Seaweed-based biosorbent for the removal of organic and inorganic contaminants from water: a systematic review

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Abstract. Inadequately treated or untreated wastewater contributes substantially to the discharge of undesirable and hazardous substances into aquatic environments. Serious concerns are raised when certain pollutants become persistent and bioaccumulative upon release into the environment. Despite the existence of alternative wastewater treatment technologies, adsorption has consistently demonstrated its efficacy in the treatment of wastewater originating from diverse industrial sources. Adsorption is selected as the optimal method due to its numerous benefits, which include greater efficacy, reduced cost, and convenient accessibility in comparison to alternative treatments. Biosorption using naturally occurring seaweeds can, however, remove contaminants from a variety of sources, including heavy metals, nitrogen, phosphorus, and phenolic compounds, and dyes from the paper, textile, and printing industries. Biosorption utilizing seaweed has surfaces as a feasible substitute for existing technologies in the effective elimination of these pollutants from effluent on account of its environmentally sustainable nature, readily available resources, and cost-effectiveness. An economical adsorbent known as seaweed is examined in this article in order to remove contaminants from effluent. In an extensive table, the application of seaweed in effluent treatment is detailed. The majority of studies, according to published research, have utilized simulated wastewater; biosorption using seaweed to remediate actual wastewater has received less attention.

1 Introduction

Algae, which range in form from unicellular microalgae to multicellular macroalgae, are a diverse group of photosynthetic organisms that inhabit both freshwater and marine environments [1]. Seaweeds, or macroalgae, are organisms that exhibit rapid growth and bear a resemblance to plants; certain species have the capacity to attain a maximum length of 60 meters [2]. Seaweeds are utilized in a multitude of industrial processes on account of their diverse intrinsic properties. These processes include bioremediation and ecosystem balancing to prevent eutrophication; seaweed extract is employed as a biobased fertilizer for crops [4], anaerobic digestion generates energy-rich biogas [5], and seaweeds are even utilized as an edible fresh food [6]. Seaweeds, especially in Asia, are commonly utilized for the production of industrially significant phycocolloids [7] or ingested raw. Additionally, seaweed provides

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a natural polymer that is integrated into traditional plastic formulations in order to produce biodegradable plastics [8]. A summary of the industrial and domestic uses of various species of seaweeds is provided in the following section (Table 1).

In recent times, there has been an increasing scholarly focus on the potential adsorption-based treatment of effluent by seaweeds. Primarily due to the presence of sulphated polysaccharides in their fibril matrix and intercellular spaces, macroalgae have a remarkable capacity to bind trace metals and other pollutants. Indeed, potent ion exchangers are the hydroxyl, sulphate, and carboxyl groups present in polysaccharides; thus, they serve as critical sites for metal cation complexation [9]. The cell wall chemical compositions mentioned above exhibit significant variation across various species of seaweeds, with the most suitable composition contingent upon its intended function.

Table 1. Several applications of seaweed in industrial and domestic

Type	Seaweed	Applications	References
Brown seaweed	*Sargassum sp.*	Animal feed, supplements for poultry feed: environmental implications and feasibility	[10]
Brown seaweed	*Eisenia bicyclis*	Phlorotannins inhibit adiposity and disorders associated with obesity, the effects of Eisenia bicyclis stems' in vitro antioxidant and antiglycation properties on the gastrointestinal microbiota of rodents fed a high-sucrose, low-fibre diet are investigated	[11]
Red seaweed	*Kappaphycus alvarezii*	The progress made in the development of biodegradable plastics by incorporating natural polymers into conventional plastic formulations	[12]
Red seaweed	*Gracilaria gracilis*	As a source of multiple products utilized in the biotechnology, nutraceutical, and pharmaceutical industries	[13]
Red seaweed	*Gracilaria fisheri*	In rodents with colonic inflammation, oligosaccharides derived from Gracilaria fisheri ameliorate gastrointestinal dysmotility and gut dysbiosis when used as a flavor supplement or as a source of savory flavor for seafood products.	[14]
Green seaweed	*Arabidopsis thaliana*	Biochar production for the purposes of carbon sequestration and soil improvement	[15]
Brown seaweed	*Saccharina latissima*	Seaweed can be utilized as a circular nutrient (N and P) management system to mitigate eutrophication in aquatic ecosystems. Resource for the production of biobased fertilizers.	[16]

Type	Seaweed	Applications	References
		Potential for bioextraction and blue growth in Danish Saccharina latissima aquaculture—A model for eco-industrial production systems that combat climate change and marine eutrophication	
Brown seaweed	*Laminaria hyperborea*	Bioenergy (methane) potential of seaweed as a promising seaweed bioenergy option	[17]
Brown seaweed	*Saccharina japonica*	Bio-oil production, which can be used as a fuel for green electricity generation, and hydrothermal liquefaction-based combined heat, hydrogen, and power production: A comprehensive feasibility study	[18]

2 Materials and Methods

In this study, we collected the references (papers) from Indonesia in Google Scholar. Recent references published between 2019 until 2023 were retrieved using some keywords " Seaweed Biosorbent". The present status of research on Seaweed Application in Wastewater Treatment.

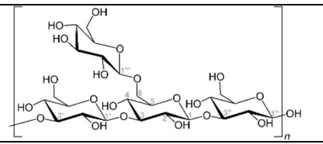
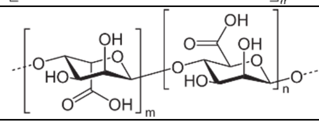
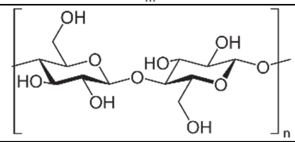
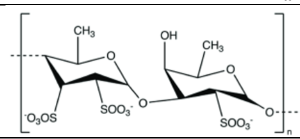
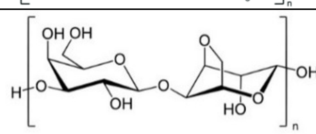
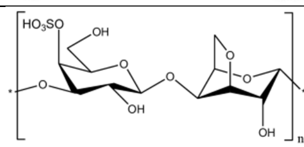
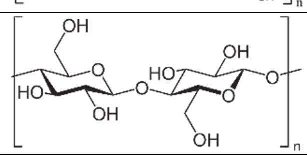
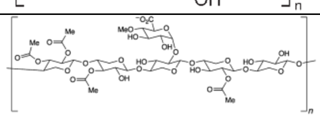
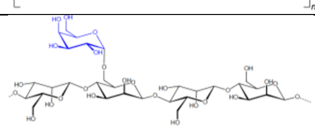
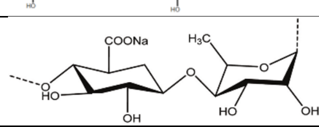
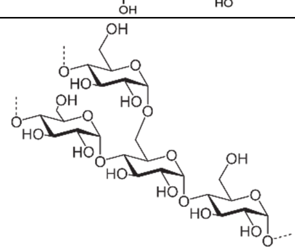
3 Results and Discussion

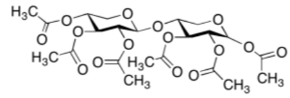
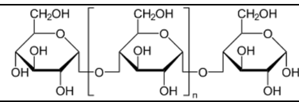
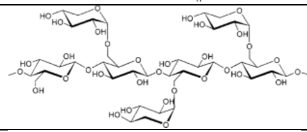
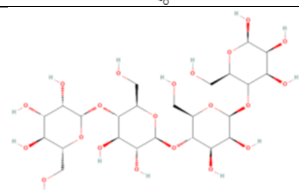
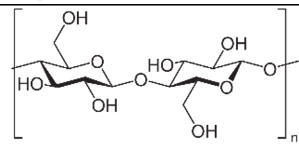
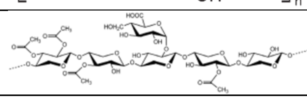
3.1 Seaweeds

Benthic algae, or seaweeds, are multicellular, large algae that grow faster than land plants. Because seaweeds have higher photosynthetic efficiencies than terrestrial plants, they acquire biomass faster [19]. It contributes significantly to the aquatic biomass, generates almost half of the primary productivity on Earth, and is widely utilized for feed and other purposes. Seaweed is quite abundant, thus during the past ten years, as demand for it has grown, seaweed agriculture has flourished. This results in a large amount of waste seaweed from various industrial processes, such as the food industry, where the seaweed needs to meet stringent quality requirements [20]. In a circular economy, these wastes can be used as a third generation of biomass for pharmaceutical, feed, agricultural, and biofuel applications. Since releasing these materials into the environment could gravely affect the marine ecology, it is imperative to reuse the waste material. It also implies that algae have a great deal of potential for use as a sustainable energy source and as high-value products [21].

Around the world, seaweed has over 10,000 different species and can grow up to 180 meters below the surface on solid surfaces like granite. It is one of the most important living resources in the ocean in terms of marine biodiversity. Seaweeds can be categorized into three classes based on the type of pigmentation: red (Rhodophyta), brown (Ochrophyta), and green (Chlorophyta). These seaweeds include a variety of bioactive compounds that have numerous uses in the medicinal, agricultural, and pharmaceutical sectors. The several varieties of seaweeds are listed in Table 1, along with corresponding polysaccharides and their molecular structures [22,23].

Table 1. Important seaweed polysaccharides and their chemical structure.

Seaweed	Polysaccharide	Chemical structure	Sugars	Ref
Brown seaweed (*Phaeophyta*)	Laminarin		Glucose, guluronate, sulphated fucose, mannuronate, mannitol	[19-12]
	Alginates			
	Cellulose			
	Fucoidan			
Red seaweed (*Rhodophyta*)	Agaropectin		D-galactose, D-fructose, 3,6-anhydro-D-galactose, glucose	[22-25]
	Carrageenan			
	Cellulose			
	Xylans			
	Mannans			
Green seaweed (*Chlorophyta*)	Ulvan		Glucose, xylose, uronic acids, rhamnose, galactose	[26-27]
	Starch			

	Xylopyranose			
	Glucopyranose			
	Xyloglucan			
	Glucuronan			
	Cellulose			
	Hemicellulose			

3.2 Seaweed Application in Wastewater Treatment

Seaweed, apart from its diverse industrial applications, has been extensively studied and implemented as an adsorbent in effluent treatment to substitute functional activated carbon. Wastewater is produced as a byproduct of any given process or activity. It may originate in households, factories, manufacturing sectors, petrochemical industries, aquaculture, agriculture, or landfills. The presence of both organic and inorganic contamination in these wastewaters is widespread. Organic pollution is defined as the existence of substantial amounts of organic compounds; the same holds true for inorganic pollution. These organic compounds are derived from various sources, including domestic sewage, urban runoff, effluents from agriculture and aquaculture, treatment facilities, and industrial effluents from processes such as paper and fiber manufacturing and food processing. Common organic pollutants include substances such as pesticides, fertilizers, hydrocarbons, phenolic compounds, plasticizers, biphenyls, lubricants, greases, detergents, and pharmaceuticals. Chemicals, dyes, benzene, toluene, ethylbenzene, and p-xylene (BTEX) are all classified as organic pollutants [28]. Typical sources of inorganic toxic pollutants include heavy metal ions, arsenides, and fluorides, which originate from industrial sectors including agriculture, paint manufacturing, and others. As a result of the stringent discharge standards established by environmental regulations, wastewater treatment has gained international attention. Numerous investigations are presently underway to examine various methodologies for treating distinct categories of effluent, and adsorption onto macroalgae is not a novel concept. It is concerned with the elimination of heavy metals, phenols, chemical oxygen demand (COD), and biological oxygen demand (BOD), among other things. The removal of carbon fixation, lipid production, total organic carbon (TOC), turbidity, and COD and BOD from wastewater using macroalgae has been the subject of very few studies, with the majority of research concentrating on the removal of heavy metals, phenols, and dyes [29].

3.2.1 Removal of Heavy Metals

In addition to its primary application in effluent purification, seaweed reduces or eliminates toxic heavy metals. The elimination of heavy metals from effluent has emerged as a substantial environmental concern in recent times, primarily due to the detrimental effects that these metals have on living organisms and the environment, particularly when they exceed regulatory limits. Certain heavy metals, even at minute concentrations, are carcinogenic and deleterious [30]. They are capable of readily accumulating in living organisms and do not biodegrade. The accumulation of heavy metals in soil and groundwater is an increasing matter of concern. Soil parent material (lithogenic source) and various anthropogenic sources contribute to the presence of heavy metals in wastewater. These sources include metal smelters, the paint industry, fertilizers, agricultural processes, leather tanning, electroplating, alloy and battery manufacturing, as well as the disposal of other industrial waste materials.

The heavy metals that cause concern on a global scale are chromium (Cr), nickel (Ni), copper (Cu), arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) [31]. Pb exhibits severe toxicity towards the reproductive system, nervous system, and kidneys, while Hg damages structures and functions as a neurotoxin by impeding the enzymatic processes involved in regular neurotransmission. Exposure to As in the environment may also result in noncancerous health complications, including the development of tumors unrelated to cancer. As it is absorbed from soils by plants, transported through water bodies into the environment, and accumulated in numerous types of food crops and aquatic plants, it poses a threat to human health. Research has established that rice could potentially serve as the principal source of inorganic As. Human activities, including the production of cement and construction materials, welding alloys, foundries, steel and alloy manufacturing, the electroplating industry, lamps, mines, urban and industrial waste incineration, coal ash, tanneries, fertilizers, and wood preservatives, contribute to environmental exposure to Cd [32].

Nickel toxicity towards plants may induce modifications in root, stem, and leaf development, in addition to germination. Furthermore, it disrupts vital plant physiological processes, including photosynthesis, water balance, and mineral nutrition. Additionally, plant metabolic processes are impacted by nickel's capacity to produce reactive oxygen species, which induce oxidative stress. Studies have also demonstrated that nickel exposure in animals causes inflammation of the lungs and liver and spleen, as well as cardiac toxicity. Chromium, being one of the hazardous elements that finds extensive application in industry, specifically in coatings and metal platings as corrosion inhibitors, ultimately infiltrates water bodies through effluents discharged from various sectors including tanneries, textiles, electroplating, mining, printing, photography, and pharmaceuticals. Excessive chromium concentration results in oxidative injury to cells and genotoxicity [33].

Additional heavy metals coexist in nature, and each heavy metal presents a distinct hazard to both the environment and human health when it surpasses permissible thresholds. Reliable methodologies are imperative in order to effectively eliminate heavy metals from effluent and aquatic environments. Considerable effort has been dedicated to the efficient elimination of heavy metals from effluent. To date, a wide range of treatment approaches have been implemented to decontaminate heavy metals. These include electrodialysis, chemical precipitation, reverse osmosis, ion exchange, ultrafiltration, nanofiltration, coagulation, flocculation, and flotation [34]. However, these approaches have their own drawbacks in comparison to alternative approaches. Adsorption, due to its cost-effectiveness, versatility, simplicity, and efficacy, has emerged as the favored method for the removal of heavy metals. Aside from this knowledge, the primary obstacles to the widespread use of activated carbon, a common adsorbent, are its exorbitant cost and restricted reusability. From this standpoint, biosorption has emerged as a potentially effective technique characterized by its minimal cost, high efficiency even at minute quantities, absence of supplementary nutrient needs, user-friendly operation, and absence of adverse environmental impacts. Seaweed's natural ecosystem-balancing function, in conjunction with the aforementioned characteristics, has prompted an abundance of research into the adsorbent performances and efficiencies of various seaweed varieties in the removal of heavy metals from diverse wastewaters.

Each of the three seaweed groups—green, brown, and red—has been extensively implemented in a multitude of effluent treatment processes. Simulated and actual effluent are evaluated in order to determine the adsorption capacity of seaweed. In conclusion, there is a scarcity of research that specifically examines adsorption using actual wastewater, whereas a substantial number of studies have employed aqueous solutions and simulated wastewater. Pb, Zn, Cd, Ni, and Fe were obviously the primary elements targeted in the majority of the interventions [35]. Research was also conducted on ion exchange theory, in which the sequestration of heavy metals present in effluent is the predominant mechanism. Additionally, it was observed that the quantity of ions bound to biomass was comparable to the quantity of metals displaced from the biomass. Indeed, the inherent ability of seaweed to exchange cations was adequately elucidated by the functional groups, including carboxylic and sulfonic groups, that were present on the outer surfaces of every red, brown, and green seaweed. The aforementioned variations in cell wall chemical compositions among distinct species of seaweeds account for the significant disparity in metal biosorption affinity between brown, green, and red seaweeds. This discrepancy is primarily due to differences in the cell wall matrix.

3.2.2 Removal of Dyes

Adsorption treatments are preferred treatment methods for the elimination of dissolved organic pollutants, such as pigments originating from various industrial sectors including textile, paper, pulp, food coloring, cosmetics, and carpet manufacturing. The dyes utilized in these sectors are reportedly in significant quantities [36]. These dyes not only have the potential to cause cancer but are also detrimental to aquatic organisms and mammals. The majority of textile industry-consumed dyes are resistant to aerobic digestion and do not degrade biologically. Malachite green and methylene blue are the two most frequently encountered dyes in wastewater. An assortment of inexpensive adsorbents were investigated and implemented to eliminate dyes, concurrently with the pursuit of more cost-effective and readily accessible substances [37]. Methylene blue removal agents include activated carbons (AC), including those derived from karanj fruit hulls and olives, as well as waste-based ACs, including those derived from cashew nut shells, Ficus carica bast fiber, Daucus carota plant, and Salix psammophila plant. Adsorbents derived from waste materials, including potato peel-based Limonia acidissima ACs, Daucus carota plant-based ACs, are employed for the purpose of eliminating malachite green dye. The prevalent dyes that cause pollution in effluent are detailed in Table 4, which includes malachite green and methylene blue. Seaweed has been employed as an adsorbent in the preponderance of removal processes; to this day, numerous ongoing investigations utilize natural seaweeds [38]. The adsorption of dyes by seaweed can be primarily attributed to the biosorption process-involved active functional groups, including hydroxyl, carboxyl, carbonyl, amine, and sulfate. Research on kinetic reactions revealed that the data exhibited a strong agreement with the pseudo-second-order kinetic model, suggesting that the chemisorption mechanism was utilized in the process of dye removal from effluent [39].

3.2.3 Removal of Nitrogen and Phosphorus

Due to anthropogenic sources, the presence of excessive inorganic nutrients, such as nitrogen and phosphorus, causes eutrophication in water bodies, which eventually results in an increase in the frequency of detrimental algal blooms and hypoxia. In the majority of freshwater and marine ecosystems, eutrophication has emerged as the most significant water quality concern due to its detrimental effects on coral reef health and community collapse, heightened frequency of fish mortality, and diminished water transparency. Ultimately, these nutrients may also be utilized to promote the proliferation of economically valuable aquatic vegetation, such as seaweeds [40]. The function of seaweed aquaculture in harmonizing ecosystems is not novel. Its most essential characteristic is seaweed's capacity to store a substantial amount of nitrogen in its tissues. The bioextraction of inorganic nutrients from seaweed has garnered significant interest from both academics and authorities.

Experimental kinetic data suit the pseudo-first order model satisfactorily, according to studies, which conclude that the biosorption process involves both extracellular and intracellular transfer [41]. Extracellular transfer encompasses both chemical bonds (chemisorption) and the attraction of phosphate by active sites on the biosorbent surface (physisorption). In contrast, intracellular transfer involves both biotransformation and intracellular accumulation. Additionally, the data provide corroborating evidence that the pseudo-second-order model is the most suitable [42]. CheMIsorption is described by a pseudo-second-order equation that incorporates valency forces resulting from the sharing or exchange of electrons between the biosorbent and adsorbate. Therefore, it can be concluded that the process of phosphate biosorption onto seaweed may involve multiple steps, including chemisorptions [43].

4 Conclusion

The considerable variety of documented applications of seaweeds has garnered the interest of numerous researchers and emphasized the significance of seaweeds during this era. The aforementioned discussion on the various functions and applications of seaweeds will ensure a consistent supply and cultivation of superior raw seaweed materials. It is anticipated that sectors dependent on seaweeds may contribute to socioeconomic development. Undoubtedly, there are numerous opportunities that remain to be discovered in these singular yet resourceful species, such as seaweeds, which are among the most intriguing and intricate forms of life. With this article, an overview of seaweeds in the wastewater treatment industry was intended to be presented. Clearly, biosorption utilizing seaweed is a prospective technique due to its use of a naturally occurring raw material, its higher efficacy, and the low cost of treatment investment. Significantly fewer studies employed actual effluent for remediation purposes, with the majority employing simulations. As a result, it is suggested that forthcoming research places greater emphasis on the purification of actual effluent. The utilization of synthetic or simulated seaweed-based wastewater treatment methods may encounter certain limitations due to their failure to replicate the intricate characteristics of natural wastewater. Furthermore, it is possible that the outcomes derived from simulated wastewater lack practical applicability when it comes to actual wastewater treatment facilities.

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