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Microbial Biopolymers: From Production to Environmental Applications—A Review

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Abstract: Industrial evolution and agricultural expansion, explained by continuing population growth, have rendered enormous problems for the world throughout the past few decades, primarily because of waste generation. To reduce environmental impact and dependence on fossil fuels, scientists have explored replacing synthetic polymers with environmentally friendly and sustainable alternatives in many emergent applications. In this regard, microbial biopolymers have gained special attention. Many biopolymers originating from various strains of bacteria, fungi, and algae have been reported and their possible applications have increased rapidly. This review focuses on the wide range of microbial biopolymers, their characteristics, and factors influencing their production. The present study also describes the environmental applications of microbial biopolymers. The use of these biopolymers is very attractive as a value-added and sustainable approach to wastewater treatment. By acting as adsorbents, coagulants, and flocculants as well as filters in membrane processes, microbial biopolymers shine as promising solutions beyond conventional methods. They can be integrated into various stages of the treatment process, further enhancing the efficiency of wastewater treatment methods. Microbial biopolymer applications in bioremediation and soil stabilization are also reviewed. Several studies have demonstrated the strong potential of biopolymers in soil improvement due to their ability to minimize permeability, eliminate heavy metals, stabilize soil, and limit erosion. Challenges related to scaling up and the downstream processing of microbial biopolymers, as well as its future perspectives in environmental applications, are also discussed.

Keywords: microbial biopolymers; production; characteristics; environmental applications

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1. Introduction

The worldwide population is consistently expanding, necessitating the expansion of the food supply and putting pressure on the limited available natural resources. This shift has ushered the agricultural sector into forming a noteworthy amount of waste. The environment is frequently being polluted due to rapid industrialization and the shift of populations to urban areas, leading to several concerns such as water pollution, waste expulsion in the surroundings, and environmental deprivation [1,2].

Faced with this significant increase in the global population, modern agriculture is proving to be an advantageous solution since it offers the opportunity to upsurge crop yield. However, it also led to an increase in the global carbon footprint, and the generation of waste from farming impacts the economic and social sectors. As per [3], agriculture comprises around 38% of the terrestrial surface area on Earth. The Food and Agricultural Organization (FAO) stated that the amount of food wasted annually during farming, post-harvesting, and agriculture processing was 1.3 billion tons [4]. The utilization of agricultural residues and their transformation into biopolymers presents a great opportunity to reduce the global carbon footprint, considering that the landfilling of residue promotes global warming.

The increasing concern for diverse environmental problems has led to the development of new approaches to diminish its deteriorated effects. Amidst various approaches, the formation of microbial biopolymers is a method that has earned great engagement due to its superiority over synthetic biopolymers in terms of sustainability, biodegradability, cost-effectiveness, structural diversity, non-toxicity nature, and bioactivity. This is due to a customized range of functional groups with defined molecular weights. Biodegradability relies on its chemical network so that it can be debased by biological attack. Moreover, the approach to the degradation of biopolymers relies on factors such as dampness, temperature, and pH. However, various functional, thermal, morphological, and rheological tests are usually executed to check its capability [5].

Nowadays, many synthetic polymers are more admissible and have become a regular part of our lives, including dyes, Teflon, plastic polyester, etc. Biopolymers are described as a considerable group of molecules separated from their cell walls and based on repeated functional units at a specific level. Microbes are cell-forming manufactories that can transform carbon and nitrogen into extensive amounts of extracellular, intracellular, and capsular biopolymers. Based on chemical configurations, microbial biopolymers are classified into polyphosphates, nucleotides, polysaccharides, polyamides, and polyesters. Among all polyesters, biopolymers are widely adequate and are manufactured through metabolic pathways [6]. Some microbial biopolymers have drawbacks such as poor functional and mechanical attributes and sensitivity towards chemicals; these can be mitigated by developing hybrids or nanobiocomposites using nanofillers.

Many researchers have recently concentrated on the utilization of biopolymers and their potential as biomaterials. Microbial biopolymers have applications in the food, textile, agriculture, and pharmaceutical industries due to their unique characteristics. Environmental applications of microbial biopolymers have grown in popularity during the last decade. Biopolymers could be generated in large quantities for cutting-edge applications such as biofilm matrices, bio-flocculants, heavy metal adsorption, bioremediation, etc. [7–10]. This review focuses on microbial biopolymers, their classifications and characteristics, the factors influencing their production, and their emerging environmental applications.

2. Microbial Polymers

Based on origin, microbial biopolymers are categorized into three categories: (i) From bacteria, (ii) From fungi, and (iii) From algae. Bacteria are capable of producing both intracellular and extracellular biopolymers. In bacterial metabolic synthesis, polysaccharides, polyamides, polyesters, and polyphosphates are originated as metabolites [11,12]. Biopolymers produced from different bacterial strains are represented in Table 1.

Table 1. Fabrication of biopolymers from Bacteria.

Biopolymer	Category	Bacterial Strain	References
Alginate	Polysaccharide	*Laminaria digitata* spp., *Macrocystis pyrifera* *Pseudomonas* spp.	[13] [14]
Bacterial Cellulose	Polysaccharide	*Komagataeibacter saccharivorans* *Komagataeibacter* spp. FXV3, *Komagataeibacter* spp. NFXK3, and *K. intermedius* LMG 18909	[15] [16]
β-glucan	Polysaccharide	*Bacillus subtilis* *Xanthomonas campestris*, *Bacillus natto*	[17] [18]
Hyaluronic acid	Polysaccharide	*Mytilus galloprovincialis* *Streptococcus zooepidemicus*	[19] [20]
Polyhydroxyalkanoates	Polyester	*Bacillus megaterium* OUAT 016 *Bacillus cereus* RBL6 and *Pseudomonas pseudoalcaligens* RBL7	[21] [22]
Poly (γ-glutamic acid)	Polyamide	*B. megaterium* WH320 *B. licheniformis* 9945a and *B. subtilis* natto	[23] [24]
Xanthan gum	Polysaccharide	*Xanthomonas campestris* bacterium *Xanthomonas campestris* WXLB-006	[25] [26]

Biopolymers produced from both fungi and algae are represented in Tables 2 and 3.

Table 2. Fabrication of biopolymers from Fungi.

Biopolymer	Category	Fungal Strain	References
β-glucan	Polysaccharide	*Aureobasidium pullulans* ATCC 15233	[27]
		Aureobasidium pullulans MTCC 1991	[28]
		Aureobasidium pullulans HIT-LCY3	[29]
		Aureobasidium pullulans ATCC 15233	[30]
		Saccharomyces cerevisiae	[31]
		Lasiodiplodia theobromae CCT 3966	[32]
		Aureobasidium thailandense NRRL 58543	[33]
		Saccharomyces cerevisiae, *Aspergillus oryzae*	[18]
		Rhizopus stolonifera	[34]
		Mucorales	[35]
		Roccella montagnei.	[36]
		Absidia coerulea and *Gongronella butleri*	[37]

Table 3. Fabrication of biopolymers from Algae.

Biopolymer	Category	Algae Species	References
Alginate	Polysaccharide	*Sargassum cristaefolium*	[38]
		Nizimuddinia zanardini	[39]
Polyhydroxyalkanoates	Polyester	*Synechococcus subsalsus*	[40]
		Chlorella minutissima	[40]
		Spirulina spp.	[41]
		Stigeoclonium spp. B23	[42]
		Chlorella fusca	[43]
		Chlorella spp.	[44]
		Microcystis spp.	[45]
Polylactide	Polyester	*Corallina elongata*	[46]
		Scenedesmus abundans	[47]

The array of biopolymers that fungi effectively create possesses a characteristic of numerous interests, which renders them beneficial assets for broad-spectrum environmental applications, including as biosurfactant agents [48] and in soil carbon sequestration [49], enzyme immobilization [50], the biosorption of heavy metals, and soil emendation [51]. Algae are photosynthetic microbes that can be grown on wastewater and are not only reliant upon pure water. Among all biopolymers, polysaccharides and polyesters have significant importance from an environmental perspective. A general overview of the production of several microbial biopolymer studies through fermentation is provided in Table 4. It illustrates the microbial biopolymers synthesized from various carbon and nitrogen sources, the nutrients used in fermentation, and the yields produced under ideal fermentation conditions, as well as emerging environmental applications. In the subsequent segment, significant microbial biopolymers and their environmental applications are reviewed.

Table 4. Overview of the production of microbial biopolymers by fermentation and its environmental applications.

Biopolymer	Microbial Strains	Carbon /Nitrogen Source	Nutrient Used	Duration of Fermentation	Type of Fermentation	Fermentation Conditions (Temperature, pH, etc.)	Maximum Yield (g/L)	Environmental Application	References
Polyhydroxybutyrate	*Bacillus subtilis* NG05	Sugarcane Molasses (Maltose)	Beef extract, Peptone	18 h	Batch	pH = 7, 30 °C	4.94	Waste utilization and development of Bioplastic	[52]
	Ralstonia eutropha ATCC 17,699	Glycerol	NaH_2PO_4, $(NH_4)_2SO_4$, $MgSO_4 \cdot 7H_2O$, K_2HPO_4	62 h	Fed-batch	pH = 10, 60 °C	68	Potential as biodegradable material	[53]
Chitosan	*Penicillium citrinum*	Rice Straw	Potato dextrose	10 days	Solid State	pH = 6.5–7.5, 30 °C	7	Heavy metal removal	[54]
	Rhizopus oryzae, *Mucor* sp. (MTCC 3340), *Absidia coerulea* (MTCC 1335)	Tannery fleshing waste	Yeast extract	70 h 140 h 200 h	Submerged	pH = 8.5, 25 °C	1.53 2.74 2.05	Utilization of leather flesh waste	[55]
	Gluconacetobacter xylinus	Glucose	Yeast extract, Peptone	10 days	Static	pH = 5; 30 °C	-	Detection of *Staphylococcus aureus*	[56]
	Gluconacetobacter sp.	Apple waste	2% Fructose	7 days	Static	pH = 6.4; 28 °C	-	Removal of chromium ions	[57]
	Gluconacetobacter xylinus	Orange peel	Yeast/Peptone extract	8 days	Static	pH = 4.75; 30 °C	6.13	Waste reduction	[58]
Hyaluronic Acid	*Streptococcus zooepidemicus*	Cheese whey	Yeast extract	2 days	Batch	pH = 6.7; 37 °C	3.37	70 % cost reduction as compared to synthetic media	[59]
Xanthan Gum	*Xanthomonas campestris*	Wastewater, Malt	Yeast broth	72 h	Batch	pH = 7; 28 °C	15.56	Improved oil recovery	[60]
	Xanthomonas campestris	Wastewater, Malt	Yeast broth	120 h	Batch	pH = 7; 28 °C	-	Enhanced oil recovery	[61]
β-glucan	*Lasiodiplodia theobromae* CCT 3966	Sugarcane straw	Yeast extract, malt extract, peptone	72 h	Batch	pH = 7; 30 °C	3.28	Waste utilization: conversion of cellulose to glucose	[32]
	Xylaria sp. BCC 1067	Glucose	Malt extract, peptone	28 days	Batch	pH = 7; 25 °C	0.115	Antifungal activity	[62]
Alginate	*Azotobacter vinelandii*	Sucrose	$K_2HPO_4 \cdot 3H_2O$, $CaSO_4 \cdot 2H_2O$, NaCl, $MgSO_4 \cdot 7H_2O$, $Na_2MoO_4 \cdot 2H_2O$, $FeSO_4 \cdot 7H_2O$	20 h	Batch	pH = 7; 30 °C	3.06	Nitrogen fixation	[63]
	Azotobacter vinelandii ATCC 9046	Sugar beet molasses/maltose/starch	Yeast extract,	72 h	Batch	pH = 7.2; 30 °C	5.44	Adsorbent for heavy metals	[64]
γ-PGA	*Bacillus subtilis*	Sago and Soyabean	Yeast Extract	5 days	Batch	pH = 6.5; 37 °C	35.32	Act as a Bio flocculant	[65]
	Bacillus subtilis	Glucose	Beef extract, Yeast extract, Peptone	2 days	Batch	pH = 7, 37 °C	25.38	Act as a Bio flocculant	[66]
Pullulan	*Aureobasidium pullulans*	Potato starch	Yeast extract, peptone	5 days	Batch	pH = 6; 26 °C	23.47	Could be used as a potential purifying agent and as a flocculant for heavy metal reduction	[29]
	Aureobasidium pullulans	Sucrose	Barley malt extract	170 h	Batch	pH = 6; 26 °C	50	Biosorbent of heavy metals; Protective agent	[67,68]
Polylactide	*Indigenous microorganism*	Mango Peel Waste	-	6 days	Anaerobic submerged	pH = 10, 35 °C	17.48	Cost-effective biodegradable material	[69]
	Lactobacillus delbrueckii	Broken rice	Yeast Extract, Peptone	50 h	Solid State	pH = 6, 40 °C	79	Cost-effective Biodegradable material	[70]

2.1. Bacterial Cellulose

Waste, including agricultural residue, food waste, and industrial leftovers, can give bacteria the nutrients and habitat they need to create bacterial cellulose. Examples of raw materials used for obtaining bacterial cellulose are by-product streams from sugarcane jaggery waste [71] waste streams from biodiesel and confectionery industries [72], oat hull [73], rice bark [74], corn stalk [75], fruit juices [76], Nylon 6-6 hydrolysate [77], cotton-based textile waste [78], the wastewater of fermentation industries [79], etc. Bacterial cellulose is chiefly isolated by both Gram-positive bacteria and Gram-negative bacteria such as *Komagataeibacter* spp. *Acetobacter* spp., *Sarcina ventriculi*, *Pseudomonas* spp., etc. [15,80,81]. In comparison to plant-derived cellulose, cellulose produced by bacteria offers a range of amenities, which include high levels of purity, superior mechanical and thermal attributes, long-term sustainability, better water- and oil-holding capacities, high surface areas, and biodegradable attributes [82,83]. Bacterial cellulose is a linear-chain polysaccharide made up of repeating glucose monomeric units linked by β (1-4) linkages. It has a complex structural arrangement with ample hydroxyl groups and robust intermolecular interactions that hamper it from dissolving in water. It is remarkably resistant to decomposing in water because it establishes an interconnected system of linked strands of cellulose, which are bound jointly by bonds of hydrogen [84]. There are some challenges involved in scaling up bacterial-cellulose production by fermentation. Agitated fermentation and static fermentation are both viable methods for producing Bacterial cellulose. Zhong [85] investigated that bacterial cellulose produced by static fermentation is a more laborious and lengthy process than agitated fermentation, also static fermentation provides poor yield as compared to agitated fermentation. Zhong [85] also concluded that due to the high cost of bacterial-cellulose production, its application is limited as compared to plant-based cellulose. Consequently, novel affordable nutrient sources such as fermentation effluent, sugarcane molasses, and waste from fruits could additionally be utilized for the bacterial-cellulose upscaling manufacturing process. The manufacturing process of bacterial cellulose and its commercial usage has been constrained by high production costs as well as low yield. Bacterial cellulose-producing bacteria have no capacity to co-produce additional compounds with cellulose, such as lignin, pectin, and hemicellulose. Bacterial cellulose has a significant purity advantage over cellulose generated from plants. Furthermore, bacterial cellulose is biocompatible since complementary polymers and other contaminants are absent from it [86]. Due to its biocompatibility and biodegradability, it offers wide applications. Galdino et al. [87] developed a filter based on bacterial cellulose for the elimination of oil from wastewater. Their findings suggested that bacterial cellulose could be used as an alternative material for oil filter development. Cazón et al. [88], Cielecka et al. [89], and Chiaoprakobkij et al. [90] utilized bacterial cellulose as a biomaterial to improve the ductility, tensile strength, biocompatibility of composites. Similarly, Alves et al. [91] made filter membranes from bacterial cellulose for industrial water treatment. Based on bacterial cellulose, various potential biosensors have been developed for multifarious applications [92]. Some were developed for the detection of bacteria and viruses [56,93], antibiotics [94], heavy metals [57,95], dyes [96], and pollutants [97]. Moreover, many researchers have investigated bacterial cellulose-based hydrogels for the removal of heavy metals and dyes [98–100].

2.2. Microbial Hyaluronic Acid

A recurring mixture of D-glucuronic acid and D-N-acetyl glucosamine connected by β (1-3) and β (1-4) linkages, respectively, makes up hyaluronic acid, also known as hyaluronan [101]. It can be isolated from animal tissues like roosters' crest, cartilage, vitreous humor, and umbilical cords through a microbial fermentation process with the help of bacterial and yeast strains such as *Streptococcus* spp., *Mytilus galloprovincialis*, *Pichia pastoris*, and *Pseudomonas* spp. [19,20,102,103]. The D-glucuronic acid and N-acetyl glucosamine moieties of hyaluronic acid are generated from glucose-6-phosphate and fructose-6-phosphate, correspondingly, by two different pathways [104]. The molecular makeup of the hyaluronic acid molecule reveals that it has several hydroxyl and carboxyl groups, which can result in a great deal of intramolecular and intermolecular hydrogen bonding in solutions. These bindings contribute to overall stiffness and exhibit gel-formation abilities [105,106]. Nevertheless, the advancement of microbial means of extraction has been prompted due to the obstacles in managing tissues from animals, excessive expenses, and moral complications related to hyaluronic acid generated from animals. Hyaluronic acid is the least explored biopolymer for environmental applications. The main challenge involved in microbial hyaluronic acid production is its low yield because of the extremely viscous nature of the broth, which makes it challenging to regulate the mixture and rapid transfer of oxygen. There is fierce competition for the same precursor molecules that are essential for cellular growth and the generation of hyaluronic acid. In addition, the build-up of lactic acid—the main metabolic waste product in hyaluronic acid fermentation activities—has a significant negative effect on both cellular development and hyaluronic acid production. Different approaches to prevail over these challenges include the systematic screening of proficient strains, optimization of tailored culture media, and development of sophisticated cultivation procedures [107–110]. Zhang et al. [111] recently developed a hybrid hydrogel for plant growth regulation and the adsorption of heavy metal ions. Taşdelen et al. [112] developed a composite hydrogel to remove manganese in wastewater. When it comes to fish waste (head, skin, fin) specifically, animal waste poses a serious environmental risk because almost 50% of the tissue is thrown away. It is essential to pursue initiatives related to research and development aimed at developing novel approaches that make it easier to obtain this biomaterial while also minimizing difficulties with waste management, emphasizing the significance of those initiatives. Refs. [113,114] extracted hyaluronic acid from *Scyliorhinus canicula* discards with the help of *Streptococcus zooepidemicus* strains. They concluded that among all approaches, fed-batch operatory was valuable in achieving a high yield and was beneficial in reducing the overall cost of production. Amado et al. [115] extracted microbial hyaluronic acid from agro-industrial by-products. They obtained a maximum yield of 3.48 g/L hyaluronic acid among three culture media. Moreover, hyaluronic acid has potential application as a nanofiber due to its water-resistant characteristics. Um et al. [116] and Wang et al. [117] constructed a water-resistant nanofiber with an electrospinning and electro-blowing technique.

2.3. Xanthan Gum

The commercially grown *Xanthomonas campestris* bacteria secretes xanthan gum, an exopolysaccharide [118]. It is a high molecular weight microbial biopolymer that belongs to the heteropolysaccharide category. Primarily, the carbon supply for the production of xanthan gum comes from the substrate's glucose and sucrose. Xanthan gum is constituted of a mixture of glucuronic acid, mannose, and glucose units of repetition adjoined by β (1-4) linkages. It is generally obtained by an aerobic fermentation approach accompanied by precipitation in isopropyl alcohol. The kind of fermenter employed, the way it is used (batch or continuous), the culture medium, and the growth parameters, such as the pH level, temperature, and oxygen in the medium, all affect the synthesis of xanthan [119]. It readily dissolves in cold water and displays strong pseudoplastic flow characteristics [120]. Its structural arrangement is extremely branched and complex. It is one of the most promising and commercialized biopolymers that has been used for the entrapment of living cells [121]. Because of its structural divergence and rheological characteristics, it can be employed for a variety of applications. Sulaiman et al. [122], Liu et al. [123], and Feng et al. [124] investigated the application of xanthan gum for soil stabilization and to improve soil water-retention efficacy. Ramos de Souza et al. [125] and Keykhosravi et al. [126] employed xanthan gum to boost oil recovery. Oil recovery was improved due to wettability modification, and increased water viscosity was achieved using a nano-polymer suspension. The findings of Ko et al. [127], Njuguna and Schönherr [128], Mohafezatkar Gohari et al. [129], Taktak and Özyaranlar [130], Hosseini et al. [131], and Hu et al. [132] described that because of its exceptional selectivity, recovery, and reusability after regeneration, xanthan gum is a phenomenal biomaterial for the immobilization of heavy metals and an adsorbent of cationic dyes. Moreover, xanthan can also be used for developing edible films and coatings for the shelf-life extension of agriculture and horticulture produce [133–135]. Palaniraj and Jayaraman [119] claimed in their study that by using ultrafiltration after fermentation, the consumption of energy while recovering xanthan gum can be reduced by 80%. The main challenges involved in producing xanthan gum through microbial fermentation are viscosity obstacles. They also concluded that by employing a centrifugal-packed bed reactor, the viscosity problem can be overcome. Additionally, it was found that membrane-assisted deposition significantly increased membrane flow while using fewer accumulating solutes, leading to a significant increase in separation efficiency.

2.4. Microbial β-Glucan

Traditionally, based on raw materials, the isolation of β-glucan is grouped into cereals and non-cereals with varying compositional structures. Additionally, certain microorganisms can also create exopolysaccharides, that may be able to meet demand on an industrial scale. Exopolysaccharides from microorganisms are advantageous replacements for natural plant polysaccharides because of their distinctive metabolic characteristics. The source from which beta-glucan was acquired affects its characteristics. Industrial scale-ups of β-glucan have some constraints—notably, lengthy extraction times and high costs—associated with the process [136]. This microbial biopolymer exists both intracellularly (typically as a storage unit of carbohydrates) and extracellularly (generally as a capsule or as slime layers and biofilms). Furthermore, there are two types of microbial beta-glucans: linear and branched. Singular β (1-3) or β (1-6) glucose units may make up linear beta-glucans. Branched beta-glucans are identified by the combination of β (1-3) and β (1-6) connections [137]. Zhu et al. [136] summed up the production of β-glucan using different processes and compared the yields and production times. The biological activity of obtained β-glucan depends upon raw material, manufacturing processes, and purifying techniques [17,18,32]. β-glucan is a significant antifungal agent for crop protection. Chavanke et al. [138] reported the valuable impact of β-glucan in plant defense pathways, resistance against disease-causing microorganisms, and in response to changing environmental circumstances. Anusuya and Sathiyabama [139] observed the antifungal effect of β-glucan against the destructive fungus *P. aphanidermatum*, which mainly harms crucial crop plants. Similarly, Jayasekara et al. [62] and Anusuya and Sathiyabama [140] reported the antifungal efficacy of β-D glucan against the *Saccharomyces cerevisiae* strain and in the prevention of rhizome rot disease of turmeric, respectively. Vetvicka [141] examined the impact of β-glucan against environmental toxins like mycotoxin, aflatoxin, and depleted uranium.

2.5. Alginate

Alginate is majorly extracted from seaweed species, e.g., *Sargassum cristaefolium*, *Laminaria digitata*, and *Ascophyllum nodosum* [13,38,39], and from some bacterial strains, e.g., *Pseudomonas* spp. and *Azotobacter* spp. Alginate is an unbranched water-soluble hydrocolloid that belongs to the polysaccharide category. Guluronic and mannuronic acid-repeating monomeric units are adjoined by glycosidic connections to form alginate. The arrangement and composition of monomers designate the overall characteristics of alginate [142]. Alginates could provide a cross-link (egg-box) structure through ionic interactions and trapping cations. This chelating structural arrangement provides alginate with the capability of quenching heavy metals from wastewater. Hydrogels can be formed from alginate with the addition of calcium ions, which are usually stimulated by the incorporation of acids such as acetic acid. The potential of alginate-based hydrogels and their usage in the removal of dyes and heavy metals have been extensively studied by numerous researchers [143–150]. Furthermore, alginate is considered to remove toxic pollutants from wastewater [151,152]. Also, after contaminant elimination, algal biorefinery is a sustainable approach to recovering biochemicals (carotenoids, acetic acid, lactic acid, and eugenol), bioenergy (biohydrogen, biomethane, bioethanol, and biogas), and biomaterials (biochar, films, coatings, and carbon fiber) from biomass [153,154] from algal biomass. As for environmental applications, Lu et al. [155] developed sodium alginate beads for wastewater treatment, which were pH-sensitive and had controllable swelling behavior, using a post-cross-linking approach. The smart polysaccharide was found to be efficient for Cu^{2+}, Ag^{+}, Fe^{3+}, and methylene blue with a maximum adsorption capacity of 54.9, 82.8, 135.5, and 572.7 mg/g, respectively. In another study, Da Cunha et al. [156] fabricated pH-stimuli-responsive alginate/chitosan microcapsules containing linseed oil for the active corrosion protection of carbon steel. Benzotriazole, used as a corrosion inhibitor, was added through a layer-by-layer approach. The use of such smart biopolymers, known for their instantaneous response to pH variations, led to an observed enhancement in the release of the corrosion inhibitor at pH levels below 5. In the study conducted by Gopishetty et al. [157], sodium alginate and polyvinyl alcohol were used to create thin, porous hydrogel films with tiny pores. Due to the stimuli-responsive properties of sodium alginate, these smart hydrogel films demonstrated an ability to regulate the dimensions of the pores in response to changes in pH, thereby enhancing their efficiency in the process of separation. From advanced drug delivery systems to adaptable separation membranes, smart biopolymers hold great promise in shaping the future of technology and science. As ongoing research delves deeper into their potential, we can anticipate even more ground-breaking developments that capitalize on their unique properties. There are some limitations involved in using alginate as a biomaterial, such as mechanical stability, broad ranges of pore size distribution, mechanical stability, and osmotic swelling when subjected to physiological conditions. Additionally, due to changing environmental conditions, it is susceptible to variability in the proportion of guluronic to mannuronic acid residues and their molecular weight [63,158]. Contreras-Abara et al. [63] found that under diazotrophic conditions, its yield can be increased, and its constant molecular weight can be controlled by utilizing a continuous culture approach.

2.6. Poly (D/L-γ-Glutamic Acid) (γ-PGA)

Poly (γ-glutamic acid) is considered one of the smartest microbial biopolymers due to its distinctive structural characteristics and applications. γ-PGA is an optically active polyamide that is structurally composed of D-L glutamic acid adjoined by a peptide bond. γ-PGA Poly (γ-glutamic acid) and Poly (α-glutamic acid) are two isomeric arrangements usually extracted extracellularly through a reaction of glutamic ester monomers with an appropriate producer bacteria under optimum fermentation conditions [23,24] The availability of free carboxyl and amine groups in γ-PGA at specific pH ranges makes it a suitable biopolymer to capture cations, especially heavy metals from noxious environments [159]. In the realm of environmental research, its emerging directive is to make sustainable material from the waste stream. γ-PGA can be used for multifarious environmental goals: in bioremediation [160,161]; as a bio-flocculant agent [65,162]; for wastewater treatment [163] or soil sedimentation [164]; as an anti-freezing agent [165] or antifungal agent [166]; for the construction of filter membranes [167,168]; and as biodegradable green plastic [169]. Although the microbial fermentation of γ-PGA has been extensively researched, costs related to manufacturing, particularly those associated with substrates and processes, continue to be high [170].

2.7. Pullulan

Pullulan is a fungal-based microbial biopolymer that belongs to the family of exopolysaccharides. It is extracted with fermentation approaches by utilizing the fungal strain *Aureobasidium pullulans*. Pullulan is comprised of replicating units of maltotriose adjoined jointly by α-(1,6) glycosidic joinings. Maltotriose is an oligosaccharide, which is further composed of three glucose units adjoined by (1,4) glycosidic joinings [171]. Elevated fermentation-broth viscosity, melanin coloring, and pullulanolysis during fermentation are the main issues encountered during the manufacturing of pullulan [172]. Other than this, the high cost of feed is a major challenge involved in producing pullulan. To overcome this, inexpensive lignocellulosic substances can be used as carbon sources for microbial fermentation [173]. Pullulan can endure high heat loads, has a versatile range of viscosities and solubilities, and is generally regarded as safe by monitoring authorities. It embraces strong adhesive attributes and has the capacity to develop non-odorous, semi-opaque, and oxygen-proof films [125,174]. Pullulan exhibits applications in the bioremediation of industrial waste streams [29], biosorption of heavy metals [67,175,176], harmful dyes [177–179], antibiotics [180,181], and other pollutants [182] in water due to its robust adhesive attributes. The use of synthetic polymers for food packaging has increased over time due to their mechanical and thermal attributes, but the decomposition of these polymers leads to the production of harmful gases [183]. One of the major uses of pullulan is to make antimicrobial films to preserve food [184–189].

2.8. Chitosan

Chitosan belongs to the family of polysaccharides. It is one of the most researched biopolymers due to its bioactivity and is known as a non-migratory bioactive polymer (Steven and Hotchkiss 2003). The deacetylated version of chitin, poly-(14)-N-acetyl-D-glucosamine, is a natural biopolymer attained from crab shells and lobsters by engaging fungal strains (Table 2) subsequently through succeeding processes of demineralization, deproteinization, and deacetylation [190]. The solid-state fermentation process has been considered a viable approach to producing chitosan from fungal stains since it allows for substantial product concentrations and has fewer apparatus requirements than liquid-submerged fermentation. Nevertheless, solid-state fermentation has its own limitations like rapid mass transfer, and, more importantly, heat exchange issues, which become crucial on an industrial scale [191]. Another advantage of producing this microbial biopolymer from fungal sources is its uniformity, convenient handling, efficient harvesting, and availability over the entire year, as well as its improved physicochemical attributes [192]. Various research analyses studied the impact of chitosan as an antimicrobial and antifungal agent and its potential to make edible films and coating solutions for diminishing the post-harvest losses of fruits and vegetables [190,193–197]. Other potential applications of chitosan for the environment are as a plant growth regulator [198–200], a flocculating agent for dye and heavy metal reduction [201–205], a water purifier [206,207], and as a bioremediation agent [208–210]. Szymańska and Winnicka [211] reported the stability concern of chitosan as a biomaterial, referring to the degradation of chitosan during storage due to the breakdown of its functional group. The degradation of chitosan is significantly influenced by both intrinsic and extrinsic factors. It is suggested to improve the stability blending of chitosan with other hydrophilic biopolymers.

2.9. Polyhydroxyalkanoates (PHA) and Polyhydroxybutyrate (PHB)

PHA and PHB come under the type of polyesters that are intracellularly extracted by both bacterial and fungal strains. PHB is one of the forms within PHA. Among both, PHA attracts more interest from both industrialists and academia because of its wider range. PHB has limited flexibility, poor thermal stability, and a slow degradation rate as compared to PHA. Worldwide, many investigators have isolated PHA and PHB with the aid of diverse strains (Tables 1 and 3). PHA is usually comprised of linear-chained repeating (R)-3-hydroxy fatty acid units adjoined together by ester bonds. PHA is categorized into short chains (C3–C5) and medium chains (C6–C14) as per their carbon chain length. Zheng et al. [212] and Mohapatra et al. [21] extracted PHA by both submerged and solid-state fermentation. The higher yield was conveyed by solid-state fermentation. Moreover, a significant difference was noted in its thermal, structural, and morphological properties. Also, the selection of a raw material as a carbon source directly influences the quality of the microbial biopolymer. PHA functions as a storage unit and serves as a terminal electron receptor for bacteria under stress conditions [213,214]. PHA is effectively being employed for the formation of bioplastic due to its biodegradability, thermoplasticity, and bio-tolerance attributes [215,216]. Dhania et al. [217] developed PHB nanoparticle-based scaffolds and concluded its benefits for tissue engineering. Meanwhile, PHA could be regarded as an alternative to conventional plastics, which supports diminishing the use of synthetic polymers. Othman et al. [218] explored the potential of PHA-based degradable mulch film in rice-seed germination. Kelwick et al. [219] designed a protease biosensor based on AL-PHA beads for the detection of proteolytic activity. Amanat et al. [220] analyzed the long-term potential of diverse types of PHA-based material for bioremediation. Apart from this, PHA can also be used for purification processes [221,222]. Tanadchangsaeng et al. [53] observed the biodegradability of both PHA and PHB in seawater by calculating the amount of carbon dioxide collected from decomposition operations. The main drawbacks of producing this microbial biopolymer are the expensive feed and inadequate thermal and mechanical properties, mainly of PHB. Improvements to the substrate types, supplying methods, growth conditions, and/or genetic modifications can lead to much improved traits [223].

2.10. Polylactide (PLA)

Polylactide or polylactic acid, also known as PLA, is a microbial biopolymer that functions identically to polyolefins and is capable of being processed utilizing standard approaches like blow molding and protrusion to produce green bioplastics. Polylactic acid comes under the class of polyester. It is comprised of lactic acid monomers. Sugars are generally converted into lactic acid with the aid of bacterial and algae strains and are afterward polymerized to polylactic acid [46,47]. A study by Balla et al. [224] concluded that advanced ring-open polymerization with catalysts like tin and zinc is beneficial to declining the cost of PLA. PLA is a biodegradable and biocompatible polymer that exists in two enantiomeric forms L-PLA and D-PLA can be selected for material properties. PLA is a promising biopolymer that can be extracted from municipal waste [225], lignocellulosic [226], and food waste streams with the aid of enzymatic and fermentation processes. Most waste biomass is comprised of the prevalent natural flora of lactic acid bacteria. Therefore, it can be anticipated that sugars in biowaste are naturally fermented to lactic acid [225]. Menezes et al. [227] explored the performance of PLA in protracted marine environments. Zhang et al. [228] emphasized the use of PLA-based films as an environmentally satisfying alternative to traditional plastic mulch. Another notable application of PLA-based fibrous membranes was analyzed for oil–water separation by Mo et al. [229]. In comparison to polymers made from petroleum, this microbial biopolymer is high-priced and has inferior mechanical characteristics. Now, copolymerization can be used to overcome this difficulty and to scale up at an industrial scale [230].

3. Characteristics of Microbial Biopolymers

Biopolymers produced by microorganisms offer a variety of roles for organisms. The expenditure of generating biodegradable substances as well as the expense of recycling waste can be decreased by using agricultural and industrial waste as substrates for the production of microbial biopolymers. Agricultural waste such as rice straw, maize cobs, oats, fruit peels, and molasses, and industrial waste such as wastewater from dairy processing, the textile and pharmaceutical industries, seafood, and slaughter waste, can be used to make biopolymers that are sustainable, bio-functional, biostable, and biologically compatible [231–236]. An overview of the production of microbial biopolymers from agro-industrial waste is illustrated in Figure 1.

Some of its features are as follows:

(i) They can adapt to altering environmental circumstances and be modified accordingly [237,238].
(ii) Microbial biopolymers such as proteins or polypeptides act as catalysts in numerous biochemical reactions. This helps to decline the activation energy when used in the chemical reaction. So, these catalysts enable microorganisms to breakdown nutrients and produce essential nutrients for cellular pathways [239].
(iii) They are storage factories that reserve energy and permit microorganisms to acclimate extra energy in case of metabolic demand [240].

(iv) They act as defensive associates for microbial cells and guard the cells against the environment. In other words, microbial biopolymers act as biofilms and stick to the surfaces of cells, defending them from physical and chemical stresses [241,242].

(v) Microbial biopolymers act as intermediaries for transmission between microorganisms and their environment. They assist in receiving and sending signals to organize their behaviors and their response to alerting environments [242].

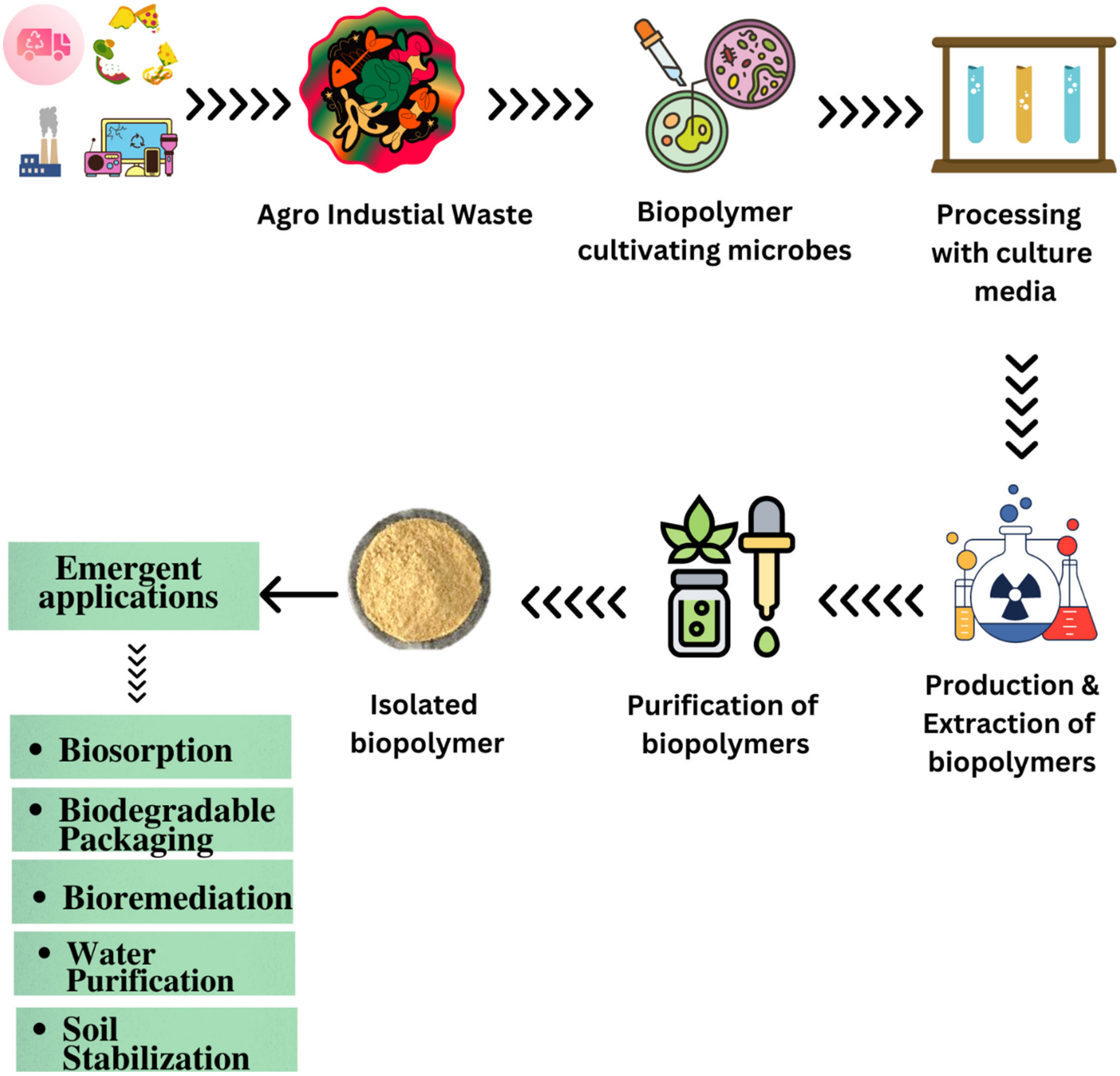

Figure 1. Overview of microbial biopolymers production from agro-industrial waste and its environmental applications.

4. Factors Influencing the Production of Microbial Biopolymers

Microbial biopolymers have garnered considerable attention lately because they have the prospect of serving as alternates for synthetic polymers. Several aspects influence the fabrication of microbial biopolymers, and they can be split into two major categories: intrinsic factors and extrinsic factors (represented in Figure 2).

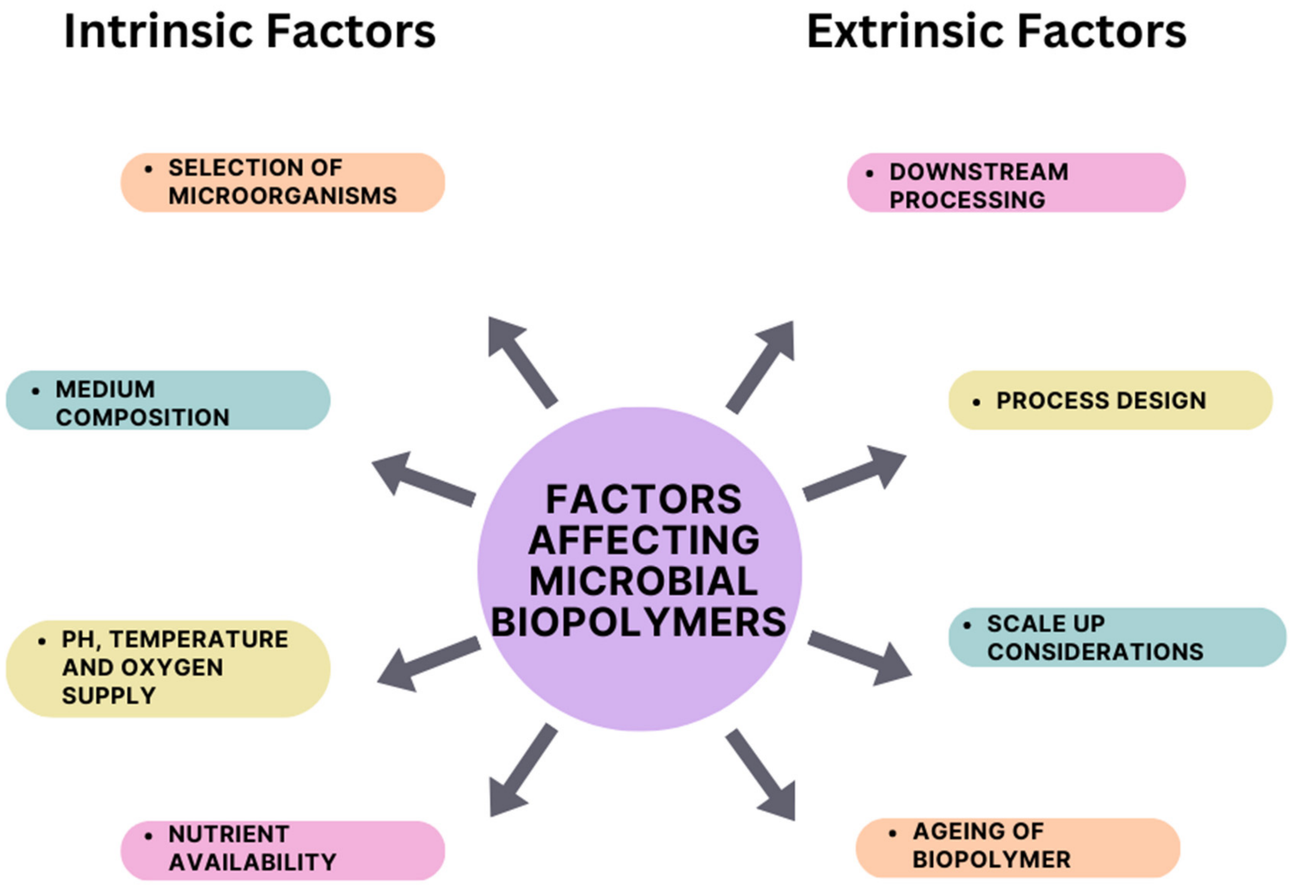

Figure 2. Factors influencing the fabrication of microbial biopolymers.

4.1. Intrinsic Factors

(i) Selection of microorganisms: The selection of microbial strains plays a vital role in the fabrication of biopolymers. There is only a limited number of commercially available strains allowed by the Food Drug Administration (FDA) for use in the fabrication process. The effectiveness, yield, and functional, mechanical, and rheological properties are directly reliant upon the selected microbial strain and its metabolic pathways [10].

(ii) Medium composition: One of the most significant factors for effective microbial fermentation is the medium composition [243]. An adequate supply of carbon and nitrogen in the culture medium is the most significant factor for the production of microbial biopolymers. Generally, microbes use polysaccharides such as glucose, sucrose, and fructose as carbon sources, as well as amino acids and ammonium salts as nitrogen sources, depending upon the type of biopolymer. Appropriate carbon-to-nitrogen ratios are desirable for the cultivation of microbial biopolymers [244]. Moreover, microbes require nutrients, minerals, and trace elements for the synthesis of microbial biopolymers (Table 4). The right concentrations of nutrients and trace elements like beef extract, yeast extract, sulfur, iron, and phosphorus are obligatory for the microbial metabolic pathway. Additionally, the medium must be free of any elements that can interfere with microbial action. Any imbalance leads to creating a disturbance in the metabolic pathway, which in turn influences the production of biopolymers [7,10,245,246].

(iii) pH, temperature, and oxygen supply: The yield and characteristics of microbial biopolymers can be reformed with the supply of oxygen. Several factors, including the microorganism, there are several pHs as well as temperature levels that are ideal for fabrication. Microbial growth rates and the fabrication of biopolymers could be impaired by deviations from the ideal circumstances.

4.2. Extrinsic Factors

(i) Downstream processing: The overall production of biopolymers is influenced by various downstream processes; filtration, precipitation, and extraction directly affect the quality of biopolymers [247]. The extraction of a biopolymer from agro-industrial waste provides less yield as compared to extraction from commercially utilized materials. Extraction of biopolymer by solvents and multiple steps in downstream processing raise the end cost of biopolymer [248]. For example, Pérez-Rivero et al. [249] and Koller [250] concluded in their studies that there are several processes in the manufacture of PHAs, and downstream processing can make up half of those steps' production costs. Periodically, the temperature step involved in downstream processing leads to a deteriorating effect on the attributes of some biopolymers.

(ii) Process design: The final attributes of fabricated biopolymers depend upon various process factors such as agitation techniques, the type of bioreactor employed, inoculum density, feeding methods, mass flow, enthalpy of stream, and processing time [251]. Simple batch reactors, continuous or fed-batch systems, and semi-continuous are possible types of bioreactors employed for the production of microbial biopolymers. In terms of the layout, scalability, ease of inspection, control, and the particular needs of the biopolymer being produced must be considered [9,252].

(iii) Scale-up considerations: There are complications in repositioning lab-scale biopolymer production on an industrial scale. For prosperous large-scale production, components like conserving constant requirements, precluding contamination, and improving nutrient and oxygen transportation are paramount [7].

(iv) Ageing of biopolymers: After the fabrication of the biopolymer, it experiences changes in its structural and rheological properties over time. This process is known as the aging of biopolymers. Changes in crystallinity and physicochemical attributes are directed towards the weakening of biopolymers. Nagaraja et al. [253], Deroiné et al. [254], Siviello et al. [255], Leceta et al. [256], Santos et al. [182] and Cui et al. [257] observed the impact of aging on poly(3-hydroxybutyrate-co-3-hydroxyvalerate, alginate, chitosan, bacterial cellulose and polylactic acid, respectively.

5. Role of Microbial Biopolymers in Wastewater Treatment Processes

Wastewater describes any water that has been contaminated by industrial processes or human activities, including both residential and commercial sources and natural sources, such as stormwater runoff and infiltration or inflow into sewer systems [258]. Wastewater contains a range of contaminants, including inorganic pollutants (heavy metals and rare earth minerals), organic pollutants (dyes, food, detergents, pesticides, herbicides, and pharmaceuticals), and other pollutants (oil, radioactive waste, spill, grease, etc.), which have detrimental effects on the environment and human health [259]. Until now, step-by-step processes like preliminary, primary, and secondary treatment have been employed to ensure water meets the required quality standards for safe discharge or reuse [258]. Various approaches have been tested in the removal of contaminants, including aerobic and anaerobic biological methods and the use of physical and chemical treatments. Coagulation and flocculation comprise fundamental stages in the removal of large, coarse, solid materials, like suspended solids, heavy metal ions, and dye molecules. Oxidation methods tackle the removal of organic impurities, while adsorption mechanisms have proceeded to capture soluble particles. Membrane-based treatment technologies have also demonstrated the capacity to separate impurities from wastewater, enhancing overall water quality [260]. Recently, the use of microbial biopolymers has gained significant attention as a value-added and sustainable approach to wastewater treatment. By acting as filtration media, adsorbents, coagulants, and flocculants, microbial biopolymers can be integrated into various stages of the treatment process, potentially further enhancing the efficiency and effectiveness of wastewater treatment methods [171]. The upcoming subsections will delve into the diverse roles of microbial biopolymers in wastewater treatment.

6. Applications of Microbial Biopolymers

6.1. Microbial Biopolymers as Adsorbents

Adsorption is a surface phenomenon that has gained popularity in water treatment in recent years. It is a well-known equilibrium separation process recognized by its simplicity, effectiveness, and efficiency [261]. This process is favored because it does not require the use of extra chemicals, excess water, or energy, thereby allowing for a low operating cost [262]. Synthetic polymers are generally derived from coal and petroleum, which are unable to fit in recycling systems. Contrarily, microbial biopolymers outperform petroleum-based polymers in terms of affordability, environmental sustainability, and usability [263]. Microbial biopolymers are composed of a variety of functional groups, including methoxyl carboxyl, phenolic hydroxyl, amines, and hydroxide. Due to chelating metal ions establishing surface complexes, these functional groups of microbial biopolymer-based adsorbents enhance the adsorption efficacy of pollutants from different samples [264]. Generally, adsorption occurs due to attractive forces between the adsorbate, which is the compound being adsorbed, and the surface of the adsorbent, the compound to which the adsorbate gets attached. Up to date, a variety of adsorbents have been used, and the common types can be classified depending on the material nature. Thus, adsorbents can be from organic, mineral, or natural origins [261]. Among the natural group, microbial biopolymers and biopolymer composites, (Table 5) play a significant part due to their porous structure, highly specific surface area, durability, and cost-effectiveness. Additionally, their abundant functional groups present on the surface can speed up decontamination and the removal of soluble particles, greasy substances, dyes, and other pollutants in water. Likewise, these functional groups have an affinity to combine with heavy metals like mercury, copper, cadmium, lead, nickel, chromium, and zinc. Biopolymers also offer a promising solution to address emerging contaminants, particularly surfactants, in wastewater. Biswas and Pal [265] discussed the use of biopolymers such as chitosan, alginate, tannin composites, and more for the removal of surfactants. Recent progress in the development of chitosan-based adsorbents, shedding light on their remarkable potential for various pollutant removal, such as heavy metal ions, and cationic and anionic dyes, has been emphasized by da Silva Alves et al. [266]. As highlighted by Benavente et al. [267], the abundant amino and hydroxyl groups on the surface of chitosan can be used to chelate heavy metal ions, specifically Cu^{2+}, Hg^{2+}, Pb^{2+} and Zn^{2+}, with a maximum adsorption capacity of 79.94 mg/g, 109.55 mg/g, 58.71 mg/g and 47.15 mg/g, respectively. Additionally, alginate, with its hydroxyl and carboxyl groups distributed across its surface, can capture metallic ions through an ion-exchange mechanism [268]. However, despite such unique advantages, limited functionality, including poor mechanical, chemical, and physical properties, has been observed. Therefore, biopolymers are often subject to modification using various synthetic or natural monomers, and they are combined with diverse materials for applications in water treatment [259]. As a low-cost adsorbent, cellulose can be chemically modified by esterification, etherification, oxidation, halogenation, and chelation. In the context of chelation, amine, carboxyl, amide, and imidazole binding ligands were seen to have better efficiency, owing to their large surface area, cost efficiency, and sustainability [171]. Another promising way to further enhance biopolymer adsorbents' ability to remove heavy metals and dyes is the utilization of low-cost sorbent hydrogels. A sodium alginate/polyethylene amine compound hydrogel has shown an adsorption capacity of 322.6 mg/g and 344.8 mg/g for the absorption of Cu^{2+} and Pb^{2+} ions, respectively, in wastewater [269]. In another case, a sodium alginate/polyethyleneimine hydrogel was used for dye adsorption and demonstrated the excellent removal performance of methylene blue with a maximum absorption capacity of 400.0 mg/g. Within 30 min, approximately 99% of the dye was removed [270]. Furthermore, graphene oxide (GO) was encapsulated in a sodium alginate/polyvinyl alcohol compound. Used as an effective adsorbent for removing Cu^{2+} and $UO_2{}^{2+}$, the hydrogels showed a maximum absorption of 247.16 mg/g and 403.78 mg/g, respectively [271]. In another research, GO was used to formulate three-dimensional graphene oxide porous biopolymer gels, which foster the establishment of hydrogen bonding and hydrophobic interactions.

This 3D network structure provides abundant active sites for the effective adsorption of cationic dyes and heavy metal ions. Another interesting technique was highlighted by Wang et al. [272], which involved the use of aquatic sodium alginate for the gelation of heavy metal ions. In this study, alginate showed the fast gelation of Pb^{2+}, Cu^{2+}, and Cd^{2+} within less than 10 min. The resulting gel–liquid separation from wastewater was achieved smoothly through gravity. Magnetic adsorbents are becoming increasingly favored in water treatment. Their rising popularity can be attributed to their capacity to enhance adsorption efficiency, minimize adsorbent wastage, and simplify separation through the use of an external magnetic field [273,274]. Abdul Rahman et al. [275] developed magnetic cellulose, chitosan, alginate, and composite hydrogel beads. The bio-sorbent demonstrated strong potential for treating heavy metal-contaminated wastewater comprised of Ca and Fe ions and showcased enhanced thermal stability when compared to raw cellulose and chitosan. The mechanical resistance of some naturally derived microbial biopolymer-based membranes is poor. This can be overcome by embedding it with compatible nano biomaterials [276]. For instance, chitosan is an interesting biopolymer for this purpose due to its film-forming ability, biocompatibility, and favorable hydrophilicity [277]. Salehi et al. [277] investigated chitosan-based membranes for adsorptive studies. They suggested the concept of cross-linking chitosan with TiO_2 to create a self-regenerating dye adsorbent. Also, cross-linking with glutaraldehyde, glyoxal, and formaldehyde was suggested to improve its solubility and mechanical attributes.

Table 5. Studies related to the use of biopolymers as adsorbents to treat wastewater.

Polymer	Pollutant	Adsorption Capacity ($mg{\cdot}g^{-1}$)	References
Inorganic contaminants			
Carboxylated cellulose nanocrystal/sodium alginate hydrogel	Pb^{2+}	335.3	[278]
Cellulose/PVA/Graphene Composite aerogel	Cu^{2+}	80.12	[279]
	Cd^{2+}	102.23	
	Cr^{3+}	123.02	
	Co^{2+}	62.38	
	Zn^{2+}	69.55	
	Pb^{2+}	57.16	
Thioglycolic Acid-Esterified Cellulose Nanocrystals	Cu^{2+}	4.244	[280]
Chitosan-glucose hydrogel	Co^{2+}	202	[281]
Chitosan/orange peel hydrogel	Cu^{2+}	116.6	[282]
	Cr^{6+}	107.5	
Xanthate-modified chitosan/poly (N-isopropylacrylamide)	Cu^{2+}	115.1	[283]
	Pb^{2+}	172.0	
	Ni^{2+}	66.9	
Cellulose/guar gum/biochar	Cu^{2+}	805.45	[284]
	Co^{2+}	772.52	
Cellulose/bentonite grafted polyacrylic acid hydrogel	Cd^{2+}	242.53	[285]
Alginate/polyethyleneimine	Cu^{2+}	322.6	[269]
	Pb^{2+}	344.8	
3D network nanostructured sodium alginate	Cd^{2+}	9.54	[286]
	Cu^{2+}	13.38	
Hyaluronic acid-supported magnetic microspheres	Cu^{2+}	12.2	[287]
Xanthan gum/n-acetyl cysteine modified mica bionanocomposite	Pb^{2+}	530.54	[288]
	Cu^{2+}	177.2	
	Ni^{2+}	51.48	
Poly (Acrylamide-*co*-Acrylic Acid)/Xanthan Gum hydrogel	Cd^{2+}	312.15	[289]
	Ni^{2+}	185.0	
Pullulan/polydopamine hydrogels	Cu^{2+}	100.9	[290]
Sodium alginate/coffee waste	Pb^{2+}	984.4	[291]
Whey protein concentrate/pullulan hydrogel	Cu^{2+}	81.6	[292]
Polylactic acid hydrogel	Pb^{2+}	416.07	[293]
	Ni^{2+}	243.10	
Organic contaminants			
Sodium hydroxide activated acrolein/chitosan	Acid blue 93	2500	[294]
Carboxymethyl cellulose/chitosan/triethylenetetramine	Direct blue	534.25	[295]
	Congo red	519.53	
Cellulose/guar gum/biochar	Methylene blue	598.28	[284]

Table 5. *Cont.*

Polymer	Pollutant	Adsorption Capacity ($mg \cdot g^{-1}$)	References
Cellulose/Poly(acrylic acid)	Methylene blue	1492.99	[296]
Chitosan/polyacrylate/graphene oxide	Methylene blue FY3	296.5 280.3	[297]
Chitosan/cellulose	Congo red	380	[298]
Chitosan/poly(n-vinyl-2-pyrrolidone)	Orange G	63.7	[299]
Xanthan gum/amantadine composites	Methylene blue	565	[300]
Polyaniline/Xanthan Gum Nanocomposite	Methylene Blue	22.52	[301]
Xanthan gum/polyacrylic acid/graphene oxide	Methyl violet Methylene Blue	1052.63 793.65	[302]
Pullulan-graft-poly(3-acrylamidopropyl trimethylammonium chloride) microspheres	Azocarmine B	113.63	[303]
Sodium alginate-polyaniline nanotube	Methyl orange	370.4	[304]
Sodium alginate/coffee waste	Acridine orange	805.3	[291]
Crosslinked chitosan films	SDBS	714	[305]
Nanofibrillated cellulose	Cationic surfactants	462.28	[306]
Hydrogel chitosan beads	SDS	1300	[307]

6.2. Microbial Biopolymers as Coagulants and Flocculants

Coagulation and flocculation are two interrelated methods commonly known as the most economical processes used in water treatment for solid-particle removal. Despite their interconnection, coagulation and flocculation are entirely different phenomena. Coagulation is an electrostatic phenomenon that occurs through the charge neutralization of suspended particles and colloids. It is induced by adding coagulants that destabilize the particles, leading to their collision and aggregation. This, in turn, initiates the formation of flocs, which precipitate from the suspension due to the influence of gravity. Flocculation takes place to further enhance the downstream processes by creating larger and heavier flocs, thereby enhancing the effective removal of impurities. While coagulation occurs in a short time frame of less than 10 s, flocculation is a long physical process lasting about 20–45 min [274,308]. A large variety of coagulants and flocculants have been used for wastewater treatment. Commonly used inorganic coagulants, such as aluminum sulfate, aluminum chloride ferrous sulfate, etc. [309–311], have caused environmental and ecological concerns due to their generation of additional sludge volume [312,313]. Hence, microbial biopolymers emerged as a viable solution [312,314]. Among the variety classes of biopolymers, polysaccharides have garnered significant attention from the scientific community, mainly due to their functional groups present on the surface, contributing to the effective adsorption of different contaminants in the flocculation process [315–317]. As described in the recent literature, chitosan, cellulose, alginate, pullulan, xanthan gum, and their derivatives are bio-based flocculants. Those polysaccharides have shown their ability as relevant agents in the elimination of turbidity, total dissolved solids (TDS), chemical oxygen demand (COD), metal cations, inorganic anions, dyes, pesticides, minerals, microorganisms, and numerous other pollutants found in various types of wastewaters [318]. Other bioflocculants based on dextran [319–321], pectin [322,323], and lignin [324], as well as their grafted derivatives, have also been reported for color-reducing, turbidity, COD, or heavy metal ions. Table 6 provides an overview of recently reported biopolymers and their derivatives as coagulants and flocculants investigated for water treatment. With the emergence of nanocomposite-based biopolymers, reports regarding the utilization of biopolymers in their unmodified form are notably limited. This can be attributed to the very developed surface area of nanoparticles, characterized by a notable abundance of active sites and functional groups, which positively enhance water treatment [325,326]. However, despite the multiple gains in using nanoflocculants, real concerns remain about the potential environmental impacts regarding the introduction of these particles into the ecosystem. Uncertainty surrounding whether nanoparticles will induce toxic effects within the natural environment persists [318]. Recent reports highlight that direct flocculation, operating independently from coagulation, is emerging as a notably cost-effective alternative, particularly attributed to its reduced cost and environmental impact, along with its enhanced safety for human well-being and efficiency in terms of time. It is a simplified method based on the dual functionality of cationic or anionic polymers, first neutralizing particle charges and then bridging their aggregation. Unlike coagulation, direct flocculation has demonstrated its effectiveness for high levels of organic contaminants across a large pH spectrum [315,327]. Several factors and mechanisms are involved, ranging from the chemical structure, properties, and charge of both the particles to be removed and the flocculant to their concentration, the pH of the environment, temperature, mixing rate, ionic strength, and even the mechanism of the process, which can significantly influence the flocculation. Thus, despite the significant progress that has been made in understanding this process, ongoing research continues to further uncover its complexities [328].

Table 6. Studies related to the use of biopolymers as coagulants flocculants to treat wastewater.

Polymer	Pollutant	Removal Rates (%)	References
Inorganic contaminants			
Chitosan/Poly(acrylamide-acryloyloxyethyl) trimethylammonium chloride	Zn^{2+}	99.3	[329]
Sodium alginate/triethylenetetramine nanoflocculant	Pb^{2+}	97	[330]
Chitosan/acrylamide/itaconic acid/3-acrylamide propyl trimethylammonium chloride	Ni^{2+}	86.3	[331]
Cationic Pullulan Derivatives	FeO	95	[332]
	TiO_2	75	
Organic contaminants			
Chitosan/poly (acrylamide-itaconic acid)	Crystal violet	81.6	[333]
Polyaluminium chloride/xanthan gum	Congo red	93.81	[334]
Cationic pullulan derivatives	Novadim	90	[335]
	Bordeaux mixture	98	
	Karate Zeon	80	
Cationic cellulose/bentonite	Methylene Blue	99	[336]
	Duasyn Direct Red	95	
	Acid Black 2	100	
	Crystal Violet	100	
	Basic Green 1	99	
Carboxymethyl cellulose/itaconic acid/sodium alginate	Crystal violet	92.2	[337]
Cellulose nanocrystals	Reactive blue 19	80	[338]
Sodium alginate/methacryloxyethyltrimethyl ammonium chloride	Dissolved Organic Carbon (DOC)	35.42	[339]
Other contaminants (Water Quality Parameters)			
Sodium alginate/methacryloxyethyltrimethyl ammonium chloride	UV_{254}	32.42	[339]
Xanthan Gum/Polyacrylamide /SiO_2	Turbidity	93.95	[340]
	Total Solids (TS)	76.97	
	Total Dissolved Solids (TDS)	48.21	
	Total Suspended (TSS)	93.75	
xanthan gum/polyacrylamide	Turbidity	52.63	[341]
Pullulan/p(N-isopropylacrylamide)	Turbidity	88	[332,342]
Poly-γ-glutamic acid	Turbidity	86.6	[343]
Chitosan/Poly(acrylamide-acryloyloxyethyl) trimethylammonium chloride	Total Phosphorus (TP)	98.8	[329]
Chitosan/poly-glutamic acid	COD	44.8	[344]
	Total Nitrogen (TN)	53.4	
	TP	28.1	
	Turbidity	98.3	
Bentonite/chitosan/poly-glutamic acid	COD	86.2	[285]
	TN	80.3	
	TP	52.3	
	Turbidity	98.2	
Sodium alginate/methacryloxyethyltrimethyl ammonium chloride	Turbidity	95.96	[339]
Sodium alginate/polysilicate aluminum calcium	Turbidity	97.2	[345]
Chitosan/Poly(acrylamide-acryloyloxyethyl) trimethylammonium chloride	COD	72.5	[329]
Cellulose Nanocrystals	Turbidity	99.7	[346]
Dicarboxyl cellulose	Turbidity	80	[347]
	COD	60	
Dicarboxyl cellulose	Turbidity	99.5	[348]

6.3. Microbial Biopolymers as Filters in Membrane Processes

The capacity of microbial biopolymers to develop biofilms, set up selective barriers, and improve filtration effectiveness is the idea underlying their application as filters in membrane processes. Impaction, electrostatic contact, diffusion, and interception are prominent processes involved in biopolymer filtering [241,349]. Filtration is a method used for the separation of solid particles and large molecules from liquid suspensions through a porous barrier such as a membrane. Membranes possess selective permeability, controlling the passage of mass through their porous surfaces through interactions with the materials to be separated. The efficiency of this technique is directly linked to the size of the membrane's pores and the characteristics of the material used [350]. A wide variety of membranes with different conformations and structures are available. Membrane filtration techniques such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are distinguished by their varying pore sizes, ranging from 5000 nm in MF to 0.2 nm in RO [351]. As with all membrane filtration processes, the main downside that limits their large-scale applications is membrane fouling, which occurs due to contaminants that adhere to the membrane's surface or get trapped within its pores over time, forming a layer that hinders the flow of desired components through the membrane. This phenomenon reduces filtration efficiency as well as the membranes' lifespan and increases energy consumption [352,353]. Recently, biopolymer nanocomposite membranes have gained popularity as a promising solution for mitigating membrane fouling. They have shown improved antifouling properties by minimizing the adhesion of floculants and improving water permeability, thereby enhancing filtration process efficiency [354,355]. This, in turn, has played a pivotal role in fueling the fast growth of membrane filtration technologies and has boosted the number of publications focused on the utilization of membranes for separating oil–water emulsions [356]. The use of natural fillers such as nitrocellulose or chitosan nanoparticles within biopolymer membranes has significantly enhanced membrane stability and reduced the dosage of chemicals and the volume of sludge. Therefore, biopolymers stand out as an environmentally friendly, efficient, and sustainable alternative to conventional membrane filtration techniques [350,357] Among the different biopolymers, hydrophilic biopolymers, such as bacterial cellulose, chitosan, alginate, and hyaluronic acid, are preferred for membrane processes due to their durability and ability to withstand corrosive substances that may be present in the wastewater. As highlighted by Galdino et al. [87], a bacterial-cellulose matrix can be used to separate almost all oil during the filtration of oily effluents and can be washed and reused up to 20 times without losing its filtration efficiency. Surface modification can further enhance retaining specific contaminants like heavy metals and dyes, thus improving the membrane's permeability and selectivity [358]. For example, Yu et al. [359] demonstrated that a modified chitosan-cellulose acetate-TiO_2-based membrane can be used for the demulsification of oil–water emulsion, reaching up to 99% in separation efficiency. As highlighted by Divya and Oh [360], recent advancements in microbial polymer thin-film nanocomposite membranes, incorporating nanofillers like carbon-based materials, metals, and metal oxides, have garnered considerable attention in the field of water purification due to their notable characteristics, including hydrophilicity, thermal stability, selectivity, permeability, and thermal resistance. However, despite advances in the biopolymeric-membrane approach, some major limitations were also observed: the potential degradation of biopolymer during extended storage periods, their requisite compatibility with the effluent being treated, and the potential high operational costs when aiming for a higher rate of solid- and liquid-phase separation [356]. Additional drawbacks, such as the potential risk of obstructing the water flow pathway due to the addition of nanomaterials; the formation of defects and non-selective porosity resulting from inadequate interaction between the polymer and nanoparticles; and the poor dispersion of fillers within the polymer matrix, leading to the aggregation and agglomeration of nanoparticle on the membrane surface or within the membrane itself, all emphasize the need for further research to address these existing challenges [355]. Table 7 summarizes recent research on membrane filtering employing biopolymer materials. Bacterial cellulose is one of the most interesting microbial biopolymers for this application due to its large surface area, nano-porous structure, and biodegradability [15]. Faria et al. [15] investigated the exceptional quality of bacterial cellulose for eliminating microplastics by 99%, which upheld performance for continuous cycles. Qalyoubi et al. [276] addressed the most common challenges associated with novel adsorptive membranes including fouling, costs associated with the process, adsorbent regrowth, adsorption capacity, barrier permeability, rates of rejection, and specificity. They also concluded that, since many novel materials have only been evaluated in research settings up to this point, creating innovative materials for hybrid matrix membranes is still an obstacle to overcome. Exploring cheaper alternatives for adsorptive membranes could be a useful area of interest because many innovative materials are unable to enter the industry due to their high price tags. Concerning superior performance and high adsorptive capacity, agro-industrial waste is a suitable candidate to be explored for this purpose.

Table 7. Studies related to the use of biopolymers as membrane filters to treat wastewater.

Polymer	Pollutant	Removal Rates (%)	References
Inorganic contaminants			
Polylactic acid/amino-activated carbon/modified mangrove particles pH-responsive adsorptive membrane	Cu^{2+} Pb^{2+} Ni^{2+}	99.95 100 99.95	[361]
Cellulose acetate/chitosan/TiO_2	Cu^{2+}	97.0	[359]
PLA/PHB/Polybutylene succinate/polypropylene carbonate/silica nanoparticles	Mn^{2+}	14.17	[362]
Cellulose acetate/nanochitosan/PEG	Cr^{6+}	95	[363]
Hyaluronic acid/polyamide	Na_2SO_4	94.90	[364]
Organic contaminants			
Cellulose acetate/PLA/polyurethane	Methylene Blue Congo Red	45 60	[365]
Cellulose microfiber/PLA/poly(butylene adipate-co-terephthalate)/maleic anhydride	Methylene Blue	97.2	[366]
Fe_3O_4/Xanthan gum/polyvinylidene fluoride	Reactive Black 5 Reactive Red 120	84.8 73.8	[367]
Xanthan Gum/polyvinylidene fluoride/dimethyl sulfoxide	Congo red	91.25	[368]
Cellulose microfiber/PLA/poly(butylene adipate-co-terephthalate)	Methylene Blue	58.7	[366,369]
Sodium alginate hydrogel/graphene oxide	MB Direct Red (DR80) Congo Red (CR) Crystal Violet (CV)	100 98.80 100 100	[369]
Chitosan/bacterial cellulose/carboxyl multi-walled carbon nanotubes	Direct Orange S, Procion Red mx-5B Stilbene Yellow Methylene Blue	99.7 97.8 62.8 27.5	[370]
Hyaluronic acid/polyamide	Perfluorohexane sulfonic acid (PFHxS)	93.40	[364]
Other contaminants			
Sodium alginate/tannic acid/β-FeOOH	Oil	99.64	[371]
Chitosan/bacterial cellulose/carboxyl multi-walled carbon nanotubes	Oil	97.67	[370]
Pristine PLA	Oil	93.9	[372]
PLA/polyethylene oxide	Oil	99.6	[373]
Cellulose acetate/chitosan/TiO_2	Oil	99.4 97.0	[359]
PLA/multi-walled carbon nanotubes/graphene oxide	Ammonium-nitrogen Phosphate	90.1 71.3	[374]
PLA/PHB/Polybutylene succinate/polypropylene carbonate/silica nanoparticles	Oil Total Dissolved Solids (TDS) Turbidity	98.6 22.56 11.33 89.15	[362]
Cellulose acetate	Sulfamethoxazole Primidone Carbamazepine Phenacetine 17β-Estradiol	82 85 85 10 29	[375]

6.4. Bioremediation and Soil Stabilization

Bioremediation is an economical and time-consuming approach usually employed for degrading, neutralizing, and detoxifying contaminants predominantly from soil, water, and sediments. Bioremediation is chiefly performed by diverse means such as biodegradation, phytoremediation, bioaugmentation, and biostimulation. These incorporated methodologies usually accelerate metabolic activities and remediate contaminated sites [376,377]. Biosorption can be accompanied by a variety of other techniques, which boost the recovery or removal of pollutants such as metalloids [378]. For example, there are challenges involved in removing metalloids. However, these challenges can be overcome by the formation of metalloid complexes with microbial biopolymers. Due to electrostatic interaction, the generation of stable complexes between metalloid and microbial biopolymers takes place [379]. Many microbial biopolymers contain negatively charged functional groups that help to bind metals, such as hydroxyl groups (OH^-) on the matrix of bacterial cellulose, carboxyl groups ($COOH^-$) in hyaluronic acid, xanthan gum, and alginate. Also, the charges present on some microbial biopolymers vary as per the pH of the surrounding environment. For example, at an acidic pH, chitosan gains hydrogen (H^+) and becomes a positively charged ammonium group (${NH_3}^+$), and at an alkaline pH, chitosan loses hydrogen ions and becomes an uncharged amine form (NH_2) [380]. Depending upon the charge, microbial biopolymers can be employed for multiple applications, which are cited in previous sections. Additionally, microbial biopolymers act as nutrients, which directly promotes the microbial activity of microorganisms involved in the bioremediation process and allows them to thrive and flourish in a variety of unfavorable conditions. Furthermore, some microbial biopolymers such as PHA and PHB produce metabolizing enzymes under particular nutritional and environmental stresses, which helps to upsurge bacterial survival during the bioremediation process [11].

Soil stabilization is an approach for altering the physiochemical attributes of the soil; it enhances the soil's effectiveness in terms of physical aspects. Biofilm-oriented bioremediation is a potent tool for the removal of environmental pollutants. Soil stabilization promises the improved structural stability of soil [381,382]. Microbial biofilms are collections of grouped microbial cells wrapped in an extracellular polymeric substance (EPS) matrix that they have self-assembled. Because they are resistant to harsh environments, biofilms serve as a shield for safeguarding microbes from factors such as exposure to ultraviolet rays, excessive temperature, elevated salinity, and abnormal pH [242]. Numerous kinds of unwanted substances have polluted both the ecosystems of land and water. The majority of these pollutants are polymers of polycyclic aromatic hydrocarbons and total petroleum hydrocarbons, which are generally considered a threat to public health [383,384]. Industrial waste such as dyes and wastewater streams are usually comprised of the aforementioned pollutants and are responsible for polluting the soil and water. The primary approaches to eliminating the metals from polluted soil are thermal desorption, adsorption, precipitation by chemicals, ion exchange, and electroplating accumulation [385]. With the advent of recent developments in microbial biopolymers, the latest developments in the industry are investigating the strategic application of microbial biopolymers and bioremediation methods as environmentally satisfactory alternatives for soil stabilization. Microbial biopolymers have prospective benefits in terms of sustainable development, biological degradation, and minimal carbon footprint [386]. Due to their distinctive qualities and compatibility with the environment, various biopolymers have been employed for dust control, erosion control, and strengthening soil [387]. For instance, xanthan gum has been used for strengthening and stabilizing soil [388–392]. Also, chitosan has been employed to minimize permeability, eliminate heavy metals, stabilize soil, hasten the separation of organic matter, and limit soil erosion [393–398]. Microbial biopolymers could transform soil engineering approaches, providing more environmentally friendly choices for persistent soil stabilization as well as encouraging a more sustainable future.

7. Challenges and Future Perspectives of Microbial Biopolymers in Environmental Applications

Microbial polymers are an attractive substitute for chemically derived materials. However, scaling up their production from a laboratory to an industrial scale is very challenging. Several variables—notably the cost of substrates, the amount of biopolymer produced over feed rate, and the expenditures of downstream processing, among others—determine how successfully biopolymers may be scaled up and if they are economically feasible to produce at an industrial scale [14]. The major challenges in the process are the production cost and the extraction of a pure biopolymer from a complex mixture. Acquiring microorganisms that can use inexpensive as well as easily accessible raw ingredients is a crucial phase in making microbial biopolymer manufacturing economically viable [399]. Using waste raw material for biopolymer production is very attractive and can largely address the issue of the high cost of raw ingredients. Moreover, the use of genetically modified strains and omics techniques to enhance the fermentation yield could greatly help to minimize the overall production cost [400].

The dewatering process of biomass following its cultivation represents one of the foremost operational expenditures in polymer recovery. Undoubtedly, one of the most popular approaches for this is settling. Gravitational settling is the most straightforward and inexpensive method, but due to the small molecule size of microbial biopolymers, filtering by membranes could potentially be employed, accompanied by centrifugation. However, it should be accurately optimized to limit the enhancement of operation costs [401].

In general, optimizing bioprocess at a pilot scale, coupled with techno-economic analysis, could help in resolving many industrial challenges.

In silico methods should be also employed to simulate the production and secretion of bacterial polymers based on the huge availability of data. This could offer valuable insights into the regulatory framework required for their safe application—a framework that is absent at present [400].

Moreover, legislative and policy unpredictability could make it challenging to meet environmental goals. Uncertainty alters the political economics of environmental policy. The acceptability, development, and scalability of microbial biopolymers also depend upon the system. The system is comprised network of actors (business organizations, research groups, policymakers, and regulatory bodies). In a nutshell, the setting up of new supply chain-hosting actors requires a lengthy approach to the development and implementation of novel economic models, among other aspects [402]. Last but not least, environmental applications come with the challenges of handling data that require computation and vast information storage units. Rodila et al. [403] commented on the features of big data, referring to the 5V principle (Volume of data, Velocity of data accumulation, Variety of data by different sources, Validity and precision of data, Value and Purpose of data). Numerous environmental applications will be more efficiently utilized by the correct mathematical framework and its mapping across different computational systems [403]. A deep understanding of the interaction between diverse ecosystem complexities and environmental and biodiversity uncertainties is required, which makes it challenging to design a model to anticipate and adapt to changes in the future to produce desirable outcomes [404,405].

8. Conclusions

In contrast to the information available on physical and chemical methods, the amount of information available on the environmental implications of microbial biopolymers is very limited. As a result, information on significant biopolymer production, recovery, processes, and the potential of environment applications was insufficient. This updated review offers exclusive knowledge of the growing interest in environmental applications of microbial biopolymers. Using biopolymers is an opportunity to solve environmental issues and an effective approach to the circular bioeconomy. There is still a large gap between industry and academia. Many research studies were conducted on a laboratory scale only.

A vast approach is required to commercialize the technology on a mass scale. Moreover, government organizations and regulatory agencies need to establish procedures for the maturation and placement of microbial biopolymers to benefit from application in practice and monetary profits.

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References

1. Roa, K.; Oyarce, E.; Boulett, A.; Alsamman, M.; Oyarzún, D.; Pizarro, G.D.C.; Sánchez, J. Lignocellulose-based materials and their application in the removal of dyes from water: A review. *Sustain. Mater. Technol.* **2021**, *29*, e00320. [CrossRef]
2. Sivakami, M.S.; Gomathi, T.; Venkatesan, J.; Jeong, H.S.; Kim, S.K.; Sudha, P.N. Preparation and characterization of nano chitosan for treatment wastewaters. *Int. J. Biol. Macromol.* **2013**, *57*, 204–212. [CrossRef]
3. FAO. *Background Notes on Sustainable, Productive and Resilient Agro-Food Systems: Value Chains, Human Capital, and the 2030 Agenda*; FAO: Rome, Italy, 2019; pp. 1–70.
4. FAO. Extent of food losses and waste. In *Global Food Losses and Food Waste—Extent, Causes and Prevention*; FAO: Rome, Italy, 2014; pp. 1–37.
5. Siracusa, V. Microbial Degradation of Synthetic Biopolymers Waste. *Polymers* **2019**, *11*, 1066. [CrossRef]
6. Zhao, C.; Liu, G.; Tan, Q.; Gao, M.; Chen, G.; Huang, X.; Xu, X.; Li, L.; Wang, J.; Zhang, Y.; et al. Polysaccharide-based biopolymer hydrogels for heavy metal detection and adsorption. *J. Adv. Res.* **2023**, *44*, 53–70. [CrossRef]
7. Fradinho, J.; Allegue, L.D.; Ventura, M.; Melero, J.A.; Reis, M.A.M.; Puyol, D. Up-scale challenges on biopolymer production from waste streams by Purple Phototrophic Bacteria mixed cultures: A critical review. *Bioresour. Technol.* **2021**, *327*, 124820. [CrossRef]
8. Das, S.; Das, P.; Lal, B. Development of Microbial Biopolymers: The Eco-friendly Sustainable Products for Environmental Applications. In *Novel Polymeric Materials for Environmental Applications*; World Scientific: Singapore, 2022; pp. 1–20.
9. Das, A.; Ringu, T.; Ghosh, S.; Pramanik, N. A comprehensive review on recent advances in preparation, physicochemical characterization, and bioengineering applications of biopolymers. *Polym. Bull.* **2023**, *80*, 7247–7312. [CrossRef]
10. Horue, M.; Berti, I.R.; Cacicedo, M.L.; Castro, G.R. Microbial production and recovery of hybrid biopolymers from wastes for industrial applications—A review. *Bioresour. Technol.* **2021**, *340*, 125671. [CrossRef]
11. Moradali, M.F.; Rehm, B.H.A. Bacterial biopolymers: From pathogenesis to advanced materials. *Nat. Rev. Microbiol.* **2020**, *18*, 195–210. [CrossRef]
12. Ghosh, S.; Lahiri, D.; Nag, M.; Dey, A.; Sarkar, T.; Pathak, S.K.; Edinur, H.A.; Pati, S.; Ray, R.R. Bacterial Biopolymer: Its Role in Pathogenesis to Effective Biomaterials. *Polymers* **2021**, *13*, 1242. [CrossRef]
13. Lee, K.Y.; Mooney, D.J. Alginate: Properties and biomedical applications. *Prog. Polym. Sci.* **2012**, *37*, 106–126. [CrossRef]
14. Rehm, B.H.A. Bacterial polymers: Biosynthesis, modifications and applications. *Nat. Rev. Microbiol.* **2010**, *8*, 578–592. [CrossRef]
15. Faria, M.; Cunha, C.; Gomes, M.; Mendonça, I.; Kaufmann, M.; Ferreira, A. Cordeiro, Bacterial cellulose biopolymers: The sustainable solution to water-polluting microplastics. *Water Res.* **2022**, *222*, 118952. [CrossRef]
16. Fatima, A.; Ortiz-Albo, P.; Neves, L.A.; Nascimento, F.X.; Crespo, J.G. Biosynthesis and characterization of bacterial cellulose membranes presenting relevant characteristics for air/gas filtration. *J. Membr. Sci.* **2023**, *674*, 121509. [CrossRef]
17. Murphy, E.J.; Rezoagli, E.; Collins, C.; Saha, S.K.; Major, I.; Murray, P. Sustainable production and pharmaceutical applications of β-glucan from microbial sources. *Microbiol. Res.* **2023**, *274*, 127424. [CrossRef] [PubMed]
18. Utama, G.L.; Dio, C.; Sulistiyo, J.; Chye, F.Y.; Lembong, E.; Cahyana, Y.; Verma, D.K.; Thakur, M.; Patel, A.R.; Singh, S. Evaluating comparative β-glucan production aptitude of *Saccharomyces cerevisiae*, *Aspergillus oryzae*, *Xanthomonas campestris*, and *Bacillus natto*. *Saudi J Biol Sci.* **2021**, *28*, 6765–6773. [PubMed]
19. Volpi, N.; Maccari, F. Purification and characterization of hyaluronic acid from the mollusc bivalve Mytilus galloprovincialis. *Biochimie* **2003**, *85*, 619–625. [CrossRef] [PubMed]
20. Kogan, G.; Šoltés, L.; Stern, R.; Gemeiner, P. Hyaluronic acid: A natural biopolymer with a broad range of biomedical and industrial applications. *Biotechnol. Lett.* **2007**, *29*, 17–25. [PubMed]
21. Mohapatra, S.; Pattnaik, S.; Maity, S.; Sharma, S.; Akhtar, J.; Pati, S.; Samantaray, D.P.; Varma, A. Comparative analysis of PHAs production by Bacillus megaterium OUAT 016 under submerged and solid-state fermentation. *Saudi J Biol Sci.* **2020**, *27*, 1242–1250. [CrossRef]

22. Ramya, R.; Devi, S.; Manikandan, A.; Kannan, V.R. Standardization of biopolymer production from seaweed associative bacteria. *Int. J. Biol. Macromol.* **2017**, *102*, 550–564.
23. Parati, M.; Khalil, I.; Tchuenbou-Magaia, F.; Adamus, G.; Mendrek, B.; Hill, R.; Radecka, I. Building a circular economy around poly(D/L-γ-glutamic acid)- a smart microbial biopolymer. *Biotechnol. Adv.* **2022**, *6*, 108049. [CrossRef]
24. Kedia, G.; Hill, D.; Hill, R.; Radecka, I. Production of Poly-γ-Glutamic Acid by Bacillus subtilis and Bacillus licheniformis with Different Growth Media. *J. Nanosci. Nanotechnol.* **2010**, *10*, 5926–5934. [CrossRef]
25. Rosalam, S.; England, R. Review of xanthan gum production from unmodified starches by *Xanthomonas comprestris* sp. *Enzyme Microb. Technol.* **2006**, *39*, 197–207. [CrossRef]
26. Wang, Z.; Wu, J.; Gao, M.-J.; Zhu, L.; Zhan, X.-B. High production of xanthan gum by a glycerol-tolerant strain Xanthomonas campestris WXLB-006. *Prep. Biochem. Biotechnol.* **2017**, *47*, 468–472. [CrossRef] [PubMed]
27. Hernandez-Tenorio, F.; Giraldo-Estrada, C. Characterization and chemical modification of pullulan produced from a submerged culture of *Aureobasidium pullulans* ATCC 15233. *Polym. Test.* **2022**, *114*, 107686. [CrossRef]
28. Wani, S.M.; Masoodi, F.A.; Mir, S.A.; Khanday, F.A. Pullulan production by *Aureobasidium pullulans* MTCC 1991 from apple pomace and its characterization. *Food Biosci.* **2023**, *51*, 102254. [CrossRef]
29. Lin, C.; Zhang, K.; Zhao, S.; Wang, W.; Ru, X.; Song, J.; Cong, H.; Yang, Q. Screening and identification of a strain of *Aureobasidium pullulans* and its application in potato starch industrial waste. *Environ. Res.* **2022**, *214*, 113947. [CrossRef] [PubMed]
30. Campana, R.; Fanelli, F.; Sisti, M. Role of melanin in the black yeast fungi Aureobasidium pullulans and Zalaria obscura in promoting tolerance to environmental stresses and to antimicrobial compounds. *Fungal Biol.* **2022**, *126*, 817–825. [CrossRef] [PubMed]
31. Samuelsen, A.B.C.; Schrezenmeir, J.; Knutsen, S.H. Effects of orally administered yeast-derived beta-glucans: A review. *Mol. Nutr. Food Res.* **2014**, *58*, 183–193. [CrossRef] [PubMed]
32. Abdeshahian, P.; Ascencio, J.J.; Philippini, R.R.; Antunes, F.A.F.; Santos, J.C.D.; da Silva, S.S. Utilization of sugarcane straw for production of β-glucan biopolymer by *Lasiodiplodia theobromae* CCT 3966 in batch fermentation process. *Bioresour. Technol.* **2020**, *314*, 123716. [CrossRef]
33. Kayanna, N.; Suppavorasatit, I.; Bankeeree, W.; Lotrakul, P.; Punnapayak, H.; Prasongsuk, S. Production of prebiotic aubasidan-like β-glucan from *Aureobasidium thailandense* NRRL 58543 and its potential as a functional food additive in gummy jelly. *LWT* **2022**, *163*, 113617. [CrossRef]
34. Almeida, R.R.; Pinto, N.A.R.; Soares, I.C.; Ferreira, L.B.C.; Lima, L.L.; Leitão, A.A.; Guimarães, L.G.D.L. Production and physicochemical properties of fungal chitosans with efficacy to inhibit mycelial growth activity of pathogenic fungi. *Carbohydr. Res.* **2023**, *525*, 108762. [CrossRef] [PubMed]
35. Berger, L.R.R.; de Araújo, M.B.; da Costa, D.P.; de Lima, M.A.B.; de Almeida, J.W.L.; de Medeiros, E.V. Agroindustrial waste as ecofriendly and low-cost alternative to production of chitosan from Mucorales fungi and antagonist effect against Fusarium solani (Mart.) Sacco and Scytalidium lignicola Pesante. *Int. J. Biol. Macromol.* **2020**, *161*, 101–108. [CrossRef] [PubMed]
36. Logesh, A.R.; Thillaimaharani, K.A.; Sharmila, K.; Kalaiselvam, M.; Raffi, S.M. Production of chitosan from endolichenic fungi isolated from mangrove environment and its antagonistic activity. *Asian Pac. J. Trop. Biomed.* **2012**, *2*, 140–143. [CrossRef] [PubMed]
37. Nwe, N.; Furuike, T.; Osaka, I.; Fujimori, H.; Kawasaki, H.; Arakawa, R.; Tokura, S.; Stevens, W.F.; Kurozumi, S.; Takamori, Y.; et al. Laboratory scale production of 13C labeled chitosan by fungi *Absidia coerulea* and *Gongronella butleri* grown in solid substrate and submerged fermentation. *Carbohydr. Polym.* **2011**, *84*, 743–750. [CrossRef]
38. Sugiono, S.; Ferdiansyah, D. Biorefinery Sequential Extraction of Alginate by Conventional and Hydrothermal Fucoidan from the Brown Alga, Sargassum cristaefolium. *Biosci. Biotechnol. Res. Commun.* **2019**, *12*, 894–903. [CrossRef]
39. Torabi, P.; Hamdami, N.; Keramat, J. Microwave-assisted extraction of sodium alginate from brown macroalgae Nizimuddinia zanardini, optimization and physicochemical properties. *Sep. Sci. Technol.* **2022**, *57*, 872–885. [CrossRef]
40. Costa, S.S.; Miranda, A.L.; Andrade, B.B.; Assis, D.D.J.; Souza, C.O.; de Morais, M.G.; Costa, J.A.V.; Druzian, J.I. Influence of nitrogen on growth, biomass composition, production, and properties of polyhydroxyalkanoates (PHAs) by microalgae. *Int. J. Biol. Macromol.* **2018**, *116*, 552–562. [CrossRef]
41. Costa, S.S.; Miranda, A.L.; de Morais, M.G.; Costa, J.A.V.; Druzian, J.I. Microalgae as source of polyhydroxyalkanoates (PHAs)—A review. *Int. J. Biol. Macromol.* **2019**, *131*, 536–547. [CrossRef]
42. Mourão, M.M.; Gradíssimo, D.G.; Santos, A.V.; Schneider, M.P.C.; Faustino, S.M.M.; Vasconcelos, V.; Xavier, L.P. Optimization of Polyhydroxybutyrate Production by Amazonian Microalga *Stigeoclonium* sp. B23. *Biomolecules* **2020**, *10*, 1628. [CrossRef]
43. Cassuriaga, A.P.A.; Freitas, B.C.B.; Morais, M.G.; Costa, J.A.V. Innovative polyhydroxybutyrate production by Chlorella fusca grown with pentoses. *Bioresour. Technol.* **2018**, *265*, 456–463. [CrossRef]
44. Kumari, P.; Kiran, B.R.; Mohan, S.V. Polyhydroxybutyrate production by Chlorella sorokiniana SVMIICT8 under Nutrient-deprived mixotrophy. *Bioresour. Technol.* **2022**, *354*, 127135. [CrossRef] [PubMed]
45. Abdo, S.M.; Ali, G.H. Analysis of polyhydroxybutrate and bioplastic production from microalgae. *Bull. Natl. Res. Cent.* **2019**, *43*, 97. [CrossRef]
46. Sayin, S.; Kohlhaas, T.; Veziroglu, S.; Okudan, E.; Naz, M.; Schröder, S.; Saygili, E.I.; Açil, Y.; Faupel, F.; Wiltfang, J.; et al. Marine Algae-PLA composites as de novo alternative to porcine derived collagen membranes. *Mater. Today Chem.* **2020**, *17*, 100276. [CrossRef]

47. Cheng, Y.R.; Wang, H.Y. Highly effective removal of microplastics by microalgae *Scenedesmus abundans*. *Chem. Eng. J.* **2022**, *435*, 135079. [CrossRef]
48. Luft, L.; Confortin, T.C.; Todero, I.; Zabot, G.L.; Mazutti, M.A. An overview of fungal biopolymers: Bioemulsifiers and biosurfactants compounds production. *Crit. Rev. Biotechnol.* **2020**, *40*, 1059–1080. [CrossRef]
49. Kathryn, M.S.; Blair, N.E.; Levinson, W.; Louise, M.E.-W. Contribution of Fungal Macromolecules to Soil Carbon Sequestration. In *Soil Carbon*; Alfred, E.H., McSweeney, K., Eds.; Springer International Publishing: Cham, Switzerland, 2014; pp. 155–161.
50. Ebinesar, A.; More, V.S.; Ramya, D.L.; Amrutha, G.R.; More, S.S. Fungal Chitosan: The Importance and Beneficiation of this Biopolymer in Industrial and Agricultural Process. In *Microbial Polymers: Applications and Ecological Perspectives*; Vaishnav, A., Choudhary, D.K., Eds.; Springer: Singapore, 2021; pp. 311–340.
51. Alsharari, S.F.; Tayel, A.A.; Moussa, S.H. Soil emendation with nano-fungal chitosan for heavy metals biosorption. *Int. J. Biol. Macromol.* **2018**, *118*, 2265–2268. [CrossRef]
52. Singh, G.; Kumari, A.; Mittal, A.; Goel, V.; Yadav, A.; Aggarwal, N.K. Cost Effective Production of Poly-β-Hydroxybutyrate by Bacillus subtilis NG05 Using Sugar Industry Waste Water. *J Polym Environ.* **2013**, *21*, 441–449. [CrossRef]
53. Tanadchangsaeng, N.; Pattanasupong, A. Evaluation of Biodegradabilities of Biosynthetic Polyhydroxyalkanoates in Thailand Seawater and Toxicity Assessment of Environmental Safety Levels. *Polymers* **2022**, *14*, 428. [CrossRef]
54. Namboodiri, M.M.T.; Paul, T.; Medisetti, R.M.N.; Pakshirajan, K.; Narayanasamy, S.; Pugazhenthi, G. Solid state fermentation of rice straw using *Penicillium citrinum* for chitosan production and application as nanobiosorbent. *Bioresour. Technol. Rep.* **2022**, *18*, 101005. [CrossRef]
55. Chatterjee, S.; Das, A.; Paul, D.; Chakraborty, S.; Choudhury, P. Utilization of fleshing waste of leather processing for the growth of zygomycetes: A new substrate for economical production of bio-polymer chitosan. *J. Environ. Manag.* **2023**, *343*, 118141. [CrossRef]
56. Farooq, U.; Ullah, M.W.; Yang, Q.; Aziz, A.; Xu, J.; Zhou, L.; Wang, S. High-density phage particles immobilization in surface-modified bacterial cellulose for ultra-sensitive and selective electrochemical detection of *Staphylococcus aureus*. *Biosens. Bioelectron.* **2020**, *157*, 112163. [CrossRef] [PubMed]
57. Stoica-Guzun, A.; Stroescu, M.; Jinga, S.I.; Mihalache, N.; Botez, A.; Matei, C.; Berger, D.; Damian, C.M.; Ionita, V. Box-Behnken experimental design for chromium(VI) ions removal by bacterial cellulose-magnetite composites. *Int. J. Biol. Macromol.* **2016**, *91*, 1062–1072. [CrossRef]
58. Kuo, C.-H.; Huang, C.-Y.; Shieh, C.-J.; Wang, H.-M.D.; Tseng, C.-Y. Hydrolysis of Orange Peel with Cellulase and Pectinase to Produce Bacterial Cellulose using Gluconacetobacter xylinus. *Waste Biomass Valorization* **2019**, *10*, 85–93. [CrossRef]
59. Amado, I.R.; Vázquez, J.A.; Pastrana, L.; Teixeira, J.A. Cheese whey: A cost-effective alternative for hyaluronic acid production by Streptococcus zooepidemicus. *Food Chem.* **2016**, *198*, 54–61. [CrossRef]
60. Nasr, S.; Soudi, M.R.; Haghighi, M. Xanthan Production by a Native Strain of X. campestris and Evaluation of Application in EOR. *Pak. J. Biol. Sci.* **2007**, *10*, 3010–3013. [CrossRef]
61. Sampaio, I.C.F.; Crugeira, P.J.L.; Soares, L.G.P.; Santos, J.N.D.; de Almeida, P.F.; Pinheiro, A.L.B.; Silveira, L. Composition of Xanthan gum produced by *Xanthomonas campestris* using produced water from a carbonated oil field through Raman spectroscopy. *J. Photochem. Photobiol. B Biol.* **2020**, *213*, 112052. [CrossRef]
62. Jayasekara, L.A.C.B.; Poonsawad, A.; Watchaputi, K.; Wattanachaisaereekul, S.; Soontorngun, N. Media optimization of antimicrobial activity production and beta-glucan content of endophytic fungi *Xylaria* sp. BCC 1067. *Biotechnol. Rep.* **2022**, *35*, e00742. [CrossRef] [PubMed]
63. Contreras-Abara, P.; Castillo, T.; Ponce, B.; Urtuvia, V.; Peña, C.; Díaz-Barrera, A. Continuous Bioproduction of Alginate Bacterial under Nitrogen Fixation and Nonfixation Conditions. *Fermentation* **2023**, *9*, 426. [CrossRef]
64. Moral, Ç.K.; Yıldız, M. Alginate Production from Alternative Carbon Sources and Use of Polymer Based Adsorbent in Heavy Metal Removal. *Int. J. Polym. Sci.* **2016**, 7109825. [CrossRef]
65. Mohanraj, R.; Gnanamangai, B.M.; Ramesh, K.; Priya, P.; Srisunmathi, R.; Poornima, S.; Ponmurugan, P.; Robinson, J.P. Optimized production of gamma poly glutamic acid (γ-PGA) using sago. *Biocatal. Agric. Biotechnol.* **2019**, *22*, 101413. [CrossRef]
66. Bajaj, I.B.; Singhal, R.S. Flocculation Properties of Poly(γ-Glutamic Acid) Produced from Bacillus subtilis Isolate. *Food Bioproc. Tech.* **2011**, *4*, 745–752. [CrossRef]
67. Lončarević, B.; Lješević, M.; Marković, M.; Anđelković, I.; Gojgić-Cvijović, G.; Jakovljević, D.; Beškoski, V. Microbial levan and pullulan as potential protective agents for reducing adverse effects of copper on *Daphnia magna* and *Vibrio fischeri*. *Ecotoxicol. Environ. Saf.* **2019**, *181*, 187–193. [CrossRef] [PubMed]
68. Radulović, M.D.; Cvetković, O.G.; Nikolić, S.D.; Dordević, D.S.; Jakovljević, D.M.; Vrvić, M.M. Simultaneous production of pullulan and biosorption of metals by *Aureobasidium pullulans* strain CH-1 on peat hydrolysate. *Bioresour. Technol.* **2008**, *99*, 6673–6677. [CrossRef] [PubMed]
69. Jawad, A.H.; Alkarkhi, A.F.M.; Jason, O.C.; Easa, A.M.; Norulaini, N.A.N. Production of the lactic acid from mango peel waste—Factorial experiment. *J. King Saud Univ. Sci.* **2013**, *25*, 39–45. [CrossRef]
70. Nakano, S.; Ugwu, C.U.; Tokiwa, Y. Efficient production of d-(−)-lactic acid from broken rice by Lactobacillus delbrueckii using $Ca(OH)_2$ as a neutralizing agent. *Bioresour. Technol.* **2012**, *104*, 791–794. [CrossRef] [PubMed]

71. Khattak, W.A.; Khan, T.; Ul-Islam, M.; Ullah, M.W.; Khan, S.; Wahid, F.; Park, J.K. Production, characterization and biological features of bacterial cellulose from scum obtained during preparation of sugarcane jaggery (gur). *J. Food Sci. Technol.* **2015**, *52*, 8343–8349. [CrossRef] [PubMed]
72. Tsouko, E.; Kourmentza, C.; Ladakis, D.; Kopsahelis, N.; Mandala, I.; Papanikolaou, S.; Paloukis, F.; Alves, V.; Koutinas, A. Bacterial Cellulose Production from Industrial Waste and by-Product Streams. *J. Food Sci. Technol.* **2015**, *16*, 14832–14849. [CrossRef]
73. Skiba, E.A.; Budaeva, V.V.; Ovchinnikova, E.V.; Gladysheva, E.K.; Kashcheyeva, E.I.; Pavlov, I.N.; Sakovich, G.V. A technology for pilot production of bacterial cellulose from oat hulls. *Chem. Eng. J.* **2020**, *383*, 123128. [CrossRef]
74. Goelzer, F.D.E.; Faria-Tischer, P.C.S.; Vitorino, J.C.; Sierakowski, M.R.; Tischer, C.A. Production and characterization of nanospheres of bacterial cellulose from *Acetobacter xylinum* from processed rice bark. *Mater. Sci. Eng. R Rep.* **2009**, *29*, 546–551. [CrossRef]
75. Cheng, Z.; Yang, R.; Liu, X.; Liu, X.; Chen, H. Green synthesis of bacterial cellulose via acetic acid pre-hydrolysis liquor of agricultural corn stalk used as carbon source. *Bioresour. Technol.* **2017**, *234*, 8–14. [CrossRef]
76. Kurosumi, A.; Sasaki, C.; Yamashita, Y.; Nakamura, Y. Utilization of various fruit juices as carbon source for production of bacterial cellulose by Acetobacter xylinum NBRC 13693. *Carbohydr. Polym.* **2009**, *76*, 333–335. [CrossRef]
77. Zhou, J.; Chen, Y.; Zhang, Y.; Sun, S.; Ullah, M.W.; Xu, W. Biotransformation of nylon-6,6 hydrolysate to bacterial cellulose. *Green Chem.* **2021**, *23*, 7805–7815. [CrossRef]
78. Hong, F.; Guo, X.; Zhang, S.; Han, S.F.; Yang, G.; Jönsson, L.J. Bacterial cellulose production from cotton-based waste textiles: Enzymatic saccharification enhanced by ionic liquid pretreatment. *Bioresour. Technol.* **2012**, *104*, 503–508. [CrossRef] [PubMed]
79. Huang, C.; Yang, X.Y.; Xiong, L.; Guo, H.J.; Luo, J.; Wang, B.; Zhang, H.R.; Lin, X.Q.; Chen, X.D. Evaluating the possibility of using acetone-butanol-ethanol (ABE) fermentation wastewater for bacterial cellulose production by Gluconacetobacter xylinus. *Lett. Appl. Microbiol.* **2015**, *60*, 491–496. [CrossRef] [PubMed]
80. Nguyen, Q.D.; Nguyen, T.V.L.; Nguyen, T.T.D.; Nguyen, N.N. Effects of different hydrocolloids on the production of bacterial cellulose by Acetobacter xylinum using Hestrin–Schramm medium under anaerobic condition. *Bioresour. Technol. Rep.* **2022**, *17*, 100878. [CrossRef]
81. Sharma, P.; Mittal, M.; Yadav, A.; Aggarwal, N.K. Bacterial cellulose: Nano-biomaterial for biodegradable face masks—A greener approach towards environment, Environmental Nanotechnology. *Monit. Manag.* **2023**, *19*, 100759. [CrossRef] [PubMed]
82. Barshan, S.; Rezazadeh-Bari, M.; Almasi, H.; Amiri, S. Optimization and characterization of bacterial cellulose produced by Komagatacibacter xylinus PTCC 1734 using vinasse as a cheap cultivation medium. *Int. J. Biol. Macromol.* **2019**, *136*, 1188–1195. [CrossRef] [PubMed]
83. Swingler, S.; Gupta, A.; Gibson, H.; Kowalczuk, M.; Heaselgrave, W.; Radecka, I. Recent Advances and Applications of Bacterial Cellulose in Biomedicine. *Polymers* **2021**, *13*, 412. [CrossRef]
84. Wang, T.; Sun, B.; Tang, K.; Shen, W.; Chen, C.; Sun, D. Sustainable bacterial cellulose derived composites for high-efficiency hydrogen evolution reaction. *Int. J. Biol. Macromol.* **2023**, *242*, 125173. [CrossRef]
85. Zhong, C. Industrial-Scale Production and Applications of Bacterial Cellulose. *Front. Bioeng. Biotechnol.* **2020**, *8*, 605374. [CrossRef]
86. Potočnik, V.; Gorgieva, S.; Trček, J. From Nature to Lab: Sustainable Bacterial Cellulose Production and Modification with Synthetic Biology. *Polymers* **2023**, *15*, 3466. [CrossRef] [PubMed]
87. Galdino, C.J.S.; Maia, A.D.; Meira, H.M.; Souza, T.C.; Amorim, J.D.P.; Almeida, F.C.G.; Costa, A.F.S.; Sarubbo, L.A. Use of a bacterial cellulose filter for the removal of oil from wastewater. *Process Biochem.* **2020**, *91*, 288–296. [CrossRef]
88. Cazón, P.; Velázquez, G.; Vázquez, M. Characterization of bacterial cellulose films combined with chitosan and polyvinyl alcohol: Evaluation of mechanical and barrier properties. *Carbohydr. Polym.* **2019**, *216*, 72–85. [CrossRef] [PubMed]
89. Cielecka, I.; Szustak, M.; Kalinowska, H.; Gendaszewska-Darmach, E.; Ryngajłło, M.; Maniukiewicz, W.; Bielecki, S. Glycerol-plasticized bacterial nanocellulose-based composites with enhanced flexibility and liquid sorption capacity. *Cellulose* **2019**, *26*, 5409–5426. [CrossRef]
90. Chiaoprakobkij, N.; Seetabhawang, S.; Sanchavanakit, N.; Phisalaphong, M. Fabrication and characterization of novel bacterial cellulose/alginate/gelatin biocomposite film. *J. Biomater. Sci. Polym. Ed.* **2019**, *30*, 961–982. [CrossRef] [PubMed]
91. Alves, A.A.; Silva, W.E.; Belian, M.F.; Lins, L.S.G.; Galembeck, A. Bacterial cellulose membranes for environmental water remediation and industrial wastewater treatment. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 3997–4008. [CrossRef]
92. Jasim, A.; Ullah, M.W.; Shi, Z.; Lin, X.; Yang, G. Fabrication of bacterial cellulose/polyaniline/single-walled carbon nanotubes membrane for potential application as biosensor. *Carbohydr. Polym.* **2017**, *163*, 62–69. [CrossRef] [PubMed]
93. Kotsiri, Z.; Vidic, J.; Vantarakis, A. Applications of biosensors for bacteria and virus detection in food and water–A systematic review. *J Environ Sci.* **2022**, *111*, 367–379. [CrossRef] [PubMed]
94. Ieamviteevanich, P.; Daneshvar, E.; Eshaq, G.; Puro, L.; Mongkolthanaruk, W.; Pinitsoontorn, S.; Bhatnagar, A. Synthesis and Characterization of a Magnetic Carbon Nanofiber Derived from Bacterial Cellulose for the Removal of Diclofenac from Water. *ACS Omega* **2022**, *7*, 7572–7584. [CrossRef]
95. Lv, P.; Yao, Y.; Li, D.; Zhou, H.; Naeem, M.A.; Feng, Q.; Huang, J.; Cai, Y.; Wei, Q. Self-assembly of nitrogen-doped carbon dots anchored on bacterial cellulose and their application in iron ion detection. *Carbohydr. Polym.* **2017**, *172*, 93–101. [CrossRef]
96. Rana, A.K.; Scarpa, F.; Thakur, V.K. Cellulose/polyaniline hybrid nanocomposites: Design, fabrication, and emerging multidimensional applications. *Ind. Crops Prod.* **2022**, *187*, 115356. [CrossRef]

97. Ray, S.; Panjikar, S.; Anand, R. Design of Protein-Based Biosensors for Selective Detection of Benzene Groups of Pollutants. *ACS Sens.* **2018**, *3*, 1632–1638. [CrossRef]
98. Hosseini, H.; Mousavi, S.M. Bacterial cellulose/polyaniline nanocomposite aerogels as novel bioadsorbents for removal of hexavalent chromium: Experimental and simulation study. *J. Clean. Prod.* **2021**, *278*, 123817. [CrossRef]
99. Kundu, R.; Mahada, P.; Chhirang, B.; Das, B. Cellulose hydrogels: Green and sustainable soft biomaterials. *Curr. Opin. Green Sustain. Chem.* **2022**, *5*, 100252. [CrossRef]
100. Kushwaha, J.; Singh, R. Cellulose hydrogel and its derivatives: A review of application in heavy metal adsorption. *Inorg. Chem. Commun.* **2023**, *152*, 110721. [CrossRef]
101. Wu, G.T.; Kam, J.; Bloom, J.D. Hyaluronic Acid Basics and Rheology. *Clin. Plast. Surg.* **2022**, *30*, 301–308. [CrossRef] [PubMed]
102. Saravanakumar, K.; Park, S.J.; Santosh, S.S.; Ganeshalingam, A.; Thiripuranathar, G.; Sathiyaseelan, A.; Vijayasarathy, S.; Swaminathan, A.; Priya, V.V.; Wang, M.H. Application of hyaluronic acid in tissue engineering, regenerative medicine, and nanomedicine: A review. *Int. J. Biol. Macromol.* **2022**, *222*, 2744–2760. [CrossRef]
103. Jeong, E.; Shim, W.Y.; Kim, J.H. Metabolic engineering of Pichia pastoris for production of hyaluronic acid with high molecular weight. *J. Biotechnol.* **2014**, *185*, 28–36. [CrossRef]
104. Sze, J.H.; Brownlie, J.C.; Love, C.A. Biotechnological production of hyaluronic acid: A mini review. *3 Biotech* **2016**, *6*, 67. [CrossRef]
105. Marinelli, L.; Cacciatore, I.; Eusepi, P.; Di Biase, G.; Morroni, G.; Cirioni, O.; Giacometti, A.; Di Stefano, A. Viscoelastic behaviour of hyaluronic acid formulations containing carvacrol prodrugs with antibacterial properties. *Int. J. Pharm.* **2020**, *582*, 119306. [CrossRef]
106. Snetkov, P.; Zakharova, K.; Morozkina, S.; Olekhnovich, R.; Uspenskaya, M. Hyaluronic Acid: The Influence of Molecular Weight on Structural, Physical, Physico-Chemical, and Degradable Properties of Biopolymer. *Polymers* **2020**, *12*, 1800. [CrossRef] [PubMed]
107. Serra, M.; Casas, A.; Toubarro, D.; Barros, A.N.; Teixeira, J.A. Microbial Hyaluronic Acid Production: A Review. *Molecules* **2023**, *28*, 2084. [CrossRef] [PubMed]
108. Chong, B.F.; Blank, L.M.; McLaughlin, R.; Nielsen, L.K. Microbial hyaluronic acid production. *Appl. Microbiol. Biotechnol.* **2005**, *66*, 341–351. [CrossRef] [PubMed]
109. Pires, A.M.B.; Macedo, A.C.; Eguchi, S.Y.; Santana, M.H.A. Microbial production of hyaluronic acid from agricultural resource derivatives. *Bioresour. Technol.* **2010**, *101*, 6506–6509. [CrossRef] [PubMed]
110. Vázquez, J.A.; Montemayor, M.I.; Fraguas, J.; Murado, M.A. Hyaluronic acid production by *Streptococcus zooepidemicus* in marine by-products media from mussel processing wastewaters and tuna peptone viscera. *Microb. Cell Factories* **2010**, *9*, 46. [CrossRef] [PubMed]
111. Zhang, Y.H.; Liu, C.S.; Tian, Y.; Wang, J.; Xin, S.; Sheng, X. An eco-friendly photo-responsive hyaluronic acid-based supramolecular polysaccharide hybrid hydrogels for plant growth regulation and heavy metal ions adsorption. *Int. J. Biol. Macromol.* **2023**, *242*, 125194. [CrossRef] [PubMed]
112. Taşdelen, B.; Çifçi, D.İ.; Meriç, S. Preparation and characterization of chitosan/hyaluronic acid/itaconic acid hydrogel composite to remove manganese in aqueous solution. *Desalination Water Treat.* **2021**, *209*, 204–211. [CrossRef]
113. Abdallah, M.M.; Fernández, N.; Matias, A.A.; Bronze, M.D.R. Hyaluronic acid and Chondroitin sulfate from marine and terrestrial sources: Extraction and purification methods. *Carbohydr. Polym.* **2020**, *243*, 116441. [CrossRef] [PubMed]
114. Vázquez, J.A.; Pastrana, L.; Piñeiro, C.; Teixeira, J.A.; Pérez-Martín, R.I.; Amado, I.R. Production of Hyaluronic Acid by Streptococcus zooepidemicus on Protein Substrates Obtained from Scyliorhinus canicula Discards. *Mar. Drugs* **2015**, *13*, 6537–6549. [CrossRef]
115. Amado, I.R.; Vázquez, J.A.; Pastrana, L.; Teixeira, J.A. Microbial production of hyaluronic acid from agro-industrial by-products: Molasses and corn steep liquor. *Biochem. Eng. J.* **2017**, *117*, 181–187. [CrossRef]
116. Um, I.C.; Fang, D.; Hsiao, B.S.; Okamoto, A.; Chu, B. Electro-Spinning and Electro-Blowing of Hyaluronic Acid. *Biomacromolecules* **2004**, *5*, 1428–1436. [CrossRef] [PubMed]
117. Wang, X.; Um, I.C.; Fang, D.; Okamoto, A.; Hsiao, B.S.; Chu, B. Formation of water-resistant hyaluronic acid nanofibers by blowing-assisted electro-spinning and non-toxic post treatments. *Polymer* **2005**, *46*, 4853–4867. [CrossRef]
118. Nsengiyumva, E.M.; Alexandridis, P. Xanthan gum in aqueous solutions: Fundamentals and applications. *Int. J. Biol. Macromol.* **2022**, *216*, 583–604. [CrossRef] [PubMed]
119. Palaniraj, A.; Jayaraman, V. Production, recovery and applications of xanthan gum by *Xanthomonas campestris*. *J. Food Eng.* **2011**, *106*, 1–12. [CrossRef]
120. Bhat, I.M.; Wani, S.M.; Mir, S.A.; Masoodi, F.A. Advances in xanthan gum production, modifications and its applications. *Biocatal. Agric. Biotechnol.* **2022**, *42*, 102328. [CrossRef]
121. Dzionek, A.; Wojcieszyńska, D.; Guzik, U. Use of xanthan gum for whole cell immobilization and its impact in bioremediation—A review. *Bioresour. Technol.* **2022**, *351*, 126918. [CrossRef] [PubMed]
122. Sulaiman, H.; Taha, M.R.; Rahman, N.A.; Taib, A.M. Performance of soil stabilized with biopolymer materials—Xanthan gum and guar gum. *Phys. Chem. Earth Parts A/B/C* **2022**, *128*, 103276. [CrossRef]
123. Liu, Y.; Zhu, Y.; Wang, Y.; Quan, Z.; Zong, L.; Wang, A. Synthesis and application of eco-friendly superabsorbent composites based on xanthan gum and semi-coke. *Int. J. Biol. Macromol.* **2021**, *179*, 230–238. [CrossRef]

124. Feng, D.; Liang, B.; He, X.; Yi, F.; Xue, J.; Wan, Y.; Xue, Q. Mechanical properties of dredged soil reinforced by xanthan gum and fibers. *J. Rock Mech. Geotech. Eng.* **2023**, *15*, 2147–2157. [CrossRef]
125. de Souza, C.K.; Ghosh, T.; Lukhmana, N.; Tahiliani, S.; Priyadarshi, R.; Hoffmann, T.G.; Purohit, S.D.; Han, S.S. Pullulan as a sustainable biopolymer for versatile applications: A review, Mater. *Today Commun.* **2023**, *36*, 106477. [CrossRef]
126. Keykhosravi, A.; Vanani, M.B.; Aghayari, C. TiO_2 nanoparticle-induced Xanthan Gum Polymer for EOR: Assessing the underlying mechanisms in oil-wet carbonates. *J. Pet. Sci. Eng.* **2021**, *204*, 108756. [CrossRef]
127. Ko, M.S.; Jeon, Y.J.; Kim, K.W. Novel application of xanthan gum-based biopolymer for heavy metal immobilization in soil. *J. Environ. Chem.* **2022**, *10*, 108240. [CrossRef]
128. Njuguna, D.G.; Schönherr, H. Smart and regeneratable Xanthan gum hydrogel adsorbents for selective removal of cationic dyes. *J. Environ. Chem. Eng.* **2022**, *10*, 107620. [CrossRef]
129. Gohari, R.M.; Safarnia, M.; Koohi, A.D.; Salehi, M.B. Adsorptive removal of cationic dye by synthesized sustainable xanthan gum-g p(AMPS-co-AAm) hydrogel from aqueous media: Optimization by RSM-CCD model. *Chem. Eng. Res. Des.* **2022**, *188*, 714–728. [CrossRef]
130. Taktak, F.F.; Özyaranlar, E. Semi-interpenetrating network based on xanthan gum-cl-2-(N-morpholinoethyl methacrylate)/titanium oxide for the single and binary removal of cationic dyes from water. *Int. J. Biol. Macromol.* **2022**, *221*, 238–255. [CrossRef] [PubMed]
131. Hosseini, H.; Pirahmadi, P.; Shakeri, S.E.; Khoshbakhti, E.; Sharafkhani, S.; Fakhri, V.; Saeidi, A.; McClements, D.J.; Chen, W.H.; Chia, H.; et al. A novel environmentally friendly nanocomposite aerogel based on the semi-interpenetrating network of polyacrylic acid into Xanthan gum containing hydroxyapatite for efficient removal of methylene blue from wastewater. *Int. J. Biol. Macromol.* **2022**, *201*, 133–142. [CrossRef] [PubMed]
132. Hu, X.; Yan, L.; Xu, M.; Tang, L. Photo-degradable salecan/xanthan gum ionic gel induced by iron (III) coordination for organic dye decontamination. *Int. J. Biol. Macromol.* **2023**, *238*, 124132. [CrossRef]
133. Lara, G.; Yakoubi, S.; Villacorta, C.M.; Uemura, K.; Kobayashi, I.; Takahashi, C.; Nakajima, M.; Neves, M.A. Spray technology applications of xanthan gum-based edible coatings for fresh-cut lotus root (*Nelumbo nucifera*). *Food Res. Int.* **2020**, *137*, 109723. [CrossRef] [PubMed]
134. Chen, J.; Zheng, M.; Tan, K.B.; Lin, J.; Chen, M.; Zhu, Y. Polyvinyl alcohol/xanthan gum composite film with excellent food packaging, storage and biodegradation capability as potential environmentally-friendly alternative to commercial plastic bag. *Int. J. Biol. Macromol.* **2022**, *212*, 402–411. [CrossRef]
135. Zheng, M.; Zhu, Y.; Zhuang, Y.; Tan, K.B.; Chen, J. Effects of grape seed extract on the properties of pullulan polysaccharide/xanthan gum active films for apple preservation. *Int. J. Biol. Macromol.* **2023**, *241*, 124617. [CrossRef]
136. Zhu, F.; Du, B.; Xu, B. A critical review on production and industrial applications of beta-glucans. *Food Hydrocoll.* **2016**, *52*, 275–288. [CrossRef]
137. Philippini, R.R.; Martiniano, S.E.; Santos, J.C.D.; da Silva, S.S.; Chandel, A.K. *Fermentative Production of Beta-Glucan: Properties and Potential Applications, Bioprocessing for Biomolecules Production*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2019; pp. 303–320.
138. Chavanke, S.N.; Penna, S.; Dalvi, S.G. β-Glucan and its nanocomposites in sustainable agriculture and environment: An overview of mechanisms and applications. *Environ. Sci. Pollut. Res.* **2022**, *29*, 80062–80087. [CrossRef]
139. Anusuya, S.; Sathiyabama, M. Preparation of β-d-glucan nanoparticles and its antifungal activity. *Int. J. Biol. Macromol.* **2014**, *70*, 440–443. [CrossRef]
140. Anusuya, S.; Sathiyabama, M. Foliar application of β-d-glucan nanoparticles to control rhizome rot disease of turmeric. *Int. J. Biol. Macromol.* **2015**, *72*, 1205–1212. [CrossRef] [PubMed]
141. Vetvicka, V. Effects of β-glucan on some environmental toxins: An overview. *Biomed. Pap.* **2014**, *158*, 001–004. [CrossRef]
142. Li, L.; Zhu, B.; Yao, Z.; Jiang, J. Directed preparation, structure–activity relationship and applications of alginate oligosaccharides with specific structures: A systematic review. *Food Res. Int.* **2023**, *170*, 112990. [CrossRef] [PubMed]
143. Zhang, H.; Han, X.; Liu, J.; Wang, M.; Zhao, T.; Kang, L.; Zhong, S.; Cui, X. Fabrication of modified alginate-based biocomposite hydrogel microspheres for efficient removal of heavy metal ions from water. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *651*, 129736. [CrossRef]
144. Shahbazi, M.; Jäger, H.; Ahmadi, S.J.; Lacroix, M. Electron beam crosslinking of alginate/nanoclay ink to improve functional properties of 3D printed hydrogel for removing heavy metal ions. *Carbohydr. Polym.* **2020**, *240*, 116211. [CrossRef]
145. Duc, T.H.; Vu, T.K.; Dang, C.T.; Nguyen, V.H.; La, D.D.; Kim, G.M.; Chang, S.W.; Bui, X.T.; Dang, T.D.; Nguyen, D.D. Synthesis and application of hydrogel calcium alginate microparticles as a biomaterial to remove heavy metals from aqueous media. *Environ. Technol. Innov.* **2021**, *22*, 101400. [CrossRef]
146. Zhang, W.; Ou, J.; Wang, B.; Wang, H.; He, Q.; Song, J.; Zhang, H.; Tang, M.; Zhou, L.; Gao, Y.; et al. Efficient heavy metal removal from water by alginate-based porous nanocomposite hydrogels: The enhanced removal mechanism and influencing factor insight. *J. Hazard. Mater.* **2021**, *418*, 126358. [CrossRef]
147. Cai, R.; Chen, Y.; Hu, J.; Xiong, J.; Lu, J.; Liu, J.; Tan, X.; Liu, W.; Zhou, Y.; Chen, Y. A self-supported sodium alginate composite hydrogel membrane and its performance in filtering heavy metal ions. *Carbohydr. Polym.* **2023**, *300*, 120278. [CrossRef] [PubMed]
148. Malik, S.A.; Dar, A.A.; Banday, J.A. Rheological, morphological and swelling properties of dysprosium-based composite hydrogel beads of alginate and chitosan: A promising material for the effective cationic and anionic dye removal. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *663*, 131046. [CrossRef]

149. Jayalakshmi, R.; Jeyanthi, J. Dynamic modelling of Alginate-Cobalt ferrite nanocomposite for removal of binary dyes from textile effluent. *J. Environ. Chem. Eng.* **2021**, *9*, 104924. [CrossRef]
150. Makhado, E.; Pandey, S.; Modibane, K.D.; Kang, M.; Hato, M.J. Sequestration of methylene blue dye using sodium alginate poly(acrylic acid)@ZnO hydrogel nanocomposite: Kinetic, Isotherm, and Thermodynamic Investigations. *Int. J. Biol. Macromol.* **2020**, *162*, 60–73. [CrossRef] [PubMed]
151. Hassan, R.M. Novel synthesis of ultrafiltration membranes by crosslinking metal (II)-Alginate hydrogels with hexamethylene 1,6-Diisocyanate in inert solvent: Application for remediation of wastewater by removal of toxic pollutants. *Chem. Eng. J.* **2023**, *452*, 139093. [CrossRef]
152. Thirumavalavan, M. Functionalized chitosan and sodium alginate for the effective removal of recalcitrant organic pollutants. *Int. J. Biol. Macromol.* **2023**, *243*, 125276. [CrossRef] [PubMed]
153. Bhatia, S.K.; Ahuja, V.; Chandel, N.; Gurav, R.; Bhatia, R.K.; Govarthanan, M.; Tyagi, V.K.; Kumar, V.; Pugazendhi, A.; Banu, J.R.; et al. Advances in algal biomass pretreatment and its valorisation into biochemical and bioenergy by the microbial processes. *Bioresour. Technol.* **2022**, *358*, 127437.
154. Zhang, H.; Guan, G.; Lou, T.; Wang, X. High performance, cost-effective and ecofriendly flocculant synthesized by grafting carboxymethyl cellulose and alginate with itaconic acid. *Int. J. Biol. Macromol.* **2023**, *231*, 123305. [CrossRef]
155. Lu, T.; Xiang, T.; Huang, X.L.; Li, C.; Zhao, W.F.; Zhang, Q.; Zhao, C.S. Post-crosslinking towards stimuli-responsive sodium alginate beads for the removal of dye and heavy metals. *Carbohydr. Polym.* **2015**, *133*, 587–595. [CrossRef]
156. da Cunha, A.B.M.; Leal, D.A.; Santos, L.R.L.; Riegel-Vidotti, I.C.; Marino, C.E.B. pH-sensitive microcapsules based on biopolymers for active corrosion protection of carbon steel at different pH. *Surf. Coat. Technol.* **2020**, *402*, 126338. [CrossRef]
157. Gopishetty, V.; Tokarev, I.; Minko, S. Biocompatible stimuli-responsive hydrogel porous membranes via phase separation of a polyvinyl alcohol and Na-alginate intermolecular complex. *J. Mater. Chem.* **2012**, *22*, 19482–19487. [CrossRef]
158. Hay, I.D.; Rehman, Z.U.; Moradali, M.F.; Wang, Y.; Rehm, B.H.A. Microbial alginate production, modification and its applications. *Microb. Biotechnol.* **2013**, *6*, 637–650. [CrossRef]
159. Wang, L.L.; Liu, Y.M.; Liu, H.M.; Shi, Q.S.; Peng, R.Q.; Xie, X.B. The role of structural evolution in the complexation and flocculation of heavy metals by the microbial product poly-γ-glutamic acid. *Chemosphere* **2022**, *308*, 136441. [CrossRef]
160. SLuo, G.; Chien, C.C.; Sheu, Y.T.; Verpoort, F.; Chen, S.C.; Kao, C.M. Enhanced bioremediation of trichloroethene-contaminated groundwater using modified γ-PGA for continuous substrate supplement and pH control: Batch and pilot-scale studies. *J. Clean. Prod.* **2021**, *278*, 123736.
161. Luo, S.G.; Chen, S.C.; Cao, W.Z.; Lin, W.H.; Sheu, Y.T.; Kao, C.M. Application of γ-PGA as the primary carbon source to bioremediate a TCE-polluted aquifer: A pilot-scale study. *Chemosphere* **2019**, *237*, 124449. [CrossRef]
162. Fernandes, A.R.A.C.; Sganzerla, W.G.; Granado, N.P.A.; Campos, V. Implication of organic solvents in the precipitation of γ-polyglutamic acid for application as a sustainable flocculating agent. *Biocatal. Agric. Biotechnol.* **2023**, *50*, 102698. [CrossRef]
163. Sakamoto, S.; Kawase, Y. Adsorption capacities of poly-γ-glutamic acid and its sodium salt for cesium removal from radioactive wastewaters. *J. Environ. Radioact.* **2016**, *165*, 151–158. [CrossRef]
164. Campos, V.; Fernandes, A.R.A.C.; Medeiros, T.A.M.; Andrade, E.L. Physicochemical characterization and evaluation of PGA bioflocculant in coagulation-flocculation and sedimentation processes. *J. Environ. Chem. Eng.* **2016**, *4*, 3753–3760. [CrossRef]
165. Abdelnaby, T.; Li, Z.; Cao, W.; Xue, C. The effect of gamma-poly glutamic acid as a cryoprotectant on crayfish physicochemical and texture properties during frozen storage. *LWT* **2023**, *184*, 109960. [CrossRef]
166. Soliman, G.M. Nanoparticles as safe and effective delivery systems of antifungal agents: Achievements and challenges. *Int. J. Pharm.* **2017**, *523*, 15–32. [CrossRef] [PubMed]
167. Lin, C.C.; Chiu, J.Y. A novel γ-PGA composite gellan membrane containing glycerol for guided bone regeneration. *Mater. Sci. Eng. C.* **2021**, *118*, 111404. [CrossRef]
168. Zhang, K.; Li, F.; Wu, Y.; Feng, L.; Zhang, L. Construction of ionic thermo-responsive PNIPAM/γ-PGA/PEG hydrogel as a draw agent for enhanced forward-osmosis desalination. *Desalination* **2020**, *495*, 114667. [CrossRef]
169. Panda, P.K.; Yang, J.M.; Chang, Y.H. Preparation and characterization of ferulic acid-modified water soluble chitosan and poly (γ-glutamic acid) polyelectrolyte films through layer-by-layer assembly towards protein adsorption. *Int. J. Biol. Macromol.* **2021**, *171*, 457–464. [CrossRef]
170. Luo, Z.; Guo, Y.; Liu, J.; Qiu, H.; Zhao, M.; Zou, W.; Li, S. Microbial synthesis of poly-γ-glutamic acid: Current progress, challenges, and future perspectives. *Biotechnol. Biofuels* **2016**, *9*, 134. [CrossRef]
171. Udayakumar, G.P.; Muthusamy, S.; Selvaganesh, B.; Sivarajasekar, N.; Rambabu, K.; Sivamani, S.; Sivakumar, N.; Maran, J.P.; Hosseini-Bandegharaei, A. Ecofriendly biopolymers and composites: Preparation and their applications in water-treatment. *Biotechnol. Adv.* **2021**, *52*, 107815. [CrossRef]
172. Kachhawa, D.K.; Bhattacharjee, P.; Singhal, R.S. Studies on downstream processing of pullulan. *Carbohydr. Polym.* **2003**, *52*, 25–28. [CrossRef]
173. Cruz-Santos, M.M.; Antunes, F.A.F.; Arruda, G.L.; Shibukawa, V.P.; Prado, C.A.; Ortiz-Silos, N.; Castro-Alonso, M.J.; Marcelino, P.R.F.; Santos, J.C. Production and applications of pullulan from lignocellulosic biomass: Challenges and perspectives. *Bioresour. Technol.* **2023**, *385*, 129460. [CrossRef]
174. Kizildag, N. Pullulan Films with PCMs: Recyclable Bio-Based Films with Thermal Management Functionality. *Coatings* **2023**, *13*, 414. [CrossRef]

175. Milenković, I.; Radotić, K.; Despotović, J.; Lončarević, B.; Lješević, M.; Spasić, S.Z.; Nikolić, A.; Beškoski, V.P. Toxicity investigation of CeO_2 nanoparticles coated with glucose and exopolysaccharides levan and pullulan on the bacterium *Vibrio fischeri* and aquatic organisms *Daphnia magna* and *Danio rerio*. *Aquat. Toxicol.* **2021**, *236*, 105867. [CrossRef]
176. Song, W.; Yang, Y.; Liang, X.; Liu, F.; Gadd, G.M. Influence of metals and metalloids on the composition and fluorescence quenching of the extracellular polymeric substances produced by the polymorphic fungus *Aureobasidium pullulans*. *Appl. Microbiol. Biotechnol.* **2020**, *104*, 7155–7164. [CrossRef]
177. Wu, L.; Shi, M.; Guo, R.; Dong, W. Development of a novel pullulan/polydopamine composite hydrogel adsorbent for dye removal. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *652*, 129632. [CrossRef]
178. Richa, A. Roy Choudhury, Synthesis of a novel gellan-pullulan nanogel and its application in adsorption of cationic dye from aqueous medium. *Carbohydr. Polym.* **2020**, *227*, 115291. [CrossRef]
179. Su, T.; Wu, L.; Zuo, G.; Pan, X.; Shi, M.; Zhang, C.; Qi, X.; Dong, W. Incorporation of dumbbell-shaped and Y-shaped cross-linkers in adjustable pullulan/polydopamine hydrogels for selective adsorption of cationic dyes. *Environ. Res.* **2020**, *182*, 109010. [CrossRef] [PubMed]
180. Cheng, S.; Zhang, C.; Li, J.; Pan, X.; Zhai, X.; Jiao, Y.; Li, Y.; Dong, W.; Qi, X. Highly efficient removal of antibiotic from biomedical wastewater using Fenton-like catalyst magnetic pullulan hydrogels. *Carbohydr. Polym.* **2021**, *262*, 117951. [CrossRef] [PubMed]
181. Pan, X.; Cheng, S.; Zhang, C.; Jiao, Y.; Lin, X.; Dong, W.; Qi, X. Mussel-inspired magnetic pullulan hydrogels for enhancing catalytic degradation of antibiotics from biomedical wastewater. *Chem. Eng. J.* **2021**, *409*, 128203. [CrossRef]
182. Santos, S.M.; Carbajo, J.M.; Quintana, E.; Ibarra, D.; Gomez, N.; Ladero, M.; Eugenio, M.E.; Villar, J.C. Characterization of purified bacterial cellulose focused on its use on paper restoration. *Carbohydr. Polym.* **2015**, *116*, 173–181. [CrossRef] [PubMed]
183. Jafarzadeh, S.; Jafari, S.M.; Salehabadi, A.; Nafchi, A.M.; Kumar, U.S.U.; Khalil, H.P.S.A. Biodegradable green packaging with antimicrobial functions based on the bioactive compounds from tropical plants and their by-products. *Trends Food Sci Technol.* **2020**, *100*, 262–277. [CrossRef]
184. Rashid, A.; Qayum, A.; Liang, Q.; Kang, L.; Raza, H.; Chi, Z.; Chi, R.; Ren, X.; Ma, H. Preparation and characterization of ultrasound-assisted essential oil-loaded nanoemulsions stimulated pullulan-based bioactive film for strawberry fruit preservation. *Food Chem.* **2023**, *422*, 136254. [CrossRef] [PubMed]
185. Kang, L.; Liang, Q.; Rashid, A.; Qayum, A.; Chi, Z.; Ren, X.; Ma, H. Ultrasound-assisted development and characterization of novel polyphenol-loaded pullulan/trehalose composite films for fruit preservation. *Ultrason Sonochem.* **2023**, *92*, 106242. [CrossRef]
186. Chen, W.; Liu, H.; Chai, Y.; Guo, C.; Luo, C.; Chen, D.; Cheng, X.; Wang, F.; Huang, C. Chitosan–pullulan films enriched with Artemisia annua essential oil: Characterization and application in grape preservation. *Int. J. Biol. Macromol.* **2023**, *243*, 125216. [CrossRef]
187. Zeng, Z.; Yang, Y.J.; Tu, Q.; Jian, Y.Y.; Xie, D.M.; Bai, T.; Li, S.S.; Liu, Y.T.; Li, C.; Wang, C.X.; et al. Preparation and characterization of carboxymethyl chitosan/pullulan composite film incorporated with eugenol and its application in the preservation of chilled meat. *Meat Sci.* **2023**, *198*, 109085. [CrossRef]
188. Gan, L.; Jiang, G.; Yang, Y.; Zheng, B.; Zhang, S.; Li, X.; Tian, Y.; Peng, B. Development and characterization of levan/pullulan/chitosan edible films enriched with ε-polylysine for active food packaging. *Food Chem.* **2022**, *388*, 132989. [CrossRef]
189. Huang, J.; Xiao, L.; Yi, Y.; Li, B.; Sun, R.; Deng, H. Preservation mechanism and flavor variation of postharvest button mushroom (Agaricus Bisporus) coated compounds of protocatechuic acid-CaCl2-NaCl-pullulan. *LWT* **2022**, *169*, 114020. [CrossRef]
190. Rasweefali, M.K.; Sabu, S.; Azad, K.S.M.; Rahman, M.K.R.; Sunooj, K.V.; Sasidharan, A.; Anoop, K.K. Influence of deproteinization and demineralization process sequences on the physicochemical and structural characteristics of chitin isolated from Deep-sea mud shrimp (*Solenocera hextii*). *Adv. Biomark. Sci. Technol.* **2022**, *4*, 12–27. [CrossRef]
191. Crognale, S.; Russo, C.; Petruccioli, M.; D'Annibale, A. Chitosan Production by Fungi: Current State of Knowledge. *Future Oppor. Constraints Ferment.* **2022**, *8*, 76.
192. Sebastian, J.; Rouissi, T.; Brar, S.K. Fungal chitosan: Prospects and challenges. In *Handbook of Chitin and Chitosan: Volume 1: Preparation and Properties*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 419–452.
193. Wang, L.; Xin, M.; Li, M.; Liu, W.; Mao, Y. Effect of the structure of chitosan quaternary phosphonium salt and chitosan quaternary ammonium salt on the antibacterial and antibiofilm activity. *Int. J. Biol. Macromol.* **2023**, *242*, 124877. [CrossRef] [PubMed]
194. Mohammadi, P.; Taghavi, E.; Foong, S.Y.; Rajaei, A.; Amiri, H.; de Tender, C.; Peng, W.; Lam, S.S.; Aghbashlo, M.; Rastegari, H.; et al. Comparison of shrimp waste-derived chitosan produced through conventional and microwave-assisted extraction processes: Physicochemical properties and antibacterial activity assessment. *Int. J. Biol. Macromol.* **2023**, *242*, 124841. [CrossRef] [PubMed]
195. Liu, F.; Zhang, X.; Xiao, X.; Duan, Q.; Bai, H.; Cao, Y.; Zhang, Y.; Alee, M.; Yu, L. Improved hydrophobicity, antibacterial and mechanical properties of polyvinyl alcohol/quaternary chitosan composite films for antibacterial packaging. *Carbohydr. Polym.* **2023**, *312*, 120755. [CrossRef] [PubMed]
196. Lan, W.; Wang, S.; Chen, M.; Sameen, D.E.; Lee, K.J.; Liu, Y. Developing poly(vinyl alcohol)/chitosan films incorporate with d-limonene: Study of structural, antibacterial, and fruit preservation properties. *Int. J. Biol. Macromol.* **2020**, *145*, 722–732. [CrossRef]

197. Paomephan, P.; Assavanig, A.; Chaturongakul, S.; Cady, N.C.; Bergkvist, M.; Niamsiri, N. Insight into the antibacterial property of chitosan nanoparticles against *Escherichia coli* and *Salmonella typhimurium* and their application as vegetable wash disinfectant. *Food Control.* **2018**, *86*, 294–301. [CrossRef]
198. Pereira, A.E.S.; Sandoval-Herrera, I.E.; Zavala-Betancourt, S.A.; Oliveira, H.C.; Ledezma-Pérez, A.S.; Romero, J.; Fraceto, L.F. γ-Polyglutamic acid/chitosan nanoparticles for the plant growth regulator gibberellic acid: Characterization and evaluation of biological activity. *Carbohydr. Polym.* **2017**, *157*, 1862–1873. [CrossRef] [PubMed]
199. Ji, H.; Wang, J.; Chen, F.; Fan, N.; Wang, X.; Xiao, Z.; Wang, Z. Meta-analysis of chitosan-mediated effects on plant defense against oxidative stress. *Sci. Total Environ.* **2022**, *851*, 158212. [CrossRef] [PubMed]
200. Ingle, P.U.; Shende, S.S.; Shingote, P.R.; Mishra, S.S.; Sarda, V.; Wasule, D.L.; Rajput, V.D.; Minkina, T.; Rai, M.; Sushkova, S.; et al. Chitosan nanoparticles (ChNPs): A versatile growth promoter in modern agricultural production. *Heliyon* **2022**, *8*, e11893. [CrossRef] [PubMed]
201. Lakkaboyana, S.K.; Soontarapa, K.; Vinaykumar; Marella, R.K.; Kannan, K. Preparation of novel chitosan polymeric nanocomposite as an efficient material for the removal of Acid Blue 25 from aqueous environment. *Int. J. Biol. Macromol.* **2021**, *168*, 760–768. [CrossRef] [PubMed]
202. Amin, K.F.; Gulshan, F.; Asrafuzzaman, F.N.U.; Das, H.; Rashid, R.; Hoque, S.M. Synthesis of mesoporous silica and chitosan-coated magnetite nanoparticles for heavy metal adsorption from wastewater. *Environ. Nanotechnol. Monit. Manag.* **2023**, *20*, 100801. [CrossRef]
203. Patel, P.K.; Pandey, L.M.; Uppaluri, R.V.S. Cyclic desorption based efficacy of polyvinyl alcohol-chitosan variant resins for multi heavy-metal removal. *Int. J. Biol. Macromol.* **2023**, *242*, 124812. [CrossRef] [PubMed]
204. Zeng, X.; Zhang, G.; Wen, J.; Li, X.; Zhu, J.; Wu, Z. Simultaneous removal of aqueous same ionic type heavy metals and dyes by a magnetic chitosan/polyethyleneimine embedded hydrophobic sodium alginate composite: Performance, interaction and mechanism. *Chemosphere* **2023**, *318*, 137869. [CrossRef] [PubMed]
205. Wu, S.; Shi, W.; Li, K.; Cai, J.; Xu, C.; Gao, L.; Lu, J.; Ding, F. Chitosan-based hollow nanofiber membranes with polyvinylpyrrolidone and polyvinyl alcohol for efficient removal and filtration of organic dyes and heavy metals. *Int. J. Biol. Macromol.* **2023**, *239*, 124264. [CrossRef]
206. Namasivayam, S.K.R.; Pandian, U.K.; Vani, C.; Bharani, R.S.A.; Kavisri, M.; Meivelu, M. Chitosan nanocomposite as an effective carrier of potential herbicidal metabolites for noteworthy phytotoxic effect against major aquatic invasive weed water hyacinth (*Eichhornia crassipes*). *Int. J. Biol. Macromol.* **2023**, *226*, 1597–1610. [CrossRef]
207. Al-Manhel, A.J.; Al-Hilphy, A.R.S.; Niamah, A.K. Extraction of chitosan, characterisation and its use for water purification. *J. Saudi Soc. Agric. Sci.* **2018**, *17*, 186–190. [CrossRef]
208. Zhang, Y.; Mei, B.; Shen, B.; Jia, L.; Liao, J.; Zhu, W. Preparation of biochar@chitosan-polyethyleneimine for the efficient removal of uranium from water environment. *Carbohydr. Polym.* **2023**, *312*, 120834. [CrossRef] [PubMed]
209. Maneechote, W.; Cheirsilp, B.; Angelidaki, I.; Suyotha, W.; Boonsawang, P. Chitosan-coated oleaginous microalgae-fungal pellets for improved bioremediation of non-sterile secondary effluent and application in carbon dioxide sequestration in bubble column photobioreactors. *Bioresour. Technol.* **2023**, *372*, 128675. [CrossRef] [PubMed]
210. Liu, Q.; Wang, Y.; Sun, S.; Tang, F.; Chen, H.; Chen, S.; Zhao, C.; Li, L. A novel chitosan-biochar immobilized microorganism strategy to enhance bioremediation of crude oil in soil. *Chemosphere* **2023**, *313*, 137367. [CrossRef] [PubMed]
211. Szymańska, E.; Winnicka, K. Stability of Chitosan—A Challenge for Pharmaceutical and Biomedical Applications. *Mar. Drugs* **2015**, *13*, 1819–1846. [CrossRef] [PubMed]
212. Zheng, Y.; Chen, J.C.; Ma, Y.M.; Chen, G.Q. Engineering biosynthesis of polyhydroxyalkanoates (PHA) for diversity and cost reduction. *Metab. Eng.* **2020**, *58*, 82–93. [CrossRef] [PubMed]
213. Aulenta, F.; Fuoco, M.; Canosa, A.; Papini, M.P.; Majone, M. Use of poly-β-hydroxy-butyrate as a slow-release electron donor for the microbial reductive dechlorination of TCE. *Water Sci. Technol.* **2008**, *57*, 921–925. [CrossRef] [PubMed]
214. Zhou, W.; Bergsma, S.; Colpa, D.I.; Euverink, G.J.W.; Krooneman, J. Polyhydroxyalkanoates (PHAs) synthesis and degradation by microbes and applications towards a circular economy. *J. Environ. Manag.* **2023**, *341*, 118033. [CrossRef] [PubMed]
215. Weng, Y.X.; Wang, X.L.; Wang, Y.Z. Biodegradation behavior of PHAs with different chemical structures under controlled composting conditions. *Polymer Test.* **2011**, *30*, 372–380. [CrossRef]
216. Sashiwa, H.; Fukuda, R.; Okura, T.; Sato, S.; Nakayama, A. Microbial Degradation Behavior in Seawater of Polyester Blends Containing Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBHHx). *Mar. Drugs* **2018**, *16*, 34. [CrossRef]
217. Dhania, S.; Bernela, M.; Rani, R.; Parsad, M.; Kumar, R.; Thakur, R. Polyhydroxybutyrate (PHB) in nanoparticulate form improves physical and biological performance of scaffolds. *Int. J. Biol. Macromol.* **2023**, *236*, 123875. [CrossRef]
218. Othman, N.A.F.; Selambakkannu, S.; Seko, N. Biodegradable dual-layer Polyhydroxyalkanoate (pha)/Polycaprolactone (pcl) mulch film for agriculture: Preparation and characterization. *Energy Nexus* **2022**, *8*, 100137. [CrossRef]
219. Kelwick, R.J.R.; Webb, A.J.; Wang, Y.; Heliot, A.; Allan, F.; Emery, A.M.; Templeton, M.R.; Freemont, P.S. AL-PHA beads: Bioplastic-based protease biosensors for global health applications. *Mater. Today* **2021**, *47*, 25–37. [CrossRef]
220. Amanat, N.; Matturro, B.; Rossi, M.M.; Valentino, F.; Villano, M.; Papini, M.P. Assessment of Long-Term Fermentability of PHA-Based Materials from Pure and Mixed Microbial Cultures for Potential Environmental Applications. *Water* **2021**, *13*, 897. [CrossRef]

221. Palmeiro-Sánchez, T.; Oliveira, C.S.S.; Gouveia, A.R.; Noronha, J.P.; Ramos, A.M.; Mosquera-Corral, A.; Reis, M.A.M. NaCl presence and purification affect the properties of mixed culture PHAs. *Eur. Polym. J.* **2016**, *85*, 256–265. [CrossRef]
222. Yang, M.; Zou, Y.; Wang, X.; Liu, X.; Wan, C.; Harder, M.; Yan, Q.; Nan, J.; Ntaikou, I.; Antonopoulou, G.; et al. Synthesis of intracellular polyhydroxyalkanoates (PHA) from mixed phenolic substrates in an acclimated consortium and the mechanisms of toxicity. *J. Environ. Chem. Eng.* **2022**, *10*, 107944. [CrossRef]
223. Singh, M.; Kumar, P.; Ray, S.; Kalia, V.C. Challenges and Opportunities for Customizing Polyhydroxyalkanoates. *Indian J. Microbiol.* **2015**, *55*, 235–249. [CrossRef]
224. Balla, E.; Daniilidis, V.; Karlioti, G.; Kalamas, T.; Stefanidou, M.; Bikiaris, N.D.; Vlachopoulos, A.; Koumentakou, I.; Bikiaris, D.N. Poly(lactic Acid): A Versatile Biobased Polymer for the Future with Multifunctional Properties—From Monomer Synthesis, Polymerization Techniques and Molecular Weight Increase to PLA Applications. *Polymers* **2021**, *13*, 1822. [CrossRef] [PubMed]
225. Thygesen, A.; Tsapekos, P.; Alvarado-Morales, M.; Angelidaki, I. Valorization of municipal organic waste into purified lactic acid. *Bioresour. Technol.* **2021**, *342*, 125933. [CrossRef] [PubMed]
226. Ahmad, A.; Othman, I.; Rambabu, K.; Bharath, G.; Taher, H.; Hasan, S.W.; Banat, F. Polymerization of lactic acid produced from food waste by metal oxide-assisted dark fermentation. *Environ. Technol. Innov.* **2021**, *24*, 101862. [CrossRef]
227. Menezes, O.; Roberts, T.; Motta, G.; Patrenos, M.H.; McCurdy, W.; Alotaibi, A.; Vanderpool, M.; Vaseghi, M.; Beheshti, A.; Davami, K. Performance of additively manufactured polylactic acid (PLA) in prolonged marine environments. *Polym. Degrad. Stab.* **2022**, *199*, 109903. [CrossRef]
228. Zhang, Y.; Gao, W.; Mo, A.; Jiang, J.; He, D. Degradation of polylactic acid/polybutylene adipate films in different ratios and the response of bacterial community in soil environments. *Environ. Pollut.* **2022**, *313*, 120167. [CrossRef] [PubMed]
229. Mo, J.; Wang, Y.; Lin, J.; Ke, Y.; Zhou, C.; Wang, J.; Wen, J.; Gan, F.; Wang, L.; Ma, C. Polylactic acid/multi-wall carbon nanotubes composite fibrous membrane and their applications in oil-water separation. *Surf. Interfaces* **2023**, *39*, 102908. [CrossRef]
230. Jem, K.J.; Tan, B. The development and challenges of poly (lactic acid) and poly (glycolic acid). *Adv. Ind. Eng. Polym. Res.* **2020**, *3*, 60–70. [CrossRef]
231. Samir, A.; Ashour, F.H.; Hakim, A.A.A.; Bassyouni, M. Recent advances in biodegradable polymers for sustainable applications. *NPJ Mater. Degrad.* **2022**, *6*, 68. [CrossRef]
232. Arun, K.B.; Madhavan, A.; Sindhu, R.; Binod, P.; Pandey, A.; R, R.; Sirohi, R. Remodeling agro-industrial and food wastes into value-added bioactives and biopolymers. *Ind. Crops. Prod.* **2020**, *154*, 112621. [CrossRef]
233. Gautam, K.; Vishvakarma, R.; Sharma, P.; Singh, A.; Gaur, V.K.; Varjani, S.; Srivastava, J.K. Production of biopolymers from food waste: Constrains and perspectives. *Bioresour. Technol.* **2022**, *361*, 127650. [CrossRef] [PubMed]
234. Klai, N.; Yadav, B.; El Hachimi, O.; Pandey, A.; Sellamuthu, B.; Tyagi, R.D. Agro-Industrial Waste Valorization for Biopolymer Production and Life-Cycle Assessment Toward Circular Bioeconomy. In *Biomass, Biofuels, Biochemicals: Circular Bioeconomy-Current Developments and Future Outlook*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 515–555.
235. da Silva, J.A.; Cardoso, L.G.; de Jesus Assis, D.; Gomes, G.V.P.; Oliveira, M.B.P.P.; de Souza, C.O.; Druzian, J.I. Xanthan Gum Production by Xanthomonas campestris pv. campestris IBSBF 1866 and 1867 from Lignocellulosic Agroindustrial Wastes. *Appl. Biochem. Biotechnol.* **2018**, *186*, 750–763. [CrossRef] [PubMed]
236. Hussain, Z.; Sajjad, W.; Khan, T.; Wahid, F. Production of bacterial cellulose from industrial wastes: A review. *Cellulose* **2019**, *26*, 2895–2911. [CrossRef]
237. Awasthi, S.K.; Kumar, M.; Kumar, V.; Sarsaiya, S.; Anerao, P.; Ghosh, P.; Singh, L.; Liu, H.; Zhang, Z.; Awasthi, M.K. A comprehensive review on recent advancements in biodegradation and sustainable management of biopolymers. *Environ. Pollut.* **2022**, *307*, 119600. [CrossRef]
238. Imre, B.; Pukánszky, B. Compatibilization in bio-based and biodegradable polymer blends. *Eur. Polym. J.* **2013**, *49*, 1215–1233. [CrossRef]
239. Schnepp, Z. Biopolymers as a Flexible Resource for Nanochemistry. *Angew. Chem. Int. Ed.* **2013**, *52*, 1096–1108. [CrossRef] [PubMed]
240. Van Loosdrecht, M.C.M.; Pot, M.A.; Heijnen, J.J. Importance of bacterial storage polymers in bioprocesses. *Water Sci. Technol.* **1997**, *35*, 41–47. [CrossRef]
241. Vu, B.; Chen, M.; Crawford, R.J.; Ivanova, E.P. Bacterial Extracellular Polysaccharides Involved in Biofilm Formation. *Molecules* **2009**, *14*, 2535–2554. [CrossRef] [PubMed]
242. Yin, W.; Wang, Y.; Liu, L.; He, J. Biofilms: The Microbial “Protective Clothing” in Extreme Environments. *Int. J. Mol. Sci.* **2019**, *20*, 3423. [CrossRef] [PubMed]
243. Yafetto, L. Application of solid-state fermentation by microbial biotechnology for bioprocessing of agro-industrial wastes from 1970 to 2020: A review and bibliometric analysis. *Heliyon* **2022**, *8*, e09173. [CrossRef] [PubMed]
244. Gupta, J.; Rathour, R.; Medhi, K.; Tyagi, B.; Thakur, I.S. Microbial-Derived Natural Bioproducts for a Sustainable Environment: A Bioprospective for Waste to Wealth. In *Refining Biomass Residues for Sustainable Energy and Bioproducts: Technology, Advances, Life Cycle Assessment, and Economics*; Academic Press: Cambridge, MA, USA, 2020; pp. 51–85.
245. Alipour, A.; Bahrami, A.; Saebnoori, E. Investigation in effect of different culture medium on the anti-corrosive performance of bacterial biopolymer. *J. Taiwan Inst. Chem. Eng.* **2017**, *77*, 64–72. [CrossRef]
246. Corsino, S.F.; Di Trapani, D.; Torregrossa, N.; Piazzese, D. Preliminary evaluation of biopolymers production by mixed microbial culture from citrus wastewater in a MBR system using respirometric techniques. *J. Water Process. Eng.* **2021**, *41*, 102003. [CrossRef]

247. Aramvash, A.; Gholami-Banadkuki, N.; Moazzeni-Zavareh, F. An Environmentally Friendly and Efficient Method for Extraction of PHB Biopolymer with Non-Halogenated Solvents. *J. Microbiol. Biotechnol.* **2015**, *25*, 1936–1943. [CrossRef] [PubMed]
248. Aramvash, A.; Zavareh, F.M.; Banadkuki, N.G. Comparison of different solvents for extraction of polyhydroxybutyrate from Cupriavidus necator. *Eng. Life Sci.* **2018**, *18*, 20–28. [CrossRef]
249. Pérez-Rivero, C.; López-Gómez, J.P.; Roy, I. A sustainable approach for the downstream processing of bacterial polyhydroxyalkanoates: State-of-the-art and latest developments. *Biochem. Eng. J.* **2019**, *150*, 107283. [CrossRef]
250. Koller, M. Biodegradable and Biocompatible Polyhydroxy-alkanoates (PHA): Auspicious Microbial Macromolecules for Pharmaceutical and Therapeutic Applications. *Molecules* **2018**, *23*, 362. [CrossRef] [PubMed]
251. Antonio, J.E.R.-S.; Martín-Hernández, E.; Briones, R.; Martín, M. Process design and scale-up study for the production of polyol-based biopolymers from sawdust. *Sustain. Prod. Consum.* **2021**, *27*, 462–470. [CrossRef]
252. Blunt, W.; Levin, D.B.; Cicek, N. Bioreactor Operating Strategies for Improved Polyhydroxyalkanoate (PHA) Productivity. *Polymers* **2018**, *10*, 1197. [CrossRef] [PubMed]
253. Nagaraja, S.; Anand, P.B.; Naik, R.N.M.; Gunashekaran, S. Effect of aging on the biopolymer composites: Mechanisms, modes and characterization. *Polym. Compos.* **2022**, *43*, 4115–4125. [CrossRef]
254. Deroiné, M.; Le Duigou, A.; Corre, Y.M.; Le Gac, P.Y.; Davies, P.; César, G.; Bruzaud, S. Accelerated ageing and lifetime prediction of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) in distilled water. *Polym. Test.* **2014**, *39*, 70–78. [CrossRef]
255. Siviello, C.; Greco, F.; Larobina, D. Analysis of the aging effects on the viscoelasticity of alginate gels. *Soft Matter* **2016**, *12*, 8726–8735. [CrossRef] [PubMed]
256. Leceta, I.; Peñalba, M.; Arana, P.; Guerrero, P.; De La Caba, K. Ageing of chitosan films: Effect of storage time on structure and optical, barrier and mechanical properties. *Eur. Polym. J.* **2015**, *66*, 170–179. [CrossRef]
257. Cui, L.; Imre, B.; Tátraaljai, D.; Pukánszky, B. Physical ageing of Poly(Lactic acid): Factors and consequences for practice. *Polymer* **2020**, *186*, 122014. [CrossRef]
258. Samer, M. (Ed.) Biological and Chemical Wastewater Treatment Processes. In *Wastewater Treatment Engineering*; IntechOpen: Rijeka, Croatia, 2015.
259. Alsamman, M.T.; Sánchez, J. Recent advances on hydrogels based on chitosan and alginate for the adsorption of dyes and metal ions from water. *Arab. J. Chem.* **2021**, *14*, 103455. [CrossRef]
260. Russo, T.; Fucile, P.; Giacometti, R.; Sannino, F. Sustainable Removal of Contaminants by Biopolymers: A Novel Approach for Wastewater Treatment. Current State and Future Perspectives. *Processes* **2021**, *9*, 719. [CrossRef]
261. Sarode, S.; Upadhyay, P.; Khosa, M.A.; Mak, T.; Shakir, A.; Song, S.; Ullah, A. Overview of wastewater treatment methods with special focus on biopolymer chitin-chitosan. *Int. J. Biol. Macromol.* **2019**, *121*, 1086–1100. [CrossRef] [PubMed]
262. Nasir, A.; Masood, F.; Yasin, T.; Hameed, A. Progress in polymeric nanocomposite membranes for wastewater treatment: Preparation, properties and applications. *J Ind Eng Chem.* **2019**, *79*, 29–40. [CrossRef]
263. Gowthaman, N.S.K.; Lim, H.N.; Sreeraj, T.R.; Amalraj, A.; Gopi, S. Advantages of Biopolymers over Synthetic Polymers: Social, Economic, and Environmental Aspects. In *Biopolymers and Their Industrial Applications*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 351–372.
264. Fouda-Mbanga, B.G.; Prabakaran, E.; Pillay, K. Carbohydrate biopolymers, lignin based adsorbents for removal of heavy metals (Cd^{2+}, Pb^{2+}, Zn^{2+}) from wastewater, regeneration and reuse for spent adsorbents including latent fingerprint detection: A review. *Biotechnol. Rep.* **2021**, *30*, e00609. [CrossRef] [PubMed]
265. Biswas, S.; Pal, A. Application of biopolymers as a new age sustainable material for surfactant adsorption: A brief review. *Carbohydr. Polym. Technol. Appl.* **2021**, *2*, 100145. [CrossRef]
266. da Silva Alves, D.C.; Healy, B.; Pinto, L.A.D.A.; Cadaval, T.R.S.A.; Breslin, C.B. Recent Developments in Chitosan-Based Adsorbents for the Removal of Pollutants from Aqueous Environments. *Molecules* **2021**, *26*, 594. [CrossRef] [PubMed]
267. Benavente, M.; Moreno, L.; Martinez, J. Sorption of heavy metals from gold mining wastewater using chitosan. *J. Taiwan Inst. Chem. Eng.* **2011**, *42*, 976–988. [CrossRef]
268. Wang, B.; Wan, Y.; Zheng, Y.; Lee, X.; Liu, T.; Yu, Z.; Huang, J.; Ok, Y.S.; Chen, J.; Gao, B. Alginate-based composites for environmental applications: A critical review. *Crit. Rev. Environ. Sci. Technol.* **2019**, *49*, 318–356. [CrossRef] [PubMed]
269. Godiya, C.B.; Liang, M.; Sayed, S.M.; Li, D.; Lu, X. Novel alginate/polyethyleneimine hydrogel adsorbent for cascaded removal and utilization of Cu^{2+} and Pb^{2+} ions. *J. Environ. Manag.* **2019**, *232*, 829–841. [CrossRef] [PubMed]
270. Godiya, C.B.; Xiao, Y.; Lu, X. Amine functionalized sodium alginate hydrogel for efficient and rapid removal of methyl blue in water. *Int. J. Biol. Macromol.* **2020**, *144*, 671–681. [CrossRef]
271. Yi, X.; Sun, F.; Han, Z.; Han, F.; He, J.; Ou, M.; Gu, J.; Xu, X. Graphene oxide encapsulated polyvinyl alcohol/sodium alginate hydrogel microspheres for Cu (II) and U (VI) removal. *Ecotoxicol. Environ. Saf.* **2018**, *158*, 309–318. [CrossRef]
272. Wang, F.; Lu, X.; Li, X.Y. Selective removals of heavy metals (Pb^{2+}, Cu^{2+}, and Cd^{2+}) from wastewater by gelation with alginate for effective metal recovery. *J. Hazard. Mater.* **2016**, *308*, 75–83. [CrossRef]
273. Kolya, H.; Kang, C.-W. Next-Generation Water Treatment: Exploring the Potential of Biopolymer-Based Nanocomposites in Adsorption and Membrane Filtration. *Polymers* **2023**, *15*, 3421. [CrossRef]
274. Kolya, H.; Kang, C.-W. Bio-Based Polymeric Flocculants and Adsorbents for Wastewater Treatment. *Sustainability* **2023**, *15*, 9844. [CrossRef]

275. Rahman, A.S.A.; Fizal, A.N.S.; Khalil, N.A.; Yahaya, A.N.A.; Hossain, M.S.; Zulkifli, M. Fabrication and Characterization of Magnetic Cellulose–Chitosan–Alginate Composite Hydrogel Bead Bio-Sorbent. *Polymers* **2023**, *15*, 2494. [CrossRef]
276. Qalyoubi, L.; Al-Othman, A.; Al-Asheh, S. Recent progress and challenges on adsorptive membranes for the removal of pollutants from wastewater. *Part I: Fundamentals and classification of membranes. Case Stud. Therm. Eng.* **2021**, *3*, 100086.
277. Salehi, E.; Daraei, P.; Shamsabadi, A.A. A review on chitosan-based adsorptive membranes. *Carbohydr. Polym.* **2016**, *152*, 419–432. [CrossRef] [PubMed]
278. Hu, Z.H.; Omer, A.M.; Ouyang, X.K.; Yu, D. Fabrication of carboxylated cellulose nanocrystal/sodium alginate hydrogel beads for adsorption of Pb(II) from aqueous solution. *Int. J. Biol. Macromol.* **2018**, *108*, 149–157. [CrossRef] [PubMed]
279. Sun, P.; Wang, M.; Wu, T.; Guo, L.; Han, W. Covalent Crosslinking Cellulose/Graphene Aerogels with High Elasticity and Adsorbability for Heavy Metal Ions Adsorption. *Polymers* **2023**, *15*, 2434. [CrossRef]
280. Dang-Bao, T.; Nguyen, T.-M.-C.; Hoang, G.-H.; Lam, H.-H.; Phan, H.-P.; Tran, T.-K.-A. Thiol-Surface-Engineered Cellulose Nanocrystals in Favor of Copper Ion Uptake. *Polymers* **2023**, *15*, 2562. [CrossRef]
281. Liu, Y.; Hu, L.; Yao, Y.; Su, Z.; Hu, S. Construction of composite chitosan-glucose hydrogel for adsorption of Co2+ ions. *Int. J. Biol. Macromol.* **2019**, *139*, 213–220. [CrossRef]
282. Pavithra, S.; Thandapani, G.; Sugashini, S.; Sudha, P.N.; Alkhamis, H.H.; Alrefaei, A.F.; Almutairi, M.H. Batch adsorption studies on surface tailored chitosan/orange peel hydrogel composite for the removal of Cr(VI) and Cu(II) ions from synthetic wastewater. *Chemosphere* **2021**, *271*, 129415. [CrossRef]
283. Wu, S.; Wang, F.; Yuan, H.; Zhang, L.; Mao, S.; Liu, X.; Alharbi, N.S.; Rohani, S.; Lu, J. Fabrication of xanthate-modified chitosan/poly(N-isopropylacrylamide) composite hydrogel for the selective adsorption of Cu(II), Pb(II) and Ni(II) metal ions. *Chem. Eng. Res. Des.* **2018**, *139*, 197–210. [CrossRef]
284. Yang, L.; Bao, L.; Dong, T.; Xie, H.; Wang, X.; Wang, H.; Wu, J.; Hao, C. Adsorption properties of cellulose/guar gum/biochar composite hydrogel for Cu2+, Co2+ and methylene blue. *Int. J. Biol. Macromol.* **2023**, *242*, 125021. [CrossRef]
285. Ding, W.; Liang, H.; Zhang, H.; Sun, H.; Geng, Z.; Xu, C. A cellulose/bentonite grafted polyacrylic acid hydrogel for highly-efficient removal of Cd(II). *J. Water Process. Eng.* **2023**, *51*, 103414. [CrossRef]
286. Tao, X.; Wang, S.; Li, Z.; Zhou, S. Green synthesis of network nanostructured calcium alginate hydrogel and its removal performance of Cd^{2+} and Cu^{2+} ions. *Mater. Chem. Phys.* **2021**, *258*, 123931. [CrossRef]
287. Lan, S.; Wu, X.; Li, L.; Li, M.; Guo, F.; Gan, S. Synthesis and characterization of hyaluronic acid-supported magnetic microspheres for copper ions removal. *Colloids Surf. A Physicochem. Eng. Asp.* **2013**, *425*, 42–50. [CrossRef]
288. Ahmad, R.; Mirza, A. Application of Xanthan gum/ n-acetyl cysteine modified mica bionanocomposite as an adsorbent for the removal of toxic heavy metals. *Groundw. Sustain. Dev.* **2018**, *7*, 101–108. [CrossRef]
289. Jafarigol, E.; Ghotli, R.A.; Hajipour, A.; Pahlevani, H.; Salehi, M.B. Tough dual-network GAMAAX hydrogel for the efficient removal of cadmium and nickle ions in wastewater treatment applications. *J. Ind. Eng. Chem.* **2021**, *94*, 352–360. [CrossRef]
290. Zeng, Q.; Qi, X.; Zhang, M.; Tong, X.; Jiang, N.; Pan, W.; Xiong, W.; Li, Y.; Xu, J.; Shen, J.; et al. Efficient decontamination of heavy metals from aqueous solution using pullulan/polydopamine hydrogels. *Int. J. Biol. Macromol.* **2020**, *145*, 1049–1058. [CrossRef] [PubMed]
291. Alraddadi, H.M.; Fagieh, T.M.; Bakhsh, E.M.; Akhtar, K.; Khan, S.B.; Khan, S.A.; Bahaidarah, E.A.; Homdi, T.A. Adsorptive removal of heavy metals and organic dyes by sodium alginate/coffee waste composite hydrogel. *Int. J. Biol. Macromol.* **2023**, *247*, 125708. [CrossRef]
292. Zhang, M.; Sun, H.; Wang, Y.; Piao, C.; Cai, D.; Wang, Y.; Liu, J.; Cheng, Z. Preparation and characterization of a novel porous whey protein concentrate/pullulan gel induced by heating for Cu^{2+} absorption. *Food Chem.* **2020**, *322*, 126772. [CrossRef] [PubMed]
293. Wang, Z.-K.; Li, T.-T.; Ren, H.-T.; Peng, H.-K.; Shiu, B.-C.; Lin, J.-H.; Lou, C.-W. Construction of a novel hydrogel composite with polylactic acid nonwoven fibers: Rapid and effective removal of Pb(II) and Ni(II). *Text. Res. J.* **2023**, *93*, 266–279. [CrossRef]
294. Li, Y.; Liu, Y.; Liu, Z.; Wan, X.; Chen, H.; Zhong, J.; Zhang, Y.F. Efficient selective recycle of acid blue 93 by NaOH activated acrolein/chitosan adsorbent via size-matching effect. *Carbohydr. Polym.* **2023**, *301*, 120314. [CrossRef] [PubMed]
295. Kumar, A.; Jeyabalan, J.; Priyan, V.V.; Patra, C.C.; Narayanasamy, S. Fabrication of a novel bio-polymer adsorbent with high adsorptive capacity towards organic dyes. *Ind. Crops Prod.* **2023**, *203*, 117166. [CrossRef]
296. Liu, A.; He, S.; Zhang, J.; Liu, J.; Shao, W. Preparation and characterization of novel cellulose based adsorbent with ultra-high methylene blue adsorption performance. *Mater. Chem. Phys.* **2023**, *296*, 127261. [CrossRef]
297. Chang, Z.; Chen, Y.; Tang, S.; Yang, J.; Chen, Y.; Chen, S.; Li, P.; Yang, Z. Construction of chitosan/polyacrylate/graphene oxide composite physical hydrogel by semi-dissolution/acidification/sol-gel transition method and its simultaneous cationic and anionic dye adsorption properties. *Carbohydr. Polym.* **2020**, *229*, 115431. [CrossRef] [PubMed]
298. Tu, H.; Yu, Y.; Chen, J.; Shi, X.; Zhou, J.; Deng, H.; Du, Y. Highly cost-effective and high-strength hydrogels as dye adsorbents from natural polymers: Chitosan and cellulose. *Polym. Chem.* **2017**, *8*, 2913–2921. [CrossRef]
299. Sutirman, Z.A.; Sanagi, M.M.; Karim, J.A.; Naim, A.A.; Ibrahim, W.A.W. New crosslinked-chitosan graft poly(N-vinyl-2-pyrrolidone) for the removal of Cu(II) ions from aqueous solutions. *Int. J. Biol. Macromol.* **2018**, *107*, 891–897. [CrossRef]
300. Li, Y.; Liu, Z.; Wan, X.; Xie, L.; Chen, H.; Qu, G.; Zhang, H.; Zhang, Y.F.; Zhao, S. Selective adsorption and separation of methylene blue by facily preparable xanthan gum/amantadine composites. *Int. J. Biol. Macromol.* **2023**, *241*, 124640. [CrossRef]

301. Tanzifi, M.; Esmizadeh, E.; Bazgir, H.; Nazari, A.; Vahidifar, A. Adsorption of Methylene Blue Dye from Aqueous Solution Using Polyaniline/Xanthan Gum Nanocomposite: Kinetic and Isotherm Studies. *J. Polym. Compos.* **2019**, *7*, 17–26.
302. Makhado, E.; Pandey, S.; Ramontja, J. Microwave assisted synthesis of xanthan gum-cl-poly (acrylic acid) based-reduced graphene oxide hydrogel composite for adsorption of methylene blue and methyl violet from aqueous solution. *Int. J. Biol. Macromol.* **2018**, *119*, 255–269. [CrossRef] [PubMed]
303. Constantin, M.; Asmarandei, I.; Harabagiu, V.; Ghimici, L.; Ascenzi, P.; Fundueanu, G. Removal of anionic dyes from aqueous solutions by an ion-exchanger based on pullulan microspheres. *Carbohydr. Polym.* **2013**, *91*, 74–84. [CrossRef] [PubMed]
304. Yildirim, S.; Isik, B.; Ugraskan, V. Methyl orange dye sequestration using polyaniline nanotube-filled sodium alginate biocomposite microbeads. *Mater. Chem. Phys.* **2023**, *307*, 128083. [CrossRef]
305. Kahya, N.; Kaygusuz, H.; Erim, F.B. Aqueous Removal of Sodium Dodecyl Benzene Sulfonate (SDBS) by Crosslinked Chitosan Films. *J. Polym. Environ.* **2018**, *26*, 2166–2172. [CrossRef]
306. Das, D.; Pal, A. Adsolubilization phenomenon perceived in chitosan beads leading to a fast and enhanced malachite green removal. *Chem. Eng. J.* **2016**, *290*, 371–380. [CrossRef]
307. Xhanari, K.; Syverud, K.; Chinga-Carrasco, G.; Paso, K.; Stenius, P. Reduction of water wettability of nanofibrillated cellulose by adsorption of cationic surfactants. *Cellulose* **2011**, *18*, 257–270. [CrossRef]
308. Bratby, J. *Coagulation and Flocculation in Water and Wastewater Treatment*, 3rd ed.; IWA Publishing: London, UK, 2016.
309. Cruz, D.; Pimentel, M.; Russo, A.; Cabral, W. Charge Neutralization Mechanism Efficiency in Water with High Color Turbidity Ratio Using Aluminium Sulfate and Flocculation Index. *Water* **2020**, *12*, 572. [CrossRef]
310. Aghyani, R.; Bidhendi, G.N.; Mehrdadi, N.; Amiri, M.J. Comparative study of Poly Aluminum Ferric and Poly Aluminum Chloride Performance for Turbidity Removal from River Water. *Environ. Energy Econ. Res.* **2023**, *7*, 1–7. [CrossRef]
311. Akinnawo, S.O.; Ayadi, P.O.; Oluwalope, M.T. Chemical coagulation and biological techniques for wastewater treatment. *Ovidius Univ. Ann. Chem.* **2023**, *34*, 14–21. [CrossRef]
312. Oladoja, N.A.; Unuabonah, E.I.; Amuda, O.S.; Kolawole, O.M. *Polysaccharides as a Green and Sustainable Resources for Water and Wastewater Treatment*; Springer International Publishing: Cham, Switzerland, 2017.
313. Kurniawan, S.B.; Abdullah, S.R.S.; Imron, M.F.; Said, N.S.M.; Ismail, N.I.; Hasan, H.A.; Othman, A.R.; Purwanti, I.F. Challenges and Opportunities of Biocoagulant/Bioflocculant Application for Drinking Water and Wastewater Treatment and Its Potential for Sludge Recovery. *Int. J. Environ. Res. Public Health* **2020**, *17*, 9312. [CrossRef]
314. Nurudeen, A.O.; Unuabonah, E.I.; Omotayo, S.A.; Olatunji, M.K. Tapping into Microbial Polysaccharides for Water and Wastewater Purifications. In *Polysaccharides as a Green and Sustainable Resources for Water and Wastewater Treatment*; Springer International Publishing: Cham, Switzerland, 2017; pp. 91–110.
315. Salehizadeh, H.; Yan, N.; Farnood, R. Recent advances in polysaccharide bio-based flocculants. *Biotechnol. Adv.* **2018**, *36*, 92–119. [CrossRef] [PubMed]
316. Yang, R.; Li, H.; Huang, M.; Yang, H.; Li, A. A review on chitosan-based flocculants and their applications in water treatment. *Water Res.* **2016**, *95*, 59–89. [CrossRef] [PubMed]
317. Grenda, K.; Gamelas, J.A.; Arnold, J.; Cayre, O.J.; Rasteiro, M.G. Evaluation of Anionic and Cationic Pulp-Based Flocculants With Diverse Lignin Contents for Application in Effluent Treatment From the Textile Industry: Flocculation Monitoring. *Front. Chem.* **2020**, *8*. [CrossRef] [PubMed]
318. Maćczak, P.; Kaczmarek, H.; Ziegler-Borowska, M. Recent Achievements in Polymer Bio-Based Flocculants for Water Treatment. *Materials* **2020**, *13*, 3951. [CrossRef] [PubMed]
319. Ghimici, L.; Nichifor, M. Dextran derivatives application as flocculants. *Carbohydr. Polym.* **2018**, *190*, 162–174. [CrossRef]
320. Zhao, C.; Zheng, H.; Sun, Y.; Zhang, S.; Liang, J.; Liu, Y.; An, Y. Evaluation of a novel dextran-based flocculant on treatment of dye wastewater: Effect of kaolin particles. *Sci. Total Environ.* **2018**, *640–641*, 243–254. [CrossRef] [PubMed]
321. Ibarra-Rodríguez, D.; Lizardi-Mendoza, J.; López-Maldonado, E.A.; Oropeza-Guzmán, M.T. Capacity of 'nopal' pectin as a dual coagulant-flocculant agent for heavy metals removal. *Chem. Eng. J.* **2017**, *323*, 19–28. [CrossRef]
322. Mao, Y.; Millett, R.; Lee, C.S.; Yakubov, G.; Harding, S.E.; Binner, E. Investigating the influence of pectin content and structure on its functionality in bio-flocculant extracted from okra. *Carbohydr. Polym.* **2020**, *241*, 116414. [CrossRef] [PubMed]
323. Yang, K.; Li, Y.; Chen, Y. Removal of Oil and Cr(VI) from Wastewater Using Modified Pectin Flocculants. *J. Environ. Eng.* **2014**, *140*, 04013004. [CrossRef]
324. Hasan, A.; Fatehi, P. Flocculation of kaolin particles with cationic lignin polymers. *Sci. Rep.* **2019**, *9*, 2672. [CrossRef]
325. Jumadi, J.; Kamari, A.; Hargreaves, J.S.J.; Yusof, N. A review of nano-based materials used as flocculants for water treatment. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 3571–3594. [CrossRef]
326. Ahsan, A.; Ismail, A.F. *Nanotechnology in Water and Wastewater Treatment*, 1st ed.; Elsevier: New York, NY, USA, 2019.
327. Dao, V.H.; Cameron, N.R.; Saito, K. Synthesis, properties and performance of organic polymers employed in flocculation applications. *Polym. Chem.* **2016**, *7*, 11–25. [CrossRef]
328. Li, S.; Hu, T.; Xu, Y.; Wang, J.; Chu, R.; Yin, Z.; Mo, F.; Zhu, L. A review on flocculation as an efficient method to harvest energy microalgae: Mechanisms, performances, influencing factors and perspectives. *Renew. Sust. Energ. Rev.* **2020**, *131*, 110005. [CrossRef]

329. Sun, Y.; Ren, M.; Zhu, C.; Xu, Y.; Zheng, H.; Xiao, X.; Wu, H.; Xia, T.; You, Z. UV-Initiated Graft Copolymerization of Cationic Chitosan-Based Flocculants for Treatment of Zinc Phosphate-Contaminated Wastewater. *Ind. Eng. Chem. Res.* **2016**, *55*, 10025–10035. [CrossRef]
330. Tian, Z.; Zhang, L.; Ni, C. Preparation of modified alginate nanoflocculant and adsorbing properties for Pb^{2+} in wastewater. *Russ. J. Appl. Chem.* **2017**, *90*, 641–647. [CrossRef]
331. Feng, L.; Zhong, K.; Zhou, W.; Liu, J.; Liu, B.; Wang, W.; Zheng, H. Synthesis of a chitosan-based flocculant CS-g-P(AM-IA-AATPAC) and evaluation of its performance on Ni2+ removal: Role of chelating-coordination and flocculation. *J. Environ. Chem. Eng.* **2023**, *11*, 109138. [CrossRef]
332. Ghimici, L.; Nafureanu, M.M.; Constantin, M. Cationic Pullulan Derivatives Based Flocculants for Removal of Some Metal Oxides from Simulated Wastewater. *Int. J. Mol. Sci.* **2023**, *24*, 4383. [CrossRef] [PubMed]
333. Liu, B.; Zheng, H.; Wang, Y.; Chen, X.; Zhao, C.; An, Y.; Tang, X. A novel carboxyl-rich chitosan-based polymer and its application for clay flocculation and cationic dye removal. *Sci. Total Environ.* **2018**, *640–641*, 107–115. [CrossRef] [PubMed]
334. Sudirgo, M.M.; Surya, R.A.; Kristianto, H.; Prasetyo, S.; Sugih, A.K. Application of xanthan gum as coagulant-aid for decolorization of synthetic Congo red wastewater. *Heliyon* **2023**, *9*, e15011. [CrossRef]
335. Ghimici, L.; Constantin, M. Removal of the commercial pesticides Novadim Progress, Bordeaux mixture and Karate Zeon by pullulan derivatives based flocculants. *J. Environ. Manag.* **2018**, *218*, 31–38. [CrossRef]
336. Grenda, K.; Arnold, J.; Gamelas, J.A.F.; Rasteiro, M.G. Environmentally friendly cellulose-based polyelectrolytes in wastewater treatment. *Water Sci. Technol.* **2017**, *76*, 1490–1499. [CrossRef] [PubMed]
337. Zhang, Y.; Li, M.; Zhang, G.; Liu, W.; Xu, J.; Tian, Y.; Wang, Y.; Xie, X.; Peng, Z.; Li, A.; et al. Efficient treatment of the starch wastewater by enhanced flocculation–coagulation of environmentally benign materials. *Sep. Purif. Technol.* **2023**, *307*, 122788. [CrossRef]
338. Jiang, X.; Lou, C.; Hua, F.; Deng, H.; Tian, X. Cellulose nanocrystals-based flocculants for high-speed and high-efficiency decolorization of colored effluents. *J. Clean. Prod.* **2020**, *251*, 119749. [CrossRef]
339. Liu, C.; Gao, B.; Wang, S.; Guo, K.; Shen, X.; Yue, Q.; Xu, X. Synthesis, characterization and flocculation performance of a novel sodium alginate-based flocculant. *Carbohydr. Polym.* **2020**, *248*, 116790. [CrossRef] [PubMed]
340. Ghorai, S.; Sarkar, A.; Panda, A.B.; Pal, S. Evaluation of the Flocculation Characteristics of Polyacrylamide Grafted Xanthan Gum/Silica Hybrid Nanocomposite. *Ind. Eng. Chem. Res.* **2013**, *52*, 9731–9740. [CrossRef]
341. Adhikary, P.; Singh, R.P. Synthesis characterization, and flocculation characteristics of hydrolyzed and unhydrolyzed polyacrylamide grafted xanthan gum. *J. Appl. Polym. Sci.* **2004**, *94*, 1411–1419. [CrossRef]
342. Ghimici, L.; Constantin, M. Novel thermosensitive flocculanting agent based on pullulan. *J. Hazard. Mater.* **2011**, *192*, 1009–1016. [CrossRef] [PubMed]
343. Shao, Y.; Zhong, H.; Wang, L.; Elbashier, M.M.A. Bacillus amyloliquefaciens (IAE635) and their metabolites could purify pollutants, *Vibrio* spp. and coliform bacteria in coastal aquaculture wastewater. *Int. J. Agric. Biol. Eng.* **2021**, *14*, 205–210. [CrossRef]
344. Li, M.; Zhu, X.; Yang, H.; Xie, X.; Zhu, Y.; Xu, G.; Hu, X.; Jin, Z.; Hu, Y.; Hai, Z.; et al. Treatment of potato starch wastewater by dual natural flocculants of chitosan and poly-glutamic acid. *J. Clean. Prod.* **2020**, *264*, 121641. [CrossRef]
345. Liu, Y.; Ma, J.; Lian, L.; Wang, X.; Zhang, H.; Gao, W.; Lou, D. Flocculation performance of alginate grafted polysilicate aluminum calcium in drinking water treatment. *Process Saf. Environ. Prot.* **2021**, *155*, 287–294. [CrossRef]
346. Morantes, D.; Muñoz, E.; Kam, D.; Shoseyov, O. Highly Charged Cellulose Nanocrystals Applied as A Water Treatment Flocculant. *Nanomaterials* **2019**, *9*, 272. [CrossRef] [PubMed]
347. Suopajärvi, T.; Liimatainen, H.; Hormi, O.; Niinimäki, J. Coagulation–flocculation treatment of municipal wastewater based on anionized nanocelluloses. *Chem. Eng. J.* **2013**, *231*, 59–67. [CrossRef]
348. Zhu, H.; Zhang, Y.; Yang, X.; Liu, H.; Zhang, X.; Yao, J. An Eco-friendly One-Step Synthesis of Dicarboxyl Cellulose for Potential Application in Flocculation. *Ind. Eng. Chem. Res.* **2015**, *54*, 2825–2829. [CrossRef]
349. Gough, C.R.; Callaway, K.; Spencer, E.; Leisy, K.; Jiang, G.; Yang, S.; Hu, X. Biopolymer-Based Filtration Materials. *ACS Omega* **2021**, *6*, 11804–11812. [CrossRef] [PubMed]
350. Medeiros, A.D.L.M.D.; Junior, C.J.G.D.S.; Amorim, J.D.P.D.; Durval, I.J.B.; Costa, A.F.D.S.; Sarubbo, L.A. Oily Wastewater Treatment: Methods, Challenges, and Trends. *Processes* **2022**, *10*, 743. [CrossRef]
351. Tanudjaja, H.J.; Hejase, C.A.; Tarabara, V.V.; Fane, A.G.; Chew, J.W. Membrane-based separation for oily wastewater: A practical perspective. *Water Res.* **2019**, *156*, 347–365. [CrossRef] [PubMed]
352. Cai, C.; Sun, W.; He, S.; Zhang, Y.; Wang, X. Ceramic membrane fouling mechanisms and control for water treatment. *Front. Environ. Sci. Eng.* **2023**, *17*, 126. [CrossRef]
353. Mpala, T.J.; Richards, H.; Etale, A.; Mahlangu, O.T.; Nthunya, L.N. Carbon nanotubes and silver nanoparticles modification of PVDF membranes for improved seawater desalination in direct contact membrane distillation. *Front. Membr. Sci Technol.* **2023**, *2*, 1165678. [CrossRef]
354. Baig, N.; Matin, A.; Faizan, M.; Anand, D.; Ahmad, I.; Khan, S.A. Antifouling low-pressure highly permeable single step produced loose nanofiltration polysulfone membrane for efficient Erichrome Black T/divalent salts fractionation. *J. Environ. Chem. Eng.* **2022**, *10*, 108166. [CrossRef]
355. Cevallos-Mendoza, J.; Amorim, C.G.; Rodríguez-Díaz, J.M.; Montenegro, M.D.C.B.S.M. Removal of Contaminants from Water by Membrane Filtration: A Review. *Membranes* **2022**, *12*, 570. [CrossRef]

356. Ehsan, M.; Razzaq, H.; Razzaque, S.; Kanwal, M.; Hussain, I. Engineering nanocomposite membranes of sodium alginate-graphene oxide for efficient separation of oil-water and antifouling performance. *J. Environ. Chem. Eng.* **2023**, *11*, 109185. [CrossRef]
357. Liu, Y.; Wang, H.; Cui, Y.; Chen, N. Removal of Copper Ions from Wastewater: A Review. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3885. [CrossRef] [PubMed]
358. Mostafavi, A.H.; Mishra, A.K.; Gallucci, F.; Kim, J.H.; Ulbricht, M.; Coclite, A.M.; Hosseini, S.S. Advances in surface modification and functionalization for tailoring the characteristics of thin films and membranes via chemical vapor deposition techniques. *J. Appl. Polym. Sci.* **2023**, *140*, e53720. [CrossRef]
359. Yu, H.; Liu, H.; Yuan, X.; Ding, W.; Li, Y.; Wang, J. Separation of oil-water emulsion and adsorption of Cu(II) on a chitosan-cellulose acetate-TiO_2 based membrane. *Chemosphere* **2019**, *235*, 239–247. [CrossRef] [PubMed]
360. Divya, S.; Oh, T.H. Polymer Nanocomposite Membrane for Wastewater Treatment: A Critical Review. *Polymers* **2022**, *14*, 1732. [CrossRef] [PubMed]
361. Khamis, F.; Hegab, H.M.; Banat, F.; Arafat, H.A.; Hasan, S.W. Development of sustainable pH-responsive adsorptive modified mangrove-based polylactic acid ultrafiltration membrane for the removal of heavy metals from aqueous solution. *Chem. Eng. J.* **2023**, *474*, 145471. [CrossRef]
362. Ghorbani, M.; Vakili, M.H.; Ameri, E. Fabrication and evaluation of a biopolymer-based nanocomposite membrane for oily wastewater treatment. *Mater. Today Commun.* **2021**, *28*, 102560. [CrossRef]
363. Vinodhini, P.A.; Sudha, P.N. Removal of heavy metal chromium from tannery effluent using ultrafiltration membrane. *Text Cloth Sustain.* **2016**, *2*, 5. [CrossRef]
364. Liu, M.; Chen, W.; Fu, J.; Wang, A.; Ding, M.; Zhang, L.; Han, L.; Gao, L. Hyaluronic acid-modified nanofiltration membrane for ultrahigh water permeance and efficient rejection of PFASs. *Process Saf. Environ. Prot.* **2022**, *166*, 214–221. [CrossRef]
365. El-Sayed, M.M.H.; Elsayed, R.E.; Attia, A.; Farghal, H.H.; Azzam, R.A.; Madkour, T.M. Novel nanoporous membranes of bio-based cellulose acetate, poly(lactic acid) and biodegradable polyurethane in-situ impregnated with catalytic cobalt nanoparticles for the removal of Methylene Blue and Congo Red dyes from wastewater. *Carbohydr. Polym. Technol. Appl.* **2021**, *2*, 100123. [CrossRef]
366. Ampawan, S.; Phreecha, N.; Chantarak, S.; Chinpa, W. Selective separation of dyes by green composite membrane based on polylactide with carboxylated cellulose microfiber from empty fruit bunch. *Int. J. Biol. Macromol.* **2023**, *225*, 1607–1619. [CrossRef] [PubMed]
367. Koyuncu, I.; Gul, B.Y.; Esmaeili, M.S.; Pekgenc, E.; Teber, O.O.; Tuncay, G.; Karimi, H.; Parvaz, S.; Maleki, A.; Vatanpour, V. Modification of PVDF membranes by incorporation Fe_3O_4@Xanthan gum to improve anti-fouling, anti-bacterial, and separation performance. *J. Environ. Chem. Eng.* **2022**, *10*, 107784. [CrossRef]
368. Chai, P.V.; Sailenra, K.R.; Chan, W.J.; Liew, J.T.; Teng, W.T.; Wong, Y.T. Green Synthesis of Polyvinylidene Fluoride using Xanthan Gum Biopolymer and Dimethyl Sulfoxide Green Solvent. *J. Appl. Membr. Sci. Technol.* **2023**, *27*, 1–11. [CrossRef]
369. Yu, J.; He, Y.; Wang, Y.; Li, S.; Tian, S. Ethylenediamine-oxidized sodium alginate hydrogel cross-linked graphene oxide nanofiltration membrane with self-healing property for efficient dye separation. *J. Membr. Sci.* **2023**, *670*, 121366. [CrossRef]
370. Zhijiang, C.; Ping, X.; Cong, Z.; Tingting, Z.; Jie, G.; Kongyin, Z. Preparation and characterization of a bi-layered nano-filtration membrane from a chitosan hydrogel and bacterial cellulose nanofiber for dye removal. *Cellulose* **2018**, *25*, 5123–5137. [CrossRef]
371. Wang, Y.; He, Y.; Yu, J.; Zhang, L.; Li, S.; Li, H. Alginate-based nanofibrous membrane with robust photo-Fenton self-cleaning property for efficient crude oil/water emulsion separation. *Sep. Purif. Technol.* **2022**, *287*, 120569. [CrossRef]
372. Cheng, X.; Li, T.; Yan, L.; Jiao, Y.; Zhang, Y.; Wang, K.; Cheng, Z.; Ma, J.; Shao, L. Biodegradable electrospinning superhydrophilic nanofiber membranes for ultrafast oil-water separation. *Sci. Adv.* **2023**, *9*, eadh8195. [CrossRef] [PubMed]
373. Cheng, C.S.; Deng, J.; Lei, B.; He, A.; Zhang, X.; Ma, L.; Li, S.; Zhao, C. Toward 3D graphene oxide gels based adsorbents for high-efficient water treatment via the promotion of biopolymers. *J. Hazard. Mater.* **2013**, *263*, 467–478. [CrossRef]
374. Nassar, L.; Wadi, V.S.; Hegab, H.M.; Khalil, H.; Banat, F.; Naddeo, V.; Hasan, S.W. Sustainable and green polylactic acid-based membrane embedded with self-assembled positively charged f-MWCNTs/GO nanohybrids for the removal of nutrients from wastewater. *NPJ Clean Water* **2022**, *5*, 57. [CrossRef]
375. Kimura, K.; Toshima, S.; Amy, G.; Watanabe, Y. Rejection of neutral endocrine disrupting compounds (EDCs) and pharmaceutical active compounds (PhACs) by RO membranes. *J. Membr. Sci.* **2004**, *245*, 71–78. [CrossRef]
376. Sharma, I. Bioremediation Techniques for Polluted Environment: Concept, Advantages, Limitations, and Prospects. In *Trace Metals in the Environment*; Murillo-Tovar, M.A., Saldarriaga-Noreña, H., Saeid, A., Eds.; IntechOpen: Rijeka, Yugoslavia, 2020.
377. Wang, M.; Chen, S.; Jia, X.; Chen, L. Concept and types of bioremediation. In *Handbook of Bioremediation: Physiological. Molecular and Biotechnological Interventions*; Academic Press: Cambridge, MA, USA, 2021; pp. 3–8.
378. Ayangbenro, A.S.; Babalola, O.O. Metal(loid) Bioremediation: Strategies Employed by Microbial Polymers. *Sustainability* **2018**, *10*, 3028. [CrossRef]
379. Gutnick, D.L.; Bach, H. Engineering bacterial biopolymers for the biosorption of heavy metals; new products and novel formulations. *Appl. Microbiol. Biotechnol.* **2000**, *54*, 451–460. [CrossRef]
380. Raafat, D.; Sahl, H.G. Chitosan and its antimicrobial potential—A critical literature survey. *Microb. Biotechnol.* **2009**, *2*, 186–201. [CrossRef]

381. Dhawi, F. How Can We Stabilize Soil Using Microbial Communities and Mitigate Desertification? *Sustainability* **2023**, *15*, 863. [CrossRef]
382. Mishra, S.; Huang, Y.; Li, J.; Wu, X.; Zhou, Z.; Lei, Q.; Bhatt, P.; Chen, S. Biofilm-mediated bioremediation is a powerful tool for the removal of environmental pollutants. *Chemosphere* **2022**, *294*, 133609. [CrossRef]
383. Abbasi, S.; Keshavarzi, B. Source identification of total petroleum hydrocarbons and polycyclic aromatic hydrocarbons in PM10 and street dust of a hot spot for petrochemical production: Asaluyeh County, Iran. *Sustain. Cities Soc.* **2019**, *45*, 214–230. [CrossRef]
384. Miri, S.; Davoodi, S.M.; Robert, T.; Brar, S.K.; Martel, R.; Rouissi, T. Enzymatic biodegradation of highly p-xylene contaminated soil using cold-active enzymes: A soil column study. *J. Hazard. Mater.* **2022**, *423*, 127099. [CrossRef]
385. Raffa, C.M.; Chiampo, F.; Shanthakumar, S. Remediation of Metal/Metalloid-Polluted Soils: A Short Review. *Appl. Sci.* **2021**, *11*, 4134. [CrossRef]
386. Correia, A.A.S.; Caldeira, J.B.; Branco, R.; Morais, P.V. Enhancing the Strength of Mine Residue Soil by Bioremediation Combined with Biopolymers. *Appl. Sci.* **2023**, *13*, 10550. [CrossRef]
387. Chang, I.; Im, J.; Prasidhi, A.K.; Cho, G.C. Effects of Xanthan gum biopolymer on soil strengthening. *Constr Build Mater.* **2015**, *74*, 65–72. [CrossRef]
388. Latifi, N.; Horpibulsuk, S.; Meehan, C.L.; Majid, M.Z.A.; Tahir, M.M.; Mohamad, E.T. Improvement of Problematic Soils with Biopolymer—An Environmentally Friendly Soil Stabilizer. *J. Mater. Civ. Eng.* **2017**, *29*, 4016204. [CrossRef]
389. Kwon, Y.-M.; Ham, S.-M.; Kwon, T.-H.; Cho, G.-C.; Chang, I. Surface-erosion behaviour of biopolymer-treated soils assessed by EFA. *Geotech. Lett.* **2020**, *10*, 106–112. [CrossRef]
390. Qureshi, M.U.; Chang, I.; Al-Sadarani, K. Strength and durability characteristics of biopolymer-treated desert sand. *Geomech. Eng.* **2017**, *12*, 785–801. [CrossRef]
391. Cabalar, A.F.; Wiszniewski, M.; Skutnik, Z. Effects of Xanthan Gum Biopolymer on the Permeability, Odometer, Unconfined Compressive and Triaxial Shear Behavior of a Sand. *Soil Mech. Found. Eng.* **2017**, *54*, 356–361. [CrossRef]
392. Ayeldeen, M.K.; Negm, A.M.; El Sawwaf, M.A. Evaluating the physical characteristics of biopolymer/soil mixtures. *Arab. J. Geosci.* **2016**, *9*, 371. [CrossRef]
393. Pal, P.; Pal, A.; Nakashima, K.; Yadav, B.K. Applications of chitosan in environmental remediation: A review. *Chemosphere* **2021**, *266*, 128934. [CrossRef]
394. Chatterjee, T.; Chatterjee, S.; Lee, D.S.; Lee, M.W.; Woo, S.H. Coagulation of soil suspensions containing nonionic or anionic surfactants using chitosan, polyacrylamide, and polyaluminium chloride. *Chemosphere* **2009**, *75*, 1307–1314. [CrossRef]
395. Zou, H.; Pan, G.; Chen, H.; Yuan, X. Removal of cyanobacterial blooms in Taihu Lake using local soils II. Effective removal of Microcystis aeruginosa using local soils and sediments modified by chitosan. *Environ. Pollut.* **2006**, *141*, 201–205. [CrossRef]
396. Zinchenko, A.; Sakai, T.; Morikawa, K.; Nakano, M. Efficient stabilization of soil, sand, and clay by a polymer network of biomass-derived chitosan and carboxymethyl cellulose. *J. Environ. Chem. Eng.* **2022**, *10*, 107084. [CrossRef]
397. Jamshidi, M.; Mokhberi, M.; Vakili, A.H.; Nasehi, A. Effect of chitosan bio-polymer stabilization on the mechanical and dynamic characteristics of marl soils. *Transp. Geotech.* **2023**, *42*, 101110. [CrossRef]
398. Ilman, B.; Balkis, A.P. Sustainable biopolymer stabilized earthen: Utilization of chitosan biopolymer on mechanical, durability, and microstructural properties. *J. Build. Eng.* **2023**, *76*, 107220399. [CrossRef]
399. Bhatia, S.K. Microbial Biopolymers: Trends in Synthesis, Modification, and Applications. *Polymers* **2023**, *15*, 1364. [CrossRef]
400. Jose, A.A.; Hazeena, S.H.; Lakshmi, N.M.; Arun, K.B.; Madhavan, A.; Sirohi, R.; Tarafdar, A.; Sindhu, R.; Awasthi, M.K.; Pandey, A.; et al. Bacterial biopolymers: From production to applications in biomedicine. *Sustain. Chem. Pharm.* **2022**, *25*, 100582. [CrossRef]
401. Alloul, A.; Ganigué, R.; Spiller, M.; Meerburg, F.; Cagnetta, C.; Rabaey, K.; Vlaeminck, S.E. Capture–Ferment–Upgrade: A Three-Step Approach for the Valorization of Sewage Organics as Commodities. *Environ. Sci. Technol.* **2018**, *52*, 6729–6742. [CrossRef]
402. Söderholm, P. The green economy transition: The challenges of technological change for sustainability. *Sustain. Earth* **2020**, *3*, 6. [CrossRef]
403. Rodila, D.; Ray, N.; Gorgan, D. Conceptual model for environmental science applications on parallel and distributed infrastructures. *Environ. Syst. Res.* **2015**, *4*, 23. [CrossRef]
404. Delacámara, G.; O'Higgins, T.G.; Lago, M.; Langhans, S. Ecosystem-Based Management: Moving from Concept to Practice. In *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity: Theory, Tools and Applications*; O'Higgins, T.G., Lago, M., DeWitt, T.H., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 39–60.
405. Bretschger, L.; Pittel, K. Twenty Key Challenges in Environmental and Resource Economics. *Environ Resour Econ.* **2020**, *77*, 725–750. [CrossRef]