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Review

Microalgae-Mediated Biosorption for Effective Heavy Metals Removal from Wastewater: A Review

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Abstract: Environmental contamination by heavy metals poses significant threats to terrestrial and aquatic ecosystems, necessitating the development of effective remediation strategies. Conventional methods for heavy metal removal exhibit limitations, including inadequate efficiency and elevated costs. In this context, microalgae have emerged as a promising bioremediation approach due to their robust metal-binding capabilities, specifically through biosorption. This review comprehensively examines the role of microalgae in addressing heavy metal pollution, with a primary focus on their effective removal from wastewater. Microalgae offer wastewater purification potential across diverse sources and capitalize on wastewater as a growth matrix, yielding valuable bioproducts, biomaterials, and bioenergy. Their versatility allows them to thrive in various wastewaters, facilitating effective contaminant removal. This study also investigates the application of microalgae in decentralized water treatment systems (DWTSs), where the decentralized nature of these systems proves advantageous in addressing heavy metal contaminants directly at the point of generation or use. This approach holds particular significance in regions where centralized systems face obstacles due to geographical constraints, inadequate infrastructure, or financial limitations. DWTSs not only provide a decentralized solution for heavy metals removal but also prove advantageous in disaster relief scenarios and rapidly growing urban areas.

Keywords: biosorption; bioaccumulation; decentralized water systems; environmental pollutants; heavy metals; microalgae

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1. Introduction

The challenge of global water scarcity has evolved into an irrefutable scientific reality, necessitating immediate attention to ensure sustainable development. This scarcity, driven by escalating demand and intensified by climate change, exerts profound economic implications and directly impacts freshwater resources, even in historically water-abundant regions [1]. The continuous growth of the global urban population, anticipated to grow by 2.7 billion between 2015 and 2050, is expected to reach over 9 billion in 2050, intensifying the strain on water resources [2]. By 2025, an estimated 1.8 billion individuals may inhabit nations facing absolute water scarcity, with two-thirds of the global population confronting water-stressed conditions [3]. Projections indicate that the global urban population experiencing water scarcity is poised to increase to 1.7–2.4 billion by 2050 [2]. The intricate interplay between urbanization and climate change significantly compounds the challenge of water scarcity, with demand consistently surpassing supply [4]. In parallel, water, an essential resource, serves as a vital raw material across diverse industrial sectors. Approximately 50% of industrial-generated wastewater is released directly into rivers or oceans without proper treatment, leading to severe environmental and health repercussions [5]. This direct discharge of contaminated water from various sectors has resulted in formidable environmental hazards, generating escalating global concerns due to the diverse array of contaminants they contain. This emphasizes the critical need for the implementation of DWTSs to provide vital support for communities without access to clean water.

Water pollution is a critical environmental issue that threatens ecosystems and human health. It occurs when harmful substances like chemicals, heavy metals, pathogens, and nutrients are introduced into water bodies such as streams, ponds, and seas [6]. These pollutants have diverse sources, including industrial activities, municipal waste, and agricultural practices [6]. The consequences of water pollution are far-reaching, leading to the degradation of aquatic ecosystems, disruption of food chains, and loss of biodiversity [7]. Furthermore, contaminated water infiltrates the human food chain, exposing individuals to hazardous agents [8], and it also adversely affects the availability of clean drinking water, which is essential for human well-being [9].

This review comprehensively examines the role of microalgae in addressing heavy metal pollution, with a primary focus on their effective removal from wastewater. The term "heavy metal" encompasses metallic chemical elements and metalloids known for their environmental and human health toxicity. These substances, originating from natural processes and human activities, are commonly released into the environment [10]. They often possess atomic weights higher than iron and densities below 5 g/cm^3, finding applications in various industries, including smelting, finishing, coal, electroplating, photography, aerospace, waste management, transportation, mining, and agriculture [11,12]. Essential metals like copper (Cu), nickel (Ni), chromium (Cr), mercury (Hg), cadmium (Cd), zinc (Zn), and lead (Pb) are prevalent in industrial processes, emphasizing their role in determining water quality [13,14]. When present in water, these pollutants can adversely affect human well-being, leading to developmental inhibition, male feminization, and waterborne diseases, impacting both developed and developing nations [7,15]. Heavy metals' contamination of aquatic ecosystems is a significant concern due to their persistent and toxic nature. Studies by Liu et al. [16], Lebelo et al. [17], and Ali et al. [18] highlight the prevalence of heavy metals in food sources, exacerbating global food safety concerns. This is attributed to their resistance to degradation, potential for bioaccumulation, and inherent toxicity, as noted by Sutar et al. [19] and Anae et al. [20].

Extensive research efforts have been directed towards removing aqueous heavy metals, employing various techniques such as adsorption, filtration, precipitation, ion exchange, and electrochemical approaches [21]. While conventional treatments exist, their widespread application could be improved in terms of cost, limited effectiveness, and ecological impact. Traditional centralized water treatment plants often struggle to efficiently and economically remove heavy metals from water sources, particularly in regions with limited infrastructure. Decentralized water systems represent a paradigm shift in water treatment, emphasizing localized, modular approaches that can be tailored to specific contaminant profiles and local conditions [22]. They incorporate various technologies, including but not limited to membrane filtration, ion exchange, adsorption, and electrocoagulation. These systems can be designed to target heavy metals through various mechanisms, such as precipitation, chemical binding, or electrochemical reduction. Decentralized systems can enhance resilience against natural disasters and other emergencies, as they are less liable to widespread failures compared to centralized facilities.

Efficient and reliable heavy metal remediation techniques are imperative. Over recent decades, diverse biosorbents have been explored for heavy metal removal [23,24]. The biosorption process, originating from studies of heavy metals' effects on microbes in fermentation, employs biomass, living or non-living, wet or dry, to cleanse wastewater [25]. Biosorption involves two stages: initial surface interactions, including physical adsorption, ion exchange, and surface complexation; followed by internal cell accumulation and microprecipitation, which necessitate energy expenditure and metabolic involvement [26]. Algae, as prokaryotic and eukaryotic single-celled organisms, emerge as promising biosorbents, particularly microalgae, which are characterized by their fast growth, short cycles, and organic content [27,28]. Table 1 provides a comprehensive assessment of the strengths and weaknesses of traditional centralized water treatment approaches. These techniques have been chosen for their widespread use and representation of different categories of waste treatment methods rather than an exhaustive list of all available options. Among these methods, adsorption stands out for its remarkable versatility and widespread adoption in removing heavy metals from aqueous solutions. However, it is crucial to acknowledge that adsorption has certain limitations [29]. While it is advantageous for final polishing steps in treated water/wastewater, the associated operation costs, including adsorbent regeneration, replacement, and solid waste management, should be considered. These factors can affect the overall cost-effectiveness and robustness of adsorption as a heavy metal remediation method [30]. Despite these considerations, adsorption remains an economical and uncomplicated approach with benefits such as straightforward operation, cost-effectiveness, robust pH adaptability, and suitability for large-scale industrial applications. Strategic functionalization can further enhance both efficiency and selectivity. This economical and uncomplicated approach, which requires minimal financial investment and energy input, proves highly desirable for efficient wastewater treatment.

Table 1. The overall advantages and drawbacks of frequent methodologies for wastewater treatment.

Waste Treatment Technique	Advantages	Disadvantages
Adsorption	Wide pH range Low cost Large capacity Simple operation	Weak selectivity Waste products
Chemical precipitation	Low cost Simple operation	Ineffective for trace ions Waste products
Ion exchange	Simple operation Large capacity High efficiency	Waste products Regeneration High cost
Membrane separation	High efficiency High selectivity	Regeneration High cost High operation cost
Electrochemical removal	High efficiency High selectivity	High cost High operation cost

Microalgae, with a vast diversity of more than 15.7×10^4 species, demonstrate enormous potential for wastewater treatment [31]. These organisms, including *Chlorophyceae* sp., *Bacillariophyceae* sp., *Chrysophyceae* sp., and *Cyanophyceae* sp., employ carbon fixation to convert inorganic carbon to biomatter while consuming nutrients [32]. Their rapid growth, short cycles, high biomass productivity, and potential for carbon fixation render them superior to earthbound plants. Miranda et al. [33] and Chen et al. [34] emphasize that microalgae flourish on marginal grounds, utilizing seawater or effluent as growth means, and they play essential roles in carbon mitigation and bioremediation.

Microalgae play a significant role in wastewater purification, offering advantages over traditional treatments, such as energy efficiency, cost-effectiveness, nutrient recycling, minimal sludge formation, greenhouse gas reduction, and biomass-nutrient recovery [35]. They exhibit remarkable potential in treating wastewater, particularly for heavy metal removal. This review delves into their efficacy, cost-effectiveness, and versatility in wastewater purification. It explores the synthesis of biochar from microalgae for wastewater treatment, addressing gaps in previous research and considering innovative applications like biochar generation [32,36]. Biochar offers several benefits, including efficient adsorption and environmental sustainability. This review also delves into the properties, operational strategies, and applications of microalgae-based treatment in heavy metal remediation from wastewater. The emphasis on commercially viable and environmentally sound microalgae-based treatment strategies highlights their potential to tackle water pollution challenges.

2. Microalgae

Microalgae, constituting a wide range of photosynthetic organisms, span from fundamental blue-green algae (cyanobacteria/prokaryotes) to complex seaweeds, rendering them one of the most diverse groups in the biological kingdom. The microalgal kingdom comprises more than 350,000 identified species as of 2017 [37]. These organisms possess a notable biochemical composition: approximately 70% lipids, 60% carbohydrates, and 65% proteins. Additionally, they contain crucial amino acids [38]. Jamshaid et al. [39] argue that microalgae offer a compelling alternative to conventional feedstocks. This preference arises from their short growth cycle, high biomass productivity, impressive harvesting efficiency, and unparalleled carbon fixation rates. Furthermore, microalgae thrive without the need for extensive arable land, instead flourishing in marginal regions using seawater or effluent as their growth medium [33].

The ecological importance of microalgae is emphasized by their extraordinary photosynthetic efficiency, surpassing terrestrial plants by 40–50% [34]. Their notable carbon sequestration capacity significantly contributes to global CO_2 sequestration, with 1 kg of microalgae absorbing 1.83 kg of CO_2 [2]. Additionally, they play a vital role in producing around 50% of Earth's atmospheric oxygen. Despite the estimated diversity of microalgae species ranging from 30,000 to over 1,000,000, only 15 are feasible for large-scale commercial cultivation [40]. Characterized by their rapid growth rate and brief life cycle, typically spanning just a few days, microalgae exhibit an exceptional capacity for biomass production [41]. This unique attribute has spurred research into various applications, including bioremediation and transforming microalgal biomass into value-added commodities, such as bio-oil and syngas [42].

Microalgae find extensive application in the remediation of diverse wastewater categories, constituting industrial, agronomic, and mining discharges. Their proficiency in nutrient removal, potent adsorption capabilities, and environmentally sustainable attributes confer them an advantage over conventional treatment methodologies [43]. Their effectiveness spans various wastewater applications, demonstrating their versatility and efficiency. Research by Ferreira et al. [44] has illustrated their capability in treating brewery wastewater, while Calicioglu et al. [45] have observed their effectiveness in managing everyday domestic wastewater. They excel in mitigating the vivid tones of textile wastewater and handling industrial and pharmaceutical effluents [46]. Additionally, they exhibit determination in addressing waters laden with heavy metals, offering a chance at redemption [47]. Hariz et al. [48] have conducted studies affirming the efficacy of microalgae in treating oil effluents and starch-containing textile wastewater. In agro-industrial settings, microalgae emerge as a steadfast wastewater quality solution, as Jayakumar et al. [49] have highlighted. Their wide-ranging applications emphasize their significance in wastewater treatment across diverse sectors.

Microalgae's genetic reservoir includes essential genes pivotal in degrading a broad spectrum of impurities [50,51]. Consequently, selecting suitable microalgal strains is paramount in determining effective strategies for remediating contaminated wastewater [52]. Specific microalgae strains hold versatile applications across various industries, including face painting, poultry, fertilizers, and medication, as well as in the production of green fuels like bio alcohols, biogas, and biodiesel [38]. Ng et al. [2] emphasize that to achieve the cost-competitiveness of algal products with fossil fuels, it is crucial to concentrate efforts on strain selection, cost-effective media, optimized conditions for augmented biomass production, and the feasibility of commercialization. Notably, integrating microalgae into wastewater treatment processes can lead to reduced production costs and a lower overall carbon footprint, owing to the nutrient-rich composition of wastewater.

Microalgae have demonstrated their efficacy in treating domestic wastewater, as shown in Table 2. These microalgae-based wastewater treatment technologies stand out because they can achieve bioremediation in a single step [53]. The harvested biomass of microalgae holds the potential for conversion into valuable biobased compounds, such as biohydrogen, biohydrocarbons, bioalcohols, and health enhancements [54]. Innovative methods have paved the way for annual biomass production of up to 70,000 Kg and the generation of 15,000 L of oil per hectare. These advancements present promising opportunities for commercial applications in aviation and vehicular biofuels [55].

Furthermore, the contribution of microalgae in mitigating eutrophication, ozone depletion, and global warming emphasizes their potential as a sustainable approach for biofuel production in conjunction with wastewater treatment [56]. In addition to biofuels, microalgal biomass is a valuable resource of carbohydrates, proteins, vitamins, lipids, and a range of low- and high-value by-products, achieved through biorefinery processes. These processes encompass the production of microalgal plastics, fertilizers, fibres, and protein-rich animal feed [53].

Table 2. Microalgae biomass production from wastewater cultivation.

Wastewater Type	Microalgae	Biomass Cultivation	Reference
Municipal effluent	*Scenedesmus obliquus*	0.22 g/L	[57]
Household effluent	*Chlorella* sp.	0.73–1.38 mg/L/d	[58]
Municipal effluent	*Chlorella sorokiniana*	1 g/L	[59]
Municipal effluent	*Scenedesmus* sp.	1.1 g/L	[60]
Household effluent	*Chlorella vaiabilis*	1.72 g/L	[61]
Municipal effluent	*Scenedesmus* sp.	1.81 g/L	[62]
Household effluent	*Scenedesmus obliquus*	3.55 g/L	[63]

While there are various methods for remediating pollutants, including physical, chemical, and biological approaches, microbial approaches have become favored for their environmentally friendly characteristics [35]. While bacteria and fungi have been extensively researched for their pollutant removal capabilities, microalgae-based remediation has received comparatively less attention [64]. Hence, there is a pressing need to explore the potential of microalgae in xenobiotic remediation from the environment. The technology of wastewater treatment using microalgae presents several benefits, including solar energy generation, adequate CO_2 fixation, and sustainable biomass production with low environmental impact. However, their growth rate, nutrient utilization, and efficiency in removing pollutants are limited under conditions where CO_2 is deficient [65].

2.1. Characteristics and Classification of Microalgae

The characteristics and classification of microalgae incorporate a range of defining features that collectively shape their diversity and ecological significance. These minute organisms typically exhibit microscopic dimensions ranging from 3 to 25 μm and are primarily unicellular, although some can form colonies or simple multicellular structures [66]. One of their most remarkable attributes is their ability to harness solar radiation for photosynthesis, which drives their growth and biomass production [67].

Microalgae comprise two main groups: prokaryotic cyanobacteria and eukaryotic protists [68]. These organisms thrive in various aquatic environments, including freshwater, marine, and brackish water habitats [67]. Their ability to thrive in varied environments showcases their adaptability and ecological flexibility [69]. The vibrant pigments found in microalgae, including chlorophyll and others, play a pivotal role in their photosynthetic capabilities [70]. This process forms the basis of their energy acquisition and is central to their ecological importance. Based on a combination of morphological, physiological, genetic, and metabolic features, microalgae are classified into distinct categories [71].

The morphological classification is a foundational system based on critical features such as cell shape, size, and the existence of flagella. This method categorizes microalgae into specific groups, including prokaryotic cyanobacteria, which display a range of blue-green and green varieties [72]. According to the research by Nitsos et al. [73], eukaryotic microalgae are classified within this framework, featuring green *Chlorophyta*, brown *Phaeophyta*, and golden *Chrysophyceae*. This method enables categorizing microalgae based on their visible physical traits, providing a valuable initial understanding of their diversity and evolutionary relationships [73].

Phylogenetic classification represents a deeper exploration of the evolutionary relationships among various microalgae species [74]. This classification method harnesses cutting-edge DNA sequencing techniques to unravel the genetic relatedness among these organisms, providing profound insights into their evolutionary history and intricate interconnections [75]. The ancestral lineages and evolutionary trajectories that have shaped these microscopic life forms over vast stretches of time can be uncovered by deciphering the genetic blueprints of microalgae. This approach offers a comprehensive understanding of their evolutionary heritage and how they are biologically interconnected [74].

Ecological classification finds its foundation in the habitat preferences of microalgae, as noted by Verdelho et al. [76]. Through a meticulous examination of their distribution patterns and thriving conditions, microalgae can be differentiated based on their predominance in specific environments, whether it be freshwater, marine, or brackish water settings, as also highlighted by Khoironi et al. [77]. This approach yields invaluable insights into the ecological niches these organisms occupy and the adaptations they have developed to thrive in their respective habitats [76]. It serves as a crucial tool for understanding how microalgae interact with and respond to their surrounding environment, shedding light on their ecological significance and contributions to various ecosystems.

Metabolic modes represent another critical aspect of microalgae classification [78]. Their energy and nutrient acquisition strategies characterize these modes. Microalgae can be classified into distinct groups based on their metabolic preferences, which include photoautotrophic (relying solely on photosynthesis), heterotrophic (acquiring organic carbon from external sources), mixotrophic (combining both autotrophic and heterotrophic strategies), and photoheterotrophic (utilizing light as an energy source while obtaining carbon from external sources) modes [79]. Their ability to thrive in diverse environmental conditions highlights their ecological resilience and survival tactics.

2.2. Cultivation Techniques and Growth Conditions

Microalgae find diverse applications across industries, including textiles, poultry, biofertilisers, pharmaceuticals, and green fuels like bioalcohols, biogas, and biodiesel [38]. However, attaining cost-competitive algal products remains a challenge, as current prices cannot match those of fossil fuels [80]. Therefore, critical aspects of algal research encompass strain selection [81], the use of economically viable growth media, optimization of conditions for increased biomass production, aligning cell stoichiometry with the desired product, ensuring effective commercialization, and minimizing operational costs, particularly in the cultivation and harvesting phases [2]. Wastewater proves to be an optimal resource for algal biomass production for several compelling reasons. It serves as a cost-effective growth medium, facilitating extensive biomass and biofuel generation and providing ample nutrients. Moreover, it holds the potential for seamless integration of algal cultivation with pre-existing wastewater treatment infrastructure [82].

Photobioreactors are specialized systems that cultivate microorganisms, particularly microalgae, under controlled environmental conditions. They are enclosed systems that meticulously regulate environmental parameters such as light intensity, temperature, pH, and nutrient availability [83]. These reactors can be categorized into two main types: aerobic and anaerobic [84]. Aerobic photobioreactors provide a controlled environment with an adequate oxygen supply to support aerobic metabolism. They are equipped with mechanisms to ensure sufficient aeration, which is crucial for the growth of oxygen-dependent microorganisms like microalgae [85,86]. Oxygen is continuously supplied to the culture to meet the metabolic demands of the microorganisms. This is typically achieved through the introduction of air or pure oxygen. The circulation of the culture ensures that oxygen is distributed evenly, promoting healthy cell growth [86]. It enables the cultivation of oxygen-dependent microorganisms and facilitates higher growth rates and biomass production due to the ample oxygen supply [85]. Unlike aerobic photobioreactors, anaerobic systems operate in the absence of oxygen. These reactors create an environment conducive to the growth of anaerobic microorganisms [87]. This is achieved by carefully controlling the ingress of air and by utilizing specialized equipment that prevents oxygen from entering the system [88]. This environment supports the growth of anaerobic microorganisms, which can thrive in the absence of oxygen, and those that may have unique properties or produce specific products.

Aerobic and anaerobic photobioreactors are crucial in various fields, including biotechnology, environmental science, and bioenergy production. They come in various designs, such as tubular, flat-panel, or bubble-column reactors, while open ponds are large, shallow basins or raceways where microalgae are cultivated under natural sunlight [89]. The choice between the two types depends on the specific microorganisms being cultured and the intended applications [88]. Some systems are designed to be versatile, allowing for aerobic and anaerobic conditions to be achieved as needed. These reactors are valuable tools in research and industry for exploring and harnessing the potential of microorganisms, particularly microalgae, for various applications [85].

Nutrient availability is crucial for microalgae growth, with essential nutrients like nitrogen, phosphorus, and trace elements being provided from sources such as synthetic fertilizers, wastewater, or agricultural runoff [90]. The nutrient concentration and ratio in the growth medium are pivotal factors influencing microalgae growth and biomass production [91]. Sufficient light exposure is essential for photosynthesis [92]. Light exposure's intensity and duration directly impact microalgae's growth rate and lipid content. The ideal light conditions differ based on the microalgal species and can be regulated using artificial lighting in indoor cultivation systems [93]. Microalgae thrive within specific temperature and pH ranges, varying depending on the species. Maintaining suitable temperature and pH levels is crucial for maximizing microalgal growth and productivity [94]. According to the study by Song et al. [95], a significant issue arises with generating a strong, unpleasant odor during the microalgae cultivation process in wastewater. As the cultivation period extends, the microalgae tend to adhere to the walls of the apparatus, thereby impeding light penetration and adversely affecting the photosynthetic activity of the algae cells. It is imperative to address both the malodor concern and the adhesion of algal cells. Given that various microalgae respond differently to distinct conditions, optimizing growth parameters that are easily modifiable becomes crucial to enhance production efficiency.

Strain selection involves considering factors like biomass productivity, nutrient requirements, and environmental stress tolerance [79]. Strains like *Chlorella vulgaris* and *Spirulina platensis* are known for high biomass productivity and nutrient content, making them suitable for biochar production [96]. Other strains, like *Nannochloropsis* sp. and *Scenedesmus* sp., are valued for their high lipid content and potential for biofuel production [97].

Cultivation optimization is pivotal for maximizing biomass productivity and quality [11]. Light intensity, temperature, pH, and nutrient availability impact microalgal growth and biomass production. For instance, optimizing light conditions and nutrient availability can significantly enhance biomass productivity [98]. Utilizing photobioreactors and closed cultivation systems offers better control over environmental factors, further improving biomass productivity [83]. Recent research has shown that, with a few exceptions, the most favorable temperature range for the growth of the majority of algae species lies between 15 °C and 35 °C. An ideal light intensity typically falls between 1850 and 14,800 lux for the optimal proliferation of microalgal species. While some algae species can withstand both acidic and basic environments, the majority thrive within a pH range of 7.0–9.0.

Furthermore, the availability of essential nutrients in the medium significantly influences the development of microalgae [99]. Effective harvesting methods like centrifugation, flocculation, and filtration are employed to separate microalgal biomass from the growth medium. The resulting biomass can then undergo processing techniques such as pyrolysis, hydrothermal carbonization, or torrefaction to yield microalgae-based biochar [100].

3. Application of Microalgae for Removal of Contaminants

3.1. Biosorption

Biosorption is an inert process that employs biological materials as sorbents to effectively combine and concentrate contaminants from wastewater. This process involves a mass transfer phenomenon, displacing a substance from the liquid phase and adhering it to a solid surface. It comprises various mechanisms, such as surface complexation, precipitation, absorption, electrostatic interaction, adsorption, and ion exchange [101]. The essence of biosorption relies on two essential elements: a biosorbent, representing the solid-phase sorbent; and a target sorbate, which exists in a dispersed state within the water. This biomaterial, whether composed of living or deceased microbes or their constituents, exhibits a remarkable affinity for the target sorbate, attracting sorbate species. The overall capacity of the biosorbent determines the quantity of sorbate molecules that can be adsorbed [102]. Until a state of equilibrium is attained between the adsorbed substance and the remaining concentration in the liquid, this process continues. The distribution of the biosorbent's preference for a specific sorbate between the solid and liquid phases is regulated by it [103].

Bioadsorption is a physicochemical process that directly extracts heavy metals from wastewater, capitalizing on the adsorptive capacity of biological materials [104]. This procedure involves binding toxic pollutants to various cellular components of microalgal cells, such as the cell wall or extracellular polysaccharides [105]. The phenomenon described involves a passive, non-metabolic interaction between contaminants and cell surfaces, as exposed by Bhatt et al. [106] in their 2022 study. This interaction manifests when heavy metals adhere to cell wall constituents or when organic compounds, such as extracellular polymeric substances (EPS), are discharged into the aquatic environment by algal cells [107]. Comprising primarily organic elements like proteins, polysaccharides, enzymes, lipids, and various functional groups, EPS assumes multifaceted roles in bolstering cell adsorption capabilities, modifying surface properties, retaining enzymes, ensuring mass transfer stability, fortifying structural integrity, and facilitating digestive functions [108]. This intricate interplay among biological materials and their constituents is pivotal in determining the efficacy of biosorption as a means of purging heavy metals from wastewater streams.

The adsorption process is notably affected by the chemical characteristics of impurities, particularly their hydrophobic nature. Contaminants with a positive charge exhibit a higher attraction to the negatively charged cell surface of microalgae, primarily driven by electrostatic interactions, in contrast to hydrophilic compounds [51]. The microalgal cell wall, composed of polysaccharides, a fibril matrix, and sulfated carbohydrates, contains diverse anionic groups with differing affinities for positively charged organic contaminants, as Nagappan et al. [109] have highlighted. The interaction between negatively charged microalgal cell walls, secretions, and heavy metals occurs through a passive, non-metabolic process, as detailed by Xiong in 2021 [110]. Notably, Chlorella vulgaris demonstrates remarkable proficiency in eliminating the antibiotic metronidazole, achieving a removal efficiency of up to 100% from an initial concentration of 5 mM through biosorption [111]. Biosorption encompasses a range of mechanisms, including ion exchange, adsorption, surface complexation, precipitation, and chelation [112]. These intricate interactions underscore the efficacy of biosorption in capturing pollutants from the environment.

The biosorption process is influenced by various physicochemical factors such as pH, temperature, and redox reactions. Notably, biosorption can occur with both living and deceased cells, owing to its non-metabolic nature. Studies have shown that cell surface receptors in microalgae retain their affinity for pollutants, even in deceased cells [113]. Employing deceased microalgae cells as a bio-adsorbent offers several advantages, including the absence of contaminant-induced toxicity, the potential for reusing microalgae biomass after desorbing the adsorbed pollutant, and lower operational costs due to not requiring the maintenance of microalgae in a viable state [114]. Table 3 provides a comprehensive overview of the biosorption capacity of heavy metals by microalgae.

Table 3. Microalgae-driven heavy metal removal efficiency.

Microalgae (Raw Biomass)	Heavy Metals	Conc. Tested	Outcome	Refs.
Spirulina sp.	Mercury (Hg) Cadminum (Cd)	Cadmium 3.82 mg/kg	Metal factor concentration: 80–4250 Bioaccumulation capacity: • Cd—0.46 µg/kg biomass; • Hg—1.34 µg/kg biomass.	[100]
Chlamydomonas reinhardtii	Mercury (Hg) Cadminum (Cd) Lead	Hg—0.76 mg/kg 100 mg/L	The Freundlich biosorption isotherm was employed to characterise the equilibrium capacity of biosorption for various metals: • Hg—0.072 mg/kg; • Cd—0.043 mg/kg; • Pb—0.096 mg/kg.	[115,116] [100]
Ulothrix zonata	Copper Cu (II)	5–52 mg/L	The Langmuir adsorption model was applied to the adsorption isotherm. • Rapid removal of Cu (II) within the initial 1200 s. • The optimum pH for effective Cu (II) removal was 4.5.	[117]
Spirofyra sp.	Lead Pb (II)	105–204 mg/L	The maximum adsorption capacity achieved was 140 mg/g of biomass within a time frame of 1.667 h, starting with a 200 mg/L concentration.	[116]
Spirulina platensis	Cadminum Lead Pb (II)	40–200 mg/L 25–210 mg/L	The Langmuir adsorption model yielded a removal efficacy of 87.69%, falling slightly below the desired 90% removal rate. Freundlich isotherm provided the best fit for the experimental data, indicating its suitability for further analysis and application.	[118,119]
Parachlorella sp.	Cadmium Cd (II)	18–180 mg/L	The Langmuir adsorption model was employed, revealing a maximum adsorption capacity of 96.20 mg/g at a temperature of 35 °C.	[120]
Scenedesmus obliquus	Cadmium Cd (II)	2.6–7.7 mg/L	With a breakthrough time of 930 min, the adsorption capacity reached 0.038 g. This was achieved under a 6 mL/min flow rate, with an influent Cd concentration of 0.008 mg/L.	[121]

Employing non-living microalgal biomass has demonstrated significant potential as a biosorbent for the removal of heavy metals. The utilization of microorganisms for biosorption has proven to be an effective strategy in addressing heavy metal contamination [122]. Under conditions favorable for algal growth, layers of microorganisms, including species like *Chlorella vulgaris*, *Spirulina platensis*, *Chlamydomonas* sp., and *Chlorella emersonii*, may accumulate on the water's surface. Microalgae play a pivotal role in biosorption, as they have the capacity to attract and capture heavy metal ions [122]. This ability is ascribed to the composition of their cell walls, which are abundant in polysaccharides and functional groups, for instance, carboxyls, hydroxyl groups, amines, phosphates, and sulfates [123].

The remarkable biosorption potential of microalgae, driven by their high metal adsorption capacity, cost-effectiveness, and overall effectiveness, has garnered significant attention [124]. They not only excel in removing heavy metals like copper and zinc, as demonstrated by *Chlorella preniodisa* and *Scenedesmus obliquus*, achieving removal rates exceeding 70% after 192 h of experimentation [125], but also exhibit proficiency in absorbing other essential elements such as potassium and phosphorus. Research indicates that microalgae hold significant potential for effectively removing various heavy metals through biosorption [126]. Several microalgae species, including *Anabaena*, *Spirogyra*, *Phormidium*, and *Oscillatoria*, have demonstrated resilience to heavy metal stress in natural aquatic environments. Additionally, microalgae contribute to flocculation, reducing suspended and total dissolved solids [127]. To shield themselves from the toxicity of heavy metals, microalgae employ various strategies, including gene regulation, immobilization of heavy metals, chelation, and the production of reducing enzymes [128,129]. These cells establish interactions between proteins and metals without disrupting other cellular processes. The resulting complexes of protein and metal are sequestered within vacuoles, effectively safeguarding microalgae from harmful effects [130]. The mechanism for degrading organic pollutants by microalgae mirrors the process used for removing heavy metal ions. This process commences with a swift physicochemical (passive) adsorption in its initial phase. Biosorption, exemplified by the exothermic and spontaneous adsorption of phenol by *Spirulina* sp. LEB18, represents a highly advantageous process [131].

Microalgae can counter heavy metal exposure's effects by synthesizing antioxidant enzymes, thereby mitigating the harmful impact of free radicals on their cellular structure. Extensive research affirms their adeptness in safeguarding against toxic heavy metals [132]. The predominant mechanism employed by microalgae for eliminating heavy metals from wastewater is biosorption [101]. This process is intricately regulated by the microalgal cell wall, where the chemical composition assumes a pivotal role in dictating the efficacy of biosorption. The presence of surface pores and the surface charge of microalgae actively contribute to the overall effectiveness of this process [122]. Within the microalgal cell wall, a diversity of chemical groups, including carboxyl, hydroxyl, and sulfate, serve as binding sites and effective ion exchangers. These attributes facilitate the complexation of metal ions and the adsorption of organic substances from contaminated water [133]. While lipids, proteins, and nucleic acids may also be present on the cell surface, their primary concentration occurs in the cytoplasm and plasma membrane, where they can interact with metal cations through various functional groups. The structural composition of the microalgal cell wall consists of a fibril matrix, imparting mechanical strength, while its flexibility is attributed to the amorphous fraction. Both these fractions, along with the intercellular spaces on the cell wall, significantly contribute to biosorption efficiency [134]. Furthermore, the porosity and roughness of the microalgal surface play a crucial role in influencing the adsorption of heavy metals [25]. Notably, smaller cell sizes result in an increased adsorbent surface area, providing a larger contact area per unit of biomass [135]. However, it is essential to emphasize that a higher quantity of biosorbent particles does not necessarily translate to enhanced biosorption properties. An excess of microalgal surfaces can lead to active site repulsion, potentially diminishing the removal efficiency [136].

Biosorption is a straightforward, rapid, reversible, and cost-effective method, especially compared to bioaccumulation. This approach efficiently concentrates heavy metals, even from highly diluted aqueous solutions. Its merits include multifunctional groups, evenly distributed binding sites on cell surfaces, minimal operating costs, lack of metal toxicity concerns, elevated efficiency, and selectivity for metal ions. Moreover, it processes no by-product and holds potential for recovering toxic heavy metals and reusing the biosorbent [137]. Several microbial strains have shown robustness against a range of metals and effectiveness in remediation. For example, a strain of Pseudomonas putida was discovered in tannery effluent with resistance to Ag^{2+} and Co^{2+}. It heightened resistance to lead and chromium, emphasizing the diverse microbial capacity to combat heavy metal contamination [138].

3.2. Bioaccumulation

Bioaccumulation is a metabolic-dependent process involving the active transportation of metal ions into living cells. In contrast to biosorption, bioaccumulation relies on the metabolic activity of living cells for the active transport of metal ions across the cellular membrane. The essential role of live microbial cells depends on a range of chemical, physical, and biological mechanisms involving processes both within and outside the cell. While passive diffusion has a limited impact on bioaccumulation, the primary uptake is driven by energy-dependent transport mechanisms fueled by cellular energy [139].

The selection of microorganisms for bioaccumulation necessitates specific attributes, such as proficiency in adapting to contaminated environments, resilience to elevated concentrations of metal ions, and possession of intracellular binding mechanisms [140]. The bioaccumulation process comprises two discernible stages: analogous to biosorption, it involves the adhesion of heavy metals onto charged functional groups located on the cell surface. Subsequently, the second step, reliant on metabolic processes and characterized by a relatively sluggish pace, comprehends the ingress and conveyance of a metal–ligand complex across the cellular membrane. Factors affecting the adsorption capacity of microorganisms in bioaccumulation include biomass concentration, contact time, pH of the solution, initial metal ion concentration, and temperature. Higher biomass concentrations generally lead to increased adsorption capacity, with the contact time influencing overall efficiency. The pH of the solution plays a crucial role in affecting the charge distribution on microalgal surfaces and influencing metal ion binding. Additionally, the initial concentration of metal ions and temperature impact adsorption capacity, with higher concentrations and suitable temperatures enhancing the effectiveness of the process [141]. Subsequent interactions transpire within the cell, involving intracellular metal-binding proteins like metallothionein and phytochelatins, culminating in the bioaccumulation phenomenon [120].

Metallothioneins (MTs) are essential in regulating intracellular metal metabolism and safeguarding against oxidative stress induced by hazardous heavy metals [142,143]. To illustrate, the introduction of the Corynebacterium glutamicum metallothionein gene into engineered recombinant E. coli led to a notable augmentation in intracellular biosorption of Pb^{2+} and Zn^{2+} [143]. In a similar vein, Shen et al. [142] have achieved the development of a biocomposite through the immobilization of metallothionein and the expression of Pseudomonas putida, thereby facilitating the sorption of Cu^{2+}. Similarly, phytochelatins, analogous to metallothioneins, represent metal-binding proteins synthesized by microalgae, proficient in intracellular chelation and the detoxification of heavy metal ions.

3.3. Removal of Heavy Metals from Wastewater Using Microalgae

Heavy metals constitute a category of naturally existing compounds emitted into the environment due to natural processes and human activities [144]. These elements and metalloids are integral components of numerous chemical substances, typically categorized by their atomic weights exceeding that of iron and densities below 5 g/cm^3 [145]. Apart from their natural occurrence, industrial discharges and runoff from industrial activities significantly contribute to the introduction of heavy metals into aquatic ecosystems [146]. Diverse sectors, such as smelting, finishing, coal processing, electroplating, photography, electronics production, aerospace, waste management, transportation, mining, and agriculture, have relied on products containing metals since the advent of global modernization [12].

Certain elements, including Co, Ni, Cu, Mn, and Zn, are essential micronutrients for growth [147]. Conversely, in addition to those, others like Fe, I, and Pb contribute to the enhancement of nutritional quality and vital biological functions [148]. However, heavy metals such as Hg, Cd, Cr, and Pb lack defined biological roles and demonstrate toxic properties [147]. Their excessive absorption disrupts metabolic processes, resulting in toxicity, mutagenesis, and allergenicity, particularly in algae [149]. Heavy metals like Hg, Cd, Pb, Zn, Cr, Cu, and Ni hold significant roles in industrial applications [13], consequently influencing water quality considerably. Given their enduring presence, wide distribution, and toxic nature, the global issue of heavy metal contamination persists, posing risks to humans and animals even at low concentrations [150].

Heavy metals, classified as radionuclides (U, Ra, Am, Th), precious metals (Au, Pd, Pt, Ru), and toxic metals (Cu, Cr, As, Zn, Ni, Ag, Sn, Co, Pb) [151,152], require efficient removal strategies. Although current conventional methods are efficient, they result in high operational and maintenance costs as well as the generation of secondary waste [150]. Therefore, developing robust, environmentally friendly, and economically viable alternatives is imperative. The selection of a remediation approach is contingent on site-specific characteristics, contamination levels, and regulatory thresholds within the particular domain. Chemical, physical, and biological techniques are the primary remediation categories for eliminating heavy metals from wastewater, utilizing various microalgae strains [153]. Essential binding sites within microalgal cell walls, including amino, hydroxyl, carboxyl, and sulfate functional groups, play a crucial role in heavy metal removal [154], primarily facilitated by the negatively charged groups on the outer cell wall layer [155].

The toxicity thresholds of heavy metal ions can vary significantly across different algae strains, leading to differing affinities for a wide range of metals. This particular trait ultimately dictates the potential effectiveness of specific algal strains in remediation efforts. For instance, compared to *A. platensis*, *C. vulgaris* displays higher biosorption efficiency [156]. *Cyanobacteria*, a subgroup of algae, hold substantial promise as microorganisms proficient in absorbing heavy metals, owing to their capacity for oxygenated photosynthesis. *A. variabilis*, in particular, demonstrates a greater capacity for sorbing heavy metals when compared to *T. ceytonica*, even surpassing the combined effectiveness of these two cyanobacterial strains [157]. Brown algae have consistently gained interest as sorbent materials due to their polysaccharide content, including alginate and fucoidan, which actively engage in ion exchange processes [158]. The extent of heavy metal uptake varies among different algae species, as demonstrated by Suresh et al. [147], who have noted disparities in the absorption of heavy metals across various algae strains.

Microorganisms exhibit an economical and sustainable capacity to sequester, transform, and reduce heavy metal ions intracellularly and extracellularly. These adaptable organisms rapidly evolve under environmental stress, establishing resistance to toxic heavy metals. Promisingly, microalgae-based biosorption emerges as a cost-effective, ecologically benign, and efficient alternative, particularly in comparison with traditional methodologies [159]. Various microalgae, including *Chlorella miniata*, *C. vulgaris*, *C. reinhardtii*, and *Sphaeroplea*, have demonstrated effectiveness in removing toxic heavy metals from wastewater [160].

In a recent study conducted by Wang et al. [161], four algal species exhibited potential in treating heavy metal contamination, with Microcystis aeruginosa being particularly effective in removing Fe and Mn from shallow groundwater in mining areas. Mechanisms included cation exchange and metal adsorption by algae. Microalgae exhibit adaptive responses to heavy metal toxicity through the regulation of gene expression, release of ligands, and production of extracellular polysaccharides [162]. Certain microalgae facilitate the bioremediation of lead-contaminated wastewater and concurrently produce biofuels [163]. For instance, *Chlorella sorokiniana* effectively removes Cr [164] (see Table 4). Several factors, including pH, temperature, biomass concentration, and co-existing pollutants, influence the efficiency of microalgae-mediated heavy metal remediation; and a comprehensive overview of the performance of various microalgae species in effectively absorbing heavy metals is tabulated in Table 4. A system's pH plays a crucial role in determining the availability of surface functional groups on microbial cells, which are vital for metal binding [165]. Temperature, however, affects the solubility and accessibility of metals. Higher biomass concentrations can enhance removal efficiency, although numerous binding sites may lead to a reduction in the uptake of specific metals. The interaction between different metal ions can also impact the overall removal process [166].

Table 4. Biosorption efficiency of microalgae for heavy metal removal.

Metal	Microalgae Species	Initial pH	Initial Metal Concentration	Contract Duration	Removal Efficiency (%)	Reference
Ni	*Scenedesmus almeriensis*		11.9 mg/L	12 days	32	[166]
As	*Scenedesmus almeriensis*		12 mg/L	3 h	40.7	[105]
Fe	*Microcystis aerugunosa*	9.0	350 µg/L	4 days	54.14	[161]
Ni	*Scenedesmus quadricauda*	6.6	5000 µg/L	10 min	66.00	[167]
Mn	*Anabaena flosaquae*	9.0	150 µg/L	6 days	72.71	[95]
Cr	*Neochloris pseudoalveolaris*	6.6	5000 µg/L	10 min	80.60	[125]
Cd	*Didymogenes Palatina* XR *Chrorella vulgaris* (dead cells)	6.0	2000 µg/L 100 mg/L	 15 min	87.99 96.8	[143] [168]
Zn	*Chlorophyceae* spp.		3 mg/L	3 h	91.9	[105]
Cu	*Desmodesmus* sp. CHX1 *Chlorella vulgaris*	6.0	410,000 µg/L 11.9 mg/L	4 days 12 days	88.35 39.0	[169] [105]
Cr	*Chlorella sorokiniana*	7.0	100 ppm	3 days	99.68	[164]

4. Enhancing Wastewater Treatment through Microalgae Co-Culturing

The integration of microalgae with various organisms and nanoparticles in co-culture systems has recently gained recognition as a potent tool for bioremediation [154]. This discussion aims to provide an overview of the advantages and limitations associated with these innovative microalgae co-culture approaches.

4.1. Microalgae-Bacteria Co-Culture

The co-culture system involving microalgae and bacteria strategically leverages their synergistic relationship. This cooperative interaction leads to increased biomass production and enhanced nutrient removal from wastewater [170]. For example, a study demonstrated that cultivating *Chlorella* alongside specific bacteria, namely *Bacillus firmus* and *Beijerinckia fluminensis*, significantly improved the efficiency of removing chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) from wastewater produced during vinegar production [171]. In another investigation, the symbiosis of microalgae and bacteria in a sequencing batch bioreactor resulted in notable improvements in TN and TP removal [172]. However, it is essential to highlight that the careful selection of compatible microalgal–bacterial pairs is pivotal for the success of this co-culture system. This ensures optimal synergies and efficient nutrient cycling within the system.

4.2. Microalgae-Activated Sludge Co-Culture

The integration of microalgae with activated sludge in wastewater treatment has demonstrated significant advantages compared to traditional single-system approaches [154]. In municipal wastewater, maintaining a low sludge-to-microalgae ratio led to a twofold increase in microalgal growth and more effective nutrient removal when compared to a pure microalgal culture [173]. Mujtaba et al. have observed elevated nutrient removal rates in a co-culture system that involved suspended activated sludge and immobilized *C. vulgaris* [174]. However, it is crucial to emphasize that determining the optimal sludge-to-microalgae ratio depends on the specific characteristics of the wastewater. Striking this balance is paramount for the system's success, ensuring that microalgae and activated sludge collaborate efficiently to maximize nutrient removal and overall treatment efficacy [175]. The effectiveness of this approach lies in a thorough evaluation of the wastewater composition and a thoughtful design of the co-culture system.

4.3. Microalgae-Fungi Co-Culture

Employing co-cultivation techniques that combine microalgae with fungi or yeast shows excellent promise in wastewater bioremediation [176]. In such systems, the careful consideration of factors like the initial inoculum ratio, nutrient availability, and environmental conditions is imperative. Research indicates that maintaining an appropriate balance between microalgae and fungi/yeast is crucial for achieving optimal biomass production and efficient nutrient removal [176,177]. The selection of microalgal–fungal or microalgal–yeast species pairs plays a pivotal role in the success of the co-culture system. Compatibility in growth rates, resource utilization, and metabolic pathways significantly influence the overall efficiency of the bioremediation process [178,179].

Introducing supplementary nutrients or substrates, such as glucose in the case of yeast co-cultivation, can elevate the system's productivity and enhance nutrient uptake rates [178,179]. Careful monitoring and adjustment of these parameters are essential for optimizing the co-culture system's performance and ensuring its effectiveness in wastewater bioremediation [179].

4.4. Microalgae-Nanoparticles Co-Culture

Utilizing nanoparticles as supportive carriers for immobilizing microorganisms, including microalgae, presents distinct advantages in pollutant removal [154]. When employing nanofibers as carriers for immobilizing microorganisms like microalgae, factors such as material composition, surface properties, and morphology of the nanofibers become crucial considerations. These attributes exert significant influence on the attachment, growth, and activity of the immobilized microorganisms [121,154]. The preparation and fabrication of the nanofibers, involving techniques like electrospinning or other advanced methods, play a pivotal role in determining their suitability as carriers for microorganisms [121]. Optimization of the co-culture system's performance can be achieved by tailoring the nanofiber composition to enhance specific interactions with the microorganisms or to provide additional nutrient support [178,179]. This level of customization can lead to increased pollutant removal efficiency. However, for potential real-world applications, considerations regarding the scalability, cost-effectiveness, and environmental impact of nanofibers as carriers are essential [154]. These aspects play a vital role in ensuring the practical viability and sustainability of the co-culture system in large-scale wastewater treatment scenarios.

While co-culture systems hold promise for bioremediation, there is a need for more targeted research on their application for heavy metal treatment. Different heavy metals possess distinct chemical properties, rendering them more or less amenable to removal by specific microorganisms [180]. Co-culture systems may be more effective for certain heavy metals, such as lead or cadmium, while demonstrating reduced effectiveness for others, like mercury or arsenic [181]. The efficiency of co-culture systems may vary based on the initial concentration of heavy metals in the wastewater [171]. Extremely high concentrations of heavy metals may overwhelm the capacity of the co-culture system, leading to incomplete removal. Conversely, the system might need to be more cost-effective at low concentrations or require extended treatment times. Further investigations in this domain are warranted.

5. Future Directions and Research Perspectives

Investigating the scalability, cost-effectiveness, and overall environmental impact of integrating microalgae-based technologies within decentralized water treatment systems is critical [182]. This assessment will determine these systems' practical viability and sustainability on a larger scale. Further exploration is warranted in various critical aspects of microalgae wastewater treatment. The primary obstacle to achieving large-scale commercialization of microalgae technology lies in its economic feasibility [183]. Numerous untapped potential microalgae strains exist for wastewater treatment, emphasizing the crucial need to identify suitable and efficient microalgae. Research should delve into fine-tuning the cultivation conditions of microalgae to maximize their capacity for heavy metal uptake. This includes exploring factors like light intensity, temperature, pH, and nutrient availability to optimize biomass productivity and heavy metal removal efficiency. While algae-based techniques offer environmental and economic advantages, they present themselves as alternative biological methods for heavy metal removal in wastewater. However, this approach faces challenges that necessitate comprehensive research. The effectiveness of adsorption and method sustainability are the primary constraints for the practical treatment of heavy metal effluents using biosorbents [137,184]. Further investigations are needed to discern the specific affinity of various microalgal species towards different heavy metals. This knowledge is crucial for selecting the most effective microalgae strains for decentralized water treatment systems targeting specific heavy metal contaminants.

While biosorbents are generally accessible, and some can be recycled, they ultimately end up in landfills or require incineration. Therefore, an ongoing research direction for biosorbents in heavy metal wastewater treatment is identifying a continuous, sustainable source. Additionally, challenges persist in applying biological treatment to real-world heavy metal effluent due to the complexities associated with actual effluent treatment. Compared to conventional methods such as ion exchange, biosorption may demonstrate lower efficiency in handling high-concentration effluents. Nevertheless, it presents several notable advantages, including high removal efficiency, cost-effectiveness for low-concentration heavy metal effluents, and a reduced risk of secondary pollution.

The potential of algae in heavy metal degradation is significant. However, different algal species exhibit varying capacities for degrading specific pollutants. Thus, developing and engineering new algal species with enhanced capabilities, affinities, and selectivity for heavy metal bioremediation represent a promising avenue of research. Genetic engineering approaches also hold considerable potential for augmenting antibiotic degradation.

One prospective avenue is to conduct further studies testing the efficiency of microalgal-based water treatment using wastewater samples with varied impurities under conditions similar to definite wastewater sites. This will aid in assessing the practical applicability and performance of microalgal-based techniques in wastewater remediation. Research efforts should also optimize microalgae cultivation conditions to maximize biomass productivity and quality. This entails fine-tuning light intensity, temperature, pH, and nutrient availability. A comprehensive understanding of the optimal conditions for microalgal growth will contribute to producing high-quality biomass for biochar production.

Addressing the challenge of separating heavy metals adsorbed by simple biological cells from water and mitigating the generation of excessive sludge that hinders cyclic utilization can be achieved through strategic combinations with other materials. This approach not only enhances the adsorption efficiency of the adsorbent but also fortifies the strength of the biosorbent and facilitates better regenerability.

6. Conclusions

This comprehensive review offers a valuable synthesis of the substantial promise held by algae-based technologies in the removal of heavy metals. The focal point on biosorption and its diverse mechanisms presents a compelling approach to water treatment. The amalgamation of the examined studies underlines the adaptability and efficacy of microalgae in addressing heavy metal contamination in various environmental contexts. Microalgae have exhibited notable proficiency in capturing and detoxifying heavy metal ions from aqueous solutions through processes encompassing biosorption, bioaccumulation, and metabolic transformations. The review also underscores critical avenues for further investigation, including odor control, strain selection, clean water retrieval, and the impacts of stress on biomass productivity.

Given the global significance of wastewater management, the utilization of microalgae for phycoremediation emerges as an adequate remedy. This approach not only enhances biomass productivity but also yields valuable secondary products. Cultivating microalgae in wastewater presents a cost-effective avenue for growth and contributes to the overall advantages of wastewater treatment. The potential to manipulate metabolic pathways to augment the production of proteins, lipids, and pigments in response to nutrient imbalances underscores the adaptability of this method.

As we advance towards sustainable water management strategies, the integration of microalgae within decentralized water treatment systems represent a noteworthy progression. This review establishes a sturdy groundwork for forthcoming research aimed at unlocking the full potential of microalgae in confronting the urgent global issue of heavy metal contamination in wastewater. Future studies should be geared towards refining cultivation conditions, exploring the potential of microalgae biochar, conducting real-world applications, and uncovering additional domains where microalgal-based wastewater treatment can wield significant influence. Through the embrace of these innovative technologies, we possess the means to usher in a more environmentally conscious and ecologically balanced future. However, it is crucial to note that these issues need further assessment to fully comprehend their practical implications and refine the proposed strategies.

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