co-Cultivation -Recent Methods, Trends in Omic-Studies, Applications, and Future Challenges. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1193424. [CrossRef] [PubMed]
208. Patel, A.; Kumar, R. Integration of Natural Biofilters for Optimal Removal of Pollutants and Recovery of Resources from Wastewater: A Comprehensive Review. *Discov. Water* **2025**, *5*, 89. [CrossRef]
209. Remias, D.; Holzinger, A.; Lütz, C. Physiology, ultrastructure and habitat of the ice alga *Mesotaenium berggrenii* (Zygnemaphyceae, Chlorophyta) from glaciers in the European Alps. *Phycologia* **2009**, *48*, 302–312. [CrossRef]
210. Pandey, B.C.; Gupta, S. Effectiveness of Algae in Wastewater Treatment Systems. *Int. J. Res. Appl. Sci. Eng. Technol.* **2022**, *10*, 520–526. [CrossRef]
211. Velasquez-Orta, S.B.; Noguez, I.Y.; Monje–Ramírez, I.; Ledesma, M.T.O. Pilot-Scale Microalgae Cultivation and Wastewater Treatment Using High-Rate Ponds: A Meta-Analysis. *Environ. Sci. Pollut. Res.* **2024**, *31*, 46994–47021. [CrossRef] [PubMed]
212. Vanitha, A.; Narayan, M.S.; Murthy, K.N.C.; Ravishankar, G. Comparative study of lipid composition of two halotolerant alga, Dunaliella bardawil and Dunaliella salina. *Int. J. Food Sci. Nutr.* **2007**, *58*, 373–382. [CrossRef] [PubMed]
213. Nneoma, U.C.; Chukwudi, O.F.; Nnenna, U.J.; Ugwu, O.P.-C. Hybrid Biofactories: Integrating Microalgae and Engineered Microbiomes for Enhanced Biofuel Production in Circular Carbon Systems. *Front. Energy Res.* **2025**, *13*, 1654079. [CrossRef]
214. Arango, J.; Muñoz, R.; Donoso-Bravo, A.; Bernard, O.; Casagli, F.; Jeison, D. A Half-Century of Research on Microalgae-Bacteria for Wastewater Treatment. *Algal Res.* **2022**, *67*, 102828. [CrossRef]
215. Nguyen, L.T.; Kumar, J.P.; Vu, M.T.; Mohammed, J.A.H.; Pathak, N.; Commault, A.S.; Sutherland, D.L.; Zdarta, J.; Tyagi, V.K.; Nghiem, L.D. Biomethane Production from Anaerobic Co-Digestion at Wastewater Treatment Plants: A Critical Review on Development and Innovations in Biogas Upgrading Techniques. *Sci. Total Environ.* **2020**, *765*, 142753. [CrossRef] [PubMed]
216. Rowe, P. Advances in Chemical Engineering. *Chem. Eng. Sci.* **1967**, *22*, 1527. [CrossRef]
217. Hedden, K. Advances in Chemical Engineering. *Z. Phys. Chem.* **1963**, *36*, 252–253. [CrossRef]
218. Almomani, F.; Ketife, A.A.; Judd, S.; Shurair, M.; Bhosale, R.R.; Znad, H.; Tawalbeh, M. Impact of CO_2 Concentration and Ambient Conditions on Microalgal Growth and Nutrient Removal from Wastewater by a Photobioreactor. *Sci. Total Environ.* **2019**, *662*, 662–671. [CrossRef] [PubMed]
219. Kharel, H.L.; Shrestha, I.; Tan, M.; Nikookar, M.; Saraei, N.; Selvaratnam, T. Cyanidiales-based bioremediation of heavy metals. *BioTech* **2023**, *12*, 29. [CrossRef] [PubMed]
220. Grama, B.S.; Chader, S.; Khelifi, D.; Agathos, S.N.; Jeffryes, C. Induction of canthaxanthin production in a *Dactylococcus* microalga isolated from the Algerian Sahara. *Bioresour. Technol.* **2014**, *151*, 297–305. [CrossRef] [PubMed]
221. Bouzidi, N.E.; Grama, S.B.; Khelef, A.E.; Yang, D.; Li, J. Inhibition of antioxidant enzyme activities enhances carotenogenesis in microalga *Dactylococcus dissociatus* MT1. *Front. Bioeng. Biotechnol.* **2022**, *10*, 1014604. [CrossRef] [PubMed]
222. Praveen, K.; Abinandan, S.; Venkateswarlu, K.; Megharaj, M. Harnessing extremophilic trait and metabolic flexibility of microalgal strains for the treatment of highly alkaline winery wastewater. *ACS EST Eng.* **2024**, *4*, 455–465. [CrossRef]
223. Liu, Y.; Yildiz, I. The effect of salinity concentration on algal biomass production and nutrient removal from municipal wastewater by *Dunaliella salina*. *Int. J. Energy Res.* **2018**, *42*, 2997–3006. [CrossRef]
224. Danouche, M.; Ghachtouli, N.E.; Arroussi, H.E. Phycoremediation Mechanisms of Heavy Metals Using Living Green Microalgae: Physicochemical and Molecular Approaches for Enhancing Selectivity and Removal Capacity. *Heliyon* **2021**, *7*, e07609. [CrossRef] [PubMed]
225. Barra, L.; Greco, S. The Potential of Microalgae in Phycoremediation. In *IntechOpen eBooks*; IntechOpen: London, UK, 2023.
226. Ansari, F.A.; Hassan, H.; Al-Ouweini, A.S.S.; Chabukdhara, M.; Shakya, A.; Sheik, A.G.; Alghamdi, S.; Naser, I.; Waqas, S.; Ahmad, I. An Integrated Algal Biorefinery Approach for Wastewater Treatment and Biomass Valorisation. *Sustainability* **2026**, *18*, 2123. [CrossRef]
227. Kalwani, M.; Vítová, M. Artificial Intelligence–Driven Microalgal Biorefineries: Advancing Wastewater Phycoremediation toward Sustainable Biofuel and High-Value Product Generation. *Algal Res.* **2026**, *95*, 104620. [CrossRef]
228. Geng, Y.; Shaukat, A.; Azhar, W.; Raza, Q.-U.-A.; Tahir, A.; Abideen, M.Z.U.; Zia, M.A.B.; Bashir, M.A.; Rehim, A. Microalgal Biorefineries: A Systematic Review of Technological Trade-Offs and Innovation Pathways. *Biotechnol. Biofuels Bioprod.* **2025**, *18*, 93. [CrossRef] [PubMed]
229. Zhu, Z.; Sun, J.; Fa, Y.; Liu, X.; Lindblad, P. Enhancing Microalgal Lipid Accumulation for Biofuel Production. *Front. Microbiol.* **2022**, *13*, 1024441. [CrossRef] [PubMed]
230. Osman, A.I.; Chen, Z.; Elgarahy, A.M.; Farghali, M.; Mohamed, I.M.A.; Priya, A.K.; Hawash, H.B.; Yap, P. Membrane Technology for Energy Saving: Principles, Techniques, Applications, Challenges, and Prospects. *Adv. Energy Sustain. Res.* **2024**, *5*, 2400011. [CrossRef]
231. Hu, J.; Meng, W.; Su, Y.; Qian, C.; Fu, W. Emerging Technologies for Advancing Microalgal Photosynthesis and Metabolism toward Sustainable Production. *Front. Mar. Sci.* **2023**, *10*, 1260709. [CrossRef]

232. European Parliament and Council. Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment (recast). *Off. J. Eur. Union* **2024**, L 2024/3019. Available online: https://eur-lex.europa.eu/eli/dir/2024/3019/oj/eng (accessed on 12 August 2026).
233. European Parliament. Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on Minimum Requirements for Water Reuse (Text with EEA Relevance). Available online: https://eur-lex.europa.eu/eli/reg/2020/741/oj/eng (accessed on 12 August 2026).

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