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Review

An Overview of Green Bioprocessing of Algae-Derived Biochar and Biopolymers: Synthesis, Preparation, and Potential Applications

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Abstract: Algae have the potential to be used as a feedstock for the synthesis of valuable compounds and biofuels. In addition, algal waste can be further transformed into biofuel, biogas, and biochar using different thermochemical processes such as microwave pyrolysis, pyrolysis, torrefaction, and hydrothermal conversion. Due to its high specific surface area, rapid electron transport, and graphitic carbon structure, algal biochar carbonized at high temperatures has shown outstanding performance for applications as CO_2 adsorbents, supercapacitors, and persulfate activation. Due to the combination of various functional groups and porous structures, the algae biomass pyrolysis at a moderate temperature produced high-quality biochar that shows high performance in terms of pollutant removal, while low-temperature pyrolysis produces coal fuel from algae via torrefaction. Over time, there have been exponentially more petroleum-based polymers created that have harmful impacts on both humans and the environment. As a result, researchers are becoming more interested in algae-based biopolymers as a potential alternative strategy for establishing a sustainable circular economy globally. The advantages of microalgal biopolymer over other feedstocks are its capacity to compost, which provides greenhouse gas credits, its quick growth ability with flexibility in a variety of settings, and its ability to minimize greenhouse gas emissions.

Keywords: microalgae; value-added products; biochar; biopolymer; circular economy

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1. Introduction

On prehistoric Earth, microalgae were the first photosynthetic organisms. By reducing significant amounts of carbon dioxide through photosynthesis, unicellular microorganisms help to lower greenhouse gases in the atmosphere. Consequently, algae are considered a feasible carbon capture technique [1]. Microalgae can be divided into prokaryotic cyanobacteria, which come in blue and green colors, and eukaryotic microalgae, such as the brown *Phaeophyta*, green *Chlorophyta*, and gold *Chrysophyceae* [2]. Additionally, they are divided into groups based on various metabolic processes (e.g., heterotrophic, photoautotrophic, photoheterotrophic, and mixotrophic) [3]. Algae's unique metabolisms contribute to a highly diverse variety of biological settings, including habitats with severe temperatures and pH levels, freshwater or saltwater, and effluents with a high concentration of organic and inorganic substances [4]. Microalgal biomass is produced at a rapid rate because of

its brief life cycle. Many studies investigated the potential uses of algae for bioremediation and the creation of added-value products such as, e.g., bio-oil, biochar, syngas, and biopolymers [5].

Biochar is a carbonaceous substance that is created from algal biomass by thermal breakdown in an oxygen-absence environment. The biomass content (such as cellulose, lignin, protein, etc.) and its thermochemical process (e.g., hydrothermal liquefaction, pyrolysis, torrefaction, gasification, direct combustion) have a significant impact on the structure and physicochemical features of biochar [6,7]. By modifying heating conditions (final temperature and heating rate) and biomass precursors, biochar with high physicochemical characteristics, porous structure, and structural stability, as well as having enough surface functional groups and ash, may be particularly developed [8]. Biochar has recently gained popularity due to its ease of production, low cost, and high sustainability [9]. As algal biochar has high adsorption capacity, the use of conventional coal-based carbons in the wastewater treatment filed may be reduced or eliminated. Biochar is comparatively stable, renewable, cost-effective, and ecologically sustainable, due to lower manufacturing costs than non-renewable activated carbons [10–13]. Various studies have examined the use of algal biochar as a low-cost, environmentally friendly biochar technology in wastewater remediation and other useful applications [14,15].

In comparison to petroleum-based synthetic polymers, microalgae-driven biopolymers are thought to be the most sustainable biomass feedstock for the synthesis of biopolymers in the direction of a global circular bioeconomy [16]. Recent research reports that when compared to petroleum-based polymers, algae-based biopolymers have better mechanical properties [17]. Additionally, algae-based biopolymers may be modified by adding additives, plasticizers, and compatibilizers to enhance the intermolecular force of contact between components, and boost material strength, flexibility, and durability [18,19]. Moreover, biopolymers are widely used in cosmetics, medicines, and food packaging. Furthermore, algal biopolymer could be used as a food additive due to its high nutritional content [20]. Utilizing innovative biopolymers such as chitosan dramatically improves processes such as medication delivery and tissue regeneration [21]. Biopolymers and their composites are intensively used in contemporary technologies such as 3D printing [22,23].

Many reviews discussing the derived value-added products from algae have been published in the literature; however, few reviews focused on both biochar and biopolymers. This review focuses on algae-based biochar and biopolymers, as well as their use as value-added products. Specifically, this review presents and discusses (1) microalgae-based biochar formation and characterization; (2) application of biochar derived from microalgae; (3) production of algae-based polymers; (4) the type of biopolymers derived from microalgae; and (5) the main applications of microalgae-based biopolymers and the degradation of biopolymers. Finally, this review gives a techno–economic analysis of both value-added products.

2. Biochar

2.1. Formation and Characterization of Microalgal-Based Biochar

Many processes for producing biochar from microalgae using thermochemical reactions have been developed. Hydrothermal carbonization (HTC), pyrolysis, and torrefaction are the main studied methods. However, post-treatment have recently received a great deal of attention. Biochemical methods such as anaerobic digestion and fermentation are also discussed in the literature. However, thermochemical methods are preferable due to their high efficiency, quality, and yield [24–26]. Biochemical methods are efficient when high moisture content microalgae, above 50%, are converted to biochar [27].

2.1.1. Torrefaction

Torrefaction is used to remove volatiles before pyrolysis; in other words, it is used as a pre-treatment step prior to the pyrolysis process. Torrefaction can be used in both wet and dry environments. Wet torrefaction is conducted at temperatures between 180 and

260 °C under higher pressures (200–700 psi) and a residence time of 5 min, while dry torrefaction conditions are: temperature (200–300 °C), pressure (atmospheric pressure), and a reaction time of 80 min. The type of torrefaction has a significant impact on the quality of the biochar produced. Wet torrefactions produce high yields with low ash content and great hydrophobicity, which significantly increase the adsorption capacity of produced biochar [28]. Moreover, moisture content increases the heat transfer rate, which decreases the cost of heating. Furthermore, hydrolysis attack, which leads to biomass decomposition, is easily triggered in a wet environment [29]. Recently, microwave-assessed wet torrefaction has gained more attention as microwave heating has advantages such as uniform heat distribution, instantaneous start/stop, and rapid heating rate [30,31]. Gan et al. [29] investigated the performance of microwave-assessed wet torrefaction in water and acid media for biochar production from microalgae (*Chlorella* sp.). The findings revealed that acid media combined with microwave-assisted torrefaction produced a high solid yield. The use of sulfuric acid could produce solids suitable for bioethanol production, while using organic acid could produce biochar applicable for solid fuel. High-yield biochar could be produced by a torrefaction system with a short time, low temperature, and low heating rate [32]. In addition, hydrophobic biochar could be produced as a torrefaction process that could destroy the hydroxyl groups of microalgal biomass by heating [33]. In contrast, some studies reported that high temperature and reaction time could decrease the H and O content in biochar [34].

2.1.2. Pyrolysis

Pyrolysis is the most common thermochemical process for converting algae biomass into value-added products such as biochar and bio-oil. The old version of pyrolysis is known as slow pyrolysis, while the other advanced pyrolysis processes are fast pyrolysis, catalytic pyrolysis, microwave-assisted pyrolysis, and hydro-pyrolysis [35,36]. Before algae undergo the pyrolysis process, pretreatment using acid is needed to remove inorganic chemicals such as Ca, Na, Mg, and K from the biomass. Differently, these chemicals could increase the ash content of biochar, which would decrease the biochar yield during pyrolysis [37].

Slow pyrolysis is the old version for high-yield biochar production thermochemically from algae biomass [25]. The slow pyrolysis process conducts at temperatures of 550–950 °C with more than a 5 min reaction time and a heating rate less than 60 °C/min [38]. One of the main advantages of slow pyrolysis is the ability to convert a wide range of microalgae sizes (5–50 mm) to biochar [39]. Optimization of pyrolysis operating parameters such as temperature, pyrolysis time, sweeping gas flow rate, and heating rate could enhance the quantity and quality of produced biochar [40]. For example, a long residence time of 450–550 days coupled with a low heating rate of 0.1–1 K/S boosts the production of biochar. This is due to restrained vapors, which undergo more reactions with solid material to produce more biochar. The microalgae strain species also significantly affects the biochar yield produced by slow pyrolysis; for example, *Chaetoceros muelleri*, *Dunaliella tertiolecta*, and *Synechococcus* produce high yields reaching up to 60%, whereas microalgae species such as *Tetraselmis chui*, *Spirulinaplatensis, Spirulina* sp., and *Chlorella vulgaris* produce moderate biochar yields [41,42]. Contrarily, fast pyrolysis produces a lower biochar yield (24–54% as a higher heating rate and shorter reaction time 1.5–3.3 s) are applied [43].

Catalyst pyrolysis is a new technology that aims to improve the quality and yield of biochar produced by the traditional pyrolysis process. Catalyst pyrolysis includes adding catalysts to promote the production of value-added products. Catalysts such as bases, acids, metals or even mixtures of these could be used as catalysts. Primary catalytic pyrolysis and secondary catalytic pyrolysis are the two main types of catalytic pyrolysis. Primary catalysis is applied in situ when the catalyst is blended with algae biomass, while secondary catalysis is an ex situ method where catalysts are fixed at the bed of the reactor and biomass is separated inside the reactor. With the help of heat from sand, catalyst activation occurs before the thermal degradation of biomass takes place. Microalgae species are an important

factor influencing the type of catalyst pyrolysis; for example, *Nanochloropsis* and *Spirulina* produce high yields when the ex situ method is used, while Pavlova biomass is more suitable for the in situ process [44,45]. The ex situ method separates catalysts and biomass, which means more control of catalytic activities and pyrolysis. Reusability of catalysts is another advantage of ex situ catalyst pyrolysis, as fewer minerals (Ca, Na, Mg, K, etc.) are deposited, which enhances the process in terms of cost. In contrast, the in situ catalyst process forms a layer of cake on the catalyst, varying its activity; thus, liquid products rather than solid products are promoted to generate. In a study, Aysu et al. [44] reported high biochar yields (35–48%) of *pavlova* biomass using in situ catalyst pyrolysis, while Jia et al. [45] examined the ex situ catalyst pyrolysis for *Spirulina* and *Nanochloropsis* biomass transfer to biochar and found that the solid yield was around 20%. Compared to conventional pyrolysis, catalyst pyrolysis has many advantages, such as low pyrolytic temperature, low energy consumption, and impurity removal ability.

2.1.3. Hydrothermal Carbonization

One more advanced thermochemical method for producing biochar from microalgal biomass is hydrothermal carbonization (HTC). The main benefit of such a method is the ability to directly convert moist biomass to biochar or hydrochar [25]. Hydrothermal carbonization includes heating carbon-rich content, for example microalgal biomass, in a moist environment at a temperature of 175–250 °C for a reaction time of 30–120 min under an applied pressure of 20–60 kPa [46]. Comparing this to other thermochemical techniques, there is no need to dry the biomass for the HTC application, which decreases the cost of heating. Moreover, the combination of water and heat inside the reactor functions as a milder environment of pressure and temperature [47,48]. These coins make HTC a cost-effective choice for value-added product production from microalgal biomass, especially hydrochar production, which differentiates HTC from pyrolysis [25]. The main parameters that control production yield through HTC are retention time and temperature. Khoo et al. [49] reported that the yield production of hydrocar decreased from 41.8% to 26.3% when the temperature and retention time of the HTC process were changed from 180 °C and 30 min to 250 °C and 4 h, respectively. The same result was reported by Yao et al. [50], who investigated the hydrochar production yield using the HTC process. The results showed that 190 °C produced the highest yield (36.7%), while 210 °C produced the lowest yield (27.2%). These two studies showed that increasing pressure and temperature reduced the yield of hydrochar. Recently, the same results were reported by Castro et al. [47], who found that a retention time of 10 min and temperature of 170 °C resulted in a high solid yield of 77.72% from microalgal biomass. Low carbonization temperature yields high-yield hydrochar with high-quality properties such as controlled porosity, electronic properties, regulated surface chemistry, and functional surfaces (e.g., -C=O, -COOH, -OH) [7]. In addition, Castro et al. [47] found that during the HTC process, the level of hydrogen and carbon was increased while the level of nitrogen and oxygen was decreased, and therefore a lower oxygen-to-carbon ration was found during the HTC process, resulting in solids with high hydrophobicity properties.

2.1.4. Post-Treatment/Activation

The biochar produced from microalgal biomass needs post-treatment, either physical or chemical, before it can be used [51]. This treatment is crucial to activate biochar before its application. The post-treatment process improves the physiochemical properties of the produced biochar, such as pore area or volume, specific surface area, surface chemistry, and functional agents. Magnetization and ball milling are two physical modification processes. Magnetization includes allocating magnetic iron oxides such as Fe_2O_4, Fe_2O_3 or Fe_3O_4 on biochar. Magnetizations make biochar recovery from solutions easier and enhance the cation exchange capacity of biochar [52,53]. Moreover, ball milling breaks chemical bonding in biochar by using kinetic energy, leading to an enhancement in the shape and size of biochar at the nanoscale. Regarding chemical modification, the oxidation process,

and acid and alkali post-treatment, the chemical modification changes the biochar's surface chemistry. Examples of chemical agents used for biochar chemical modification are H_2O_2, $KMnO_4$, KOH, NaOH, HNO_3, and HCl.

2.2. Characteristics of Microalgal-Based Biochar

The performance of biochar produced from microalgal biomass is characterized by surface charge and special pH, specific surface area, mineral components, and surface functional groups [54]. In this section, the relation between microalgae-based biochar characteristics and adsorption capacity is discussed.

2.2.1. Surface Charge and pH

In general, the pH of biochar derived from microalgal biomass is alkaline (pH above 7). Examples of microalgae strains that produce alkaline biochar are marine *Chlorella* sp., *Lacustrine* algae, *Spirulina* sp., and *Scenedesmus dimorphus*. Nevertheless, acidic biochar is produced from *Chlorella* sp. [55]. The surface charge of biochar is highly influenced by solution pH. To be more specific, the pH at zero charge (pHpzc) refers to the solution pH at which the surface net charge is zero. The importance of such parameters is attributed to their effects on the electrostatic attraction between charged contaminants such as high-energy minerals and biochar [56]. When pH is lower than pHpzc, biochar is positively charged and binds to negatively charged metals. On the other hand, when the solution pH is higher than pHpzc, biochar is negatively charged and binds with positively charged metals [57].

2.2.2. Physical Properties

The physical properties include pore area, surface area, bulk density, microspores, pore volume, etc. The specific surface area of biochar produced from microalgal biomass is considered low (>3 m^2/g), especially the biochar derived via pyrolysis and hydrothermal liquefaction from *Spirulina* [58]. However, the surface area could be increased as the pyrolytic temperature is increased. Ge et al. [59] reported high surface area biochar (15 m^2/g) derived from *Spirulina* when the pyrolytic temperature was increased from 300 to 700 °C. Remarkably, Amin and Chetpattananondh [60] reported extra-high surface area biochar (266 m^2/g) produced from *Chlorella* via sonication. High surface area and pore volumes increase biochar affinity and uptake of pollutants [61,62].

2.2.3. Chemical Properties

The chemical properties include ash content, moisture content, fixed carbon, and volatile matter. According to Yu et al. [7], biochar produced from *Gracilaria* sp. have more moisture content than biochar derived from *Chlorella vulgaris*. Microalgae-based biochar has a low moisture content (10 wt.%), while volatile matter contents and ash depend on the microalgae species. In addition, microalgae-derived biochar has a high fixed carbon content ranging from 40 to 70%. As O/C and H/C fractions significantly affect the aromaticity degree and the stability of biochar, the ultimate analysis to estimate chemical elements such as (hydrogen, carbon, sulfur, nitrogen, and oxygen) is crucial [63,64]. Biochar's high hydrophilicity could be figured out by its high O/C ratio, meaning that such biochar is useful for heavy meatal removal [60]. Higher O/C ratios contribute to high oxygen functional groups that enhance the adsorption of heavy metals. On the other hand, low H/C or O/C ratios revealed high hydrophobicity and aromaticity, which led to the favorable removal of non-polar organic compounds [56].

2.2.4. Mineral Elements

Microalgae-derived biochar could contain mineral elements such as K, P, Na, Ca, etc.; these elements promote the formation of the oxygen functional group. Moreover, alkali metals could increase the pH of biochar [65]. The mineral elements may perform as natural pore-forming agents, which generate a hierarchically porous structure on the biochar. Furthermore, contaminants could be adsorbed to mineral elements [66].

2.2.5. Surface Functional Groups

Adsorptive mechanisms, hydrophobicity, and hydrophilicity are important properties that could be determined by the surface functional groups of biochar. These surface functional groups could interact with metallic ions and interact with heavy metals through mechanisms such as complexation, surface precipitation, and electrostatic attraction [67]. Nevertheless, important acidic functional groups such as CH and OH could be destroyed by high pyrolytic temperatures. However, high pyrolytic temperatures could produce basic functional groups, pH, carbon stability, ash content, and gaseous yield [68]. Therefore, low pyrolytic temperatures could produce biochar with an acidic functional group, which improved heavy metal removal, while high pyrolytic temperatures resulted in biochar with high hydrophobicity, which enhanced organic pollutants' removal [64,67]. Furthermore, high hydrophobicity leads to humidity resistance [46].

2.3. Application of Microalgal-Based Biochar

2.3.1. Inorganic Contaminants Removal

Toxic heavy metals could be absorbed and accumulated in organisms, thus presenting a severe threat to both human health and natural water [46,69]. Biochar derived from microalgae could eliminate and adsorb heavy metals such as Zn (II), Cr (VI), Co (II), Ni (II), and Hg (II) from aqueous solutions. Many studies in the literature have reported the performance of biochar derived from microalgae for heavy metal removal. In a study, Daneshvar et al. [70] produced biochar from *Scenedesmus quadricauda* using the pyrolysis process at a temperature of 500 °C. The authors evaluated the performance of derived biochar for Cr (VI) removal. The results showed complete removal of Cr (VI) when the initial concentration was in the range of 1–10 mg/L. In addition, the authors reported that the mechanisms of removal of Cr (VI) were electrostatic interaction, ionic exchange, and Cr (VI) reduction. Previously, Bordoloi et al. [71] performed many equilibrium studies such as Langmuir and Freundlich adsorption isotherms to examine the application of biochar derived from *Scenedesmus* microalgae for Co (II) ion removal. The results revealed that the adsorption capacity of the produced biochar was 0.672 mg/g. Ge et al. [59] reported that biochar derived from high-salinity *Spirulina* microalgae was able to remove Hg (II) ions by immobilization and reach a sorption capacity of 6–12.7 mg/g for long-term uptake. *Microcystis* sp. biochar is capable of successfully removing chelated nickel from alloy electroplating wastewater [53]. In another study, biochar derived from marine algae such as *Sargassum fusiforme* and *Saccharina japonica* was used to remove Zn, Cd, and Cu from aqueous solutions. The results reported that a high number of oxygen functional groups was the main mechanism for heavy-metal removal. In addition, cation exchange was another removal mechanism by biochar as marine algae have a high number of minerals such as Na, K, Mg, Ca, etc. [72].

2.3.2. Organic Contaminants Removal

Organic contaminants such as personal care products, antibiotics, pharmaceuticals, plasticizers, and flame retardants are environmentally hazardous, societally ubiquitous, and structurally diverse chemicals [10]. Conventional wastewater treatment cannot remove such undegradable compounds; thus, more effective remediation methods such as adsorption have been developed. Microalgae-based biochar is a promising adsorbent that efficiently removes organic pollutants [73]. The removal mechanism of organic pollutants by biochar is due to one or a combination of the following mechanisms: electrostatic attractions, polar-selective interactions, pore filling, hydrophobic interactions, and p-p interactions. Ho et al. [74] investigated the removal of *sulfamethoxazole* (antibiotics) by N-doped graphitic biochar produced from *Spirulina*. The results showed that the derived biochar could absorb *sulfamethoxazole* via electron transfer. In another study, Zheng et al. [75] reported p-nitrophenol removal using biochar derived from *chlorella*. Nautiyal et al. [76] examined acidic Congo red dye removal using biochar produced from *Spirulina*. The removal efficiency of the investigated dye was 82% at pH of 2, initial dye concentration

of 90 mg/L, and 0.2 g/100 mL biochar dosage. Figure 1 shows the biochar adsorption mechanism for both organic and inorganic pollutants.

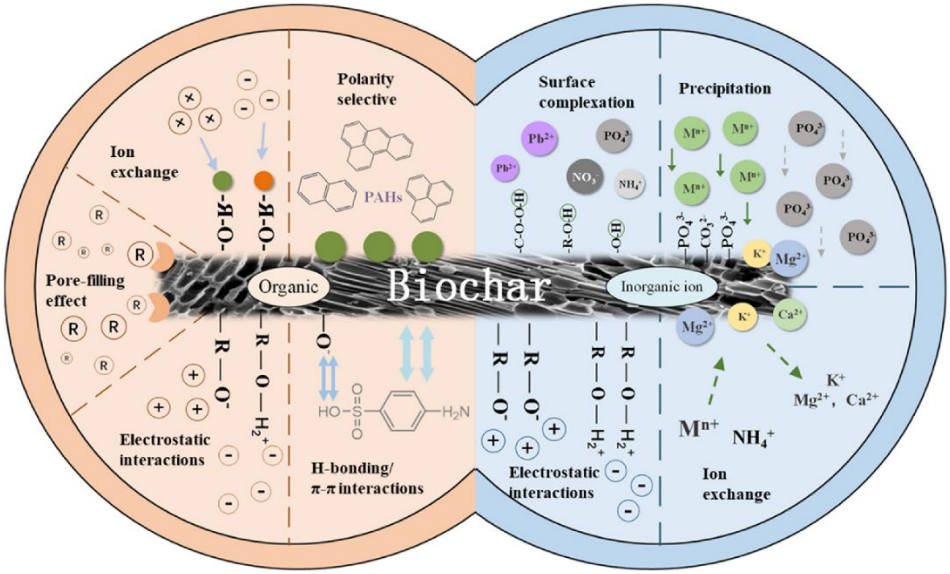

Figure 1. Adsorption mechanism of microalgae-based biochar [77].

2.3.3. Carbon Dioxide Removal

Human and industrial activities release a huge amount of CO_2 every day, causing disastrous environmental problems. Among CO_2 mitigation measures, adsorption is considered a promising technology to decrease the CO_2 concentration through chemical and physical processes. Microalgae-based biochar has a high specific surface area (SSA), active surface functional groups, and a highly porous structure, which make this type of biochar an ideal adsorbent for CO_2 [78,79]. High N content and large SSA are crucial for CO_2 adsorption. Creamer et al. [80] produced biochar from *sugarcane bagasse* at 600 °C. The author reported high CO_2 adsorption efficiency due to the presence of N-functional groups and high SSA. In addition. The author suggested that the enhancement in CO_2 adsorption was due to Lewis's acid–base interaction, which is increased in the presence of an N-functional group [81]. Another factor that affects CO_2 adsorption is the size of the pores, as it controls the rate of gas transport through the pore system [82]. Plaza et al. [83] reported that microalgae-based biochar pyrolyzed at 600 °C under N_2 flow had a high CO_2 capacity due to its micro-porous structure. For high CO_2 absorptivity, the optimal biochar pore diameter was between 0.5 nm and 0.8 nm, as reported by Creamer and Gao [84].

2.3.4. Other Applications

Using microalgae-based biochar to produce coal fuel is a promising method to produce green energy. The torrefaction process is used to convert biochar into coal fuel. Higher heating value (HHV), O/C, and H/C ratios all have an impact on coal-based biochar. Congyu Zhang et al. [85] examined the production of coal fuel-based biochar using the torrefaction process in the absence and presence of O_2. The results revealed that oxidative torrefaction (the presence of O_2) could produce biochar with a large SSA, high HHV, and high hydrophobicity that could be used for industrial applications as coal fuel. Non-oxidative torrefaction, on the other hand, produced biochar with good storage and transportation characteristics. Supercapacitors are emerging energy storage devices with many advantages such as high-power density, fast charge–discharge, low cost, low environmental impact, and a long life cycle. The use of biochar produced from algae as a supercapacitor has been investigated in many studies. To enhance the supercapacitors' specific capacity, characteristics such as the hierarchical porosity and SSA of the produced biochar should be improved [86]. Wang et al. [53] produced KOH-activated biochar derived from *Enteromorpha prolifera* with a high

capacitance of 440 F/g at A/g and an SSA of 3345 m^2/g. Subsequently, Wang et al. [87] confirmed that carbonaceous materials derived from *Nostoc flagelliforme* were characterized by lower internal resistance, a more porous structure, and high specific capacitance (283 F/g). Table 1 presents the process parameters, microorganisms, and synthesis techniques used for biochar production.

Table 1. Application of biochar derived from microalgae.

Microalgae Strain	Biochar Yield	Biochar Production Method	Synthesis Conditions	Biochar Characterization	Biochar Application	Reference
Gongolaria barbata	40 wt.%.	Microwave assisted method	• Activating agent (phosphoric acid). • Microwave power (700 W), • Residence time (18 min)	• Micropore volume 0.181 cm^3/g. • Surface area 1089 m^2/g.	Aniline removal.	[88]
Three types of marine biomass waste (*kelp*, *undaria pinnatifida*, and *Enteromorpha prolifer*)	-	Pyrolysis	• Temperature (800 °C). • Residence time (1 h).	• Specific surface areas (621–1140 m^2/g). • Energy storage characteristics (190.0–278.5 F/g at 0.5 A/g)	Electrochemical energy storage	[89]
Agardhiella subulata	67.6 wt.%.	Pyrolysis	• Temperature (300–900) °C. • Residence time (1 h).	• Surface area (119.2 m^2/g).	4-Nonylphenol (4-NP), a phenolic endocrine disruptor chemical (EDC) removal	[90]
Chlorella sp.	57%	Pyrolysis	• Temperature (450 °C). • Residence time (1 h).	• Surface area (266 m^2/g);	Heavy metal removal (Cr (VI), Zn (II), Ni (II))	[60]
Sargassum sp.	70%	Pyrolysis	• Temperature (300–500 °C). • Residence time (10–60 min).	• Surface area (250 m^2/g). • Pore volume (cm^3/g)	Agronomy as a soil ameliorant	[91]

3. Biopolymers

3.1. Production of Biopolymers from Algae Biomass

Algae can grow everywhere, from marine environments to lichens to freshwater springs, displaying heterotrophic, mixotrophic, and autotrophic lifestyles. The growth of algae can be controlled in large-scale cultivation to increase the yield of lipids, hydrocarbons, and polysaccharides [92]. To produce biopolymer from algae, two linked stages are required. In the first stage, the algae are cultivated under high concentrations of nitrogen and nutrients to reach high cell densities. After reaching this point, some algae are transferred to the second stage, where salinity and nitrogen starvation are applied [93]. At this point, the biopolymer production phase is started by algae cells [23,94]. Many methods, such as solvent extraction, microwave-assisted extraction, ultrasound-assisted extraction, and supercritical water extraction, are used to extract polymers from algae biomass.

3.1.1. Solvent Extraction

The use of a solvent for biopolymer extraction is an easy method; however, the application of this method requires vast quantity of chemicals. In addition, compared to fermentation, solvent extraction is simpler and requires less downstream processing. Solvent extraction includes chemical agents added to and mixed with algal biomass to produce polymer precipitates [95]. To improve the accumulation process of biopolymers, optimization of all parameters (physical and chemical) is needed. Faidi et al. [96] used mineral acids (pH of 1.5) to extract alginate biopolymer from *Padina pavonica* algae. The authors reported that operation conditions such as centrifugation, sifting, and filtration

significantly affected the extraction process. However, to reduce the effect of mechanical operation conditions, screening of productive algae is needed. For example, Morales-Jiménez et al. [97] investigated the biopolymer productivity of six algae strains, *Porphridiun purpureum*, *Synechocystis* sp., and *Nostoc* sp. which produced high biopolymer yields of 83, 204, and 323 mg/L, respectively. To conclude, biopolymer solvent extraction is a simple and easy method; however, the main disadvantage is the use of chemical solvents in huge quantities.

3.1.2. Microwave Assisted Extraction

Microwave-assisted extraction is a green and novel method to extract value-added products from algae biomass. The biopolymer inside an algae cell can be extracted using a microwave-assisted extraction approach. The advantages of microwave extraction are compactness, a quick and uniform process, low consumption of solvents, short experiment times, and no requirement of energy [98,99]. In a study, microwave-assisted water extraction was used to extract high yields from *Mastocarpus stellatus* red algae. The study reported that a 6 min operation time and a temperature of 150 °C were the optimum conditions [99]. In addition, the strength of biopolymers can be promoted when the temperature is increased. Microwave-assisted extraction is suitable for industrial applications as syneresis of biopolymeric gels is avoidable, and one can investigate the use of electromagnetic waves to aid in the manufacturing of biopolymers and create new methods to reach high yield and cost-effectiveness. However, because the microwave extraction method uses a small quintile of solvent, optimizing operating conditions remains a challenge that requires further investigation.

3.1.3. Ultrasound Assisted Extraction

Ultrasound waves cause cavitation, which causes turbulence and causes agitation and collisions in microparticles found in algae biomass. Ultrasound energy produces vibrant energy, which disrupts the cell walls of algae, improving the transfer rate and the removal of biopolymers [100]. Compared to conventional methods, the advantages of ultrasound-assisted extraction include decreasing extraction time from hours to minutes and using room temperature to process the extraction. Extra separation methods such as membrane separation could be used, which are considered environmentally friendly and could reduce the material losses [101]. Moreover, the biopolymer yield extracted by ultrasound was 33% higher than the conventional method. Flórez-Fernández et al. [102] reported that the ultrasound extraction method minimized the extraction time four times when alginate was isolated from *Sargassum muticum*. Furthermore, the authors found that temperature, ultrasound frequency, and sonication time were the main parameters that affected all processes. The authors reported that an increase in sonication time from 5 min to 30 min resulted in 10% more yield (from 5% to 10%). Although the ultrasound extraction method saves time and energy, much development is needed to increase the yield of biopolymers.

3.1.4. Subcritical Water Extraction

Subcritical water extraction is a promising extraction technology used to remove a value-added product from algae biomass. In this process, the water is heated above boiling temperature (up to 373 °C) and pressurized under the critical pressure point (221.2 bar) [103]. Compared to conventional extraction methods, supercritical extraction has many advantages, such as the use of water as the solvent, which eliminates the use of harmful chemicals and results in high yield and quality, low energy consumption, and a short reaction time [104]. In a study, Saravana et al. [105] used supercritical water extraction to extract fucoidan biopolymer from *Saccharina japonica* algae. The authors reported that using supercritical water extraction resulted in 4.85% of fucoidan being removed from algae biomass while conventional methods removed 2.47%. Alboofetileh et al. [104] reported that under optimal conditions of 29 min extraction time and 150 °C temperature, fucoidan

removal efficiency from *Nizamuddinia zanardinii* was 25.98%. Likewise, Saravana et al. [106] examined the performance of supercritical water extraction combined with a deep eutectic solvent for the removal of fucoidan and alginate biopolymers from *Saccharina japonica* algae. The results reported that high removal efficiencies for alginate (28.1%) and fucoidan (14.93%) can be achieved using supercritical water extraction. More investigation is required to optimize the operation conditions, such as temperature and pressure.

3.2. Biopolymers Produced from Algae Biomass

3.2.1. Poly Hydroxy Alkanoate (PHA)

PHA produced by microorganisms is environmentally friendly and resembles petrochemical polymers in terms of its characteristics [107]. Stress brought on by a nitrogen deficiency can encourage the development of biopolymers. Many microalgae strains such as *Synechococcus subsalsus* and *Spirulina* were able to develop novel 14–18 carbon chain PHA biopolymers, but *Chlorella minutissima* was unable to do so, even in the absence of nitrogen. PHA monomer composition is strongly influenced by microbial strains and culture strains [108]. The optimization of algal PHA production is an essential step; thus, more bioprocess lab-scale studies are required to upscale all processes. Ramos et al. [109] suggested a mixed-integer nonlinear programming model. The authors chose the best circumstances that are suitable for the plant and maximized its net present value. Additionally, this can be useful in deciding between several options for extracting biopolymers from cells and choosing the best strategy to extract the highest quantity of biopolymers.

3.2.2. Poly Hydroxy Butyrate (PHB)

PHB, a polar and optically active biodegradable polymer, has received a great deal of interest because of PHB similarities to polypropylene in terms of physical and chemical characteristics [110]. In comparison to lignocellulosic biomasses, the presence of high starch content promotes the synthesis of PHB in the highest quantities [111]. Only a small amount of material has been published that uses algae as a precursor in the creation of PHB, as the synthesis of PHB requires a significant amount of lipid [112]. Lipids are often accumulated in large amounts for the formation of biopolymers when cell growth rates are low. Cassuriaga et al. [107] investigated the impact of several factors on *chlorella fusca* PHB production. Their investigation yielded the highest level of PHB (17.4%), exceeding that produced by *Botryococcus braunii*, as reported by Kavitha et al. [113]. Recently, the possibility of producing PHB from agricultural runoff was investigated. Despite the modest PHB concentrations found, bacterial PHB production has a large potential [110].

3.2.3. Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV)

PHBV is produced by introducing 3-hydroxyvalerate, which decreases the crystallite nature of PHB [114]. The use of PHBV in medicine, especially, in drug delivery systems has been reported. The unique PHBV physiochemical properties and slow rate degradation make them as good candidates for drug delivery systems. Many recent studies reported producing nano-structural systems using PHBV derived from alga. For instance, in the absence of a precursor, the PHBV production from glucose can be enhanced using the *Recombinant Bacillus megaterium* strain [115]. In the same study, more than 80% of PHBV was produced using the fed-batch method, whereas the batch approach produced just 46% of PHBV, revealing that fed-batch cultivation system is a promising technology for PHBV production from algae. These results showed the possibility of producing PHBV in large industrial scale from algal glucose.

3.2.4. Polylactide (PLA) and Polyalcohol

Polylactide and polyalcohol are polymers with wide applications in biomedical industries such as braces, sutures, bone screws, and bandages; thus, these biopolymers have received more attention in recent years. Many investigations have studied the composites of PLA produced from algae [116]. The biopolymer contents of algae can be modified

to produce PLA biopolymers, which can be used in many medicine applications such as wound treatment, tissue regeneration, and tissue augmentation. Regarding polyalcohol produced from algae, they have many advantages such as water solubility, biodegradability, and high tensile strength. Bio-polyalcohol is generally used to produce biomaterials that have many applications. For example, one of the polyalcohol types is PVA that acts as a protective film, sizing agent, and emulsifier. In addition, bio-products made from PVAs can result in high-quality compositions. In a study, lipid-extracted algae were used to produce PVA, which was used to manufacture a bio-composites filter. The results showed that the introduction of PVA enhanced the thermal stability of the bio-composites by improving the mechanical characteristics [117].

3.2.5. Polysaccharides

Long-chain polysaccharides are used in the production of bio-materials due to their unique properties; these polymers are highly compatible with human systems as well as being biodegradable [118]. Algae can be used to produce polysaccharides including fucoidans, alginates, galectins, glucans, ulvans, carrageenan, and porphyrin. Cosmetics, tissue engineering, and cosmetic surgery are the main application of polysaccharides.

3.2.6. Alginate

Alginate is freely available in many *undaria pinnatifida* species (more than half). Alginate is used in many sectors such as drug delivery systems and tissue engineering. The introduction of alginates to produce hydrogels can enhance the stiffness, recoverability, and flexibility of these hydrogels. In addition, alginate has high adsorption capacity and absorption abilities [119]. Yuan and Macquarrie [120] examined the extraction of alginate from algae biomass by two methods: extraction and a bio-refining process. the results showed that the extraction method produced alginate of 23.13% more than the biorefinery method. Nevertheless, the biorefining approach generally produces two different types of alginates that differ in characteristics [121]. Moreover, pH is a significant factor affecting the alginate extraction process from algae. Alginate extraction under acidic pH produced insoluble alginic acids that adversely affect the alginate extraction. On the other hand, alkaline pH environment could produce high alginate yields [122].

3.2.7. Fucoidan

Fucoidan is widely used in cancer therapy, health products, and medicines. Brown algae is rich in Fucoidan, which has a heterogeneous structure. Fucoidan's structure can be determined in part by the source and extraction technique. Fucoidans have a high level of anticancer action at low molecular weights and high sulfur concentrations [123]. High-molecular-weight fucoidan is used in nanomedicine and medication delivery and can be produced by non-degrading extraction [124]. Fucoidan produced from *F. evanescens* has valuable properties such as a high monosaccharide content (96.1%), a low molecular weight (188 kDa), excellent anticomplement activity, and a high degree of sulfation (0.5). Moreover, fucoidan has high neutrophil transmigration inhibition (93%), significant anticancer efficacy, and equivalent anti-tumor effects compared to the conventional approach [101].

3.2.8. Laminarin

Laminarin is a non-hydrocolloid polysaccharide that includes long chains of glucose [125]. In terms of Laminarin structure, the predominance of single chain and low polydispersity are the main characteristics. Laminarin is consumed in the ethanol production process, marine carbon cycle, and medication administration [126]. Oxidation-reduction reactions enhance the performance of anti-inflammatory, antioxidants, and antitumor. In the Rajauria et al. [125] study, the authors increased laminarin content by purification. The laminarin has high anisometric stretching intensity and high antioxidant activity. Seaweed algae extract contains low-molecular-weight laminarin, which can be separated by using the membrane process [122].

3.2.9. Carrageenan

Carrageenan Red seaweed is often used to extract the polysaccharide carrageenan. It is used in medication delivery systems for the prevention of membrane fouling [127]. Using an ultrasonic pre-treatment at 90 °C for 15 min, carrageenan was extracted from *K. alvarezii* with a 56% extraction yield. The extraction technique affects the yield of the carrageenan. The molecular weights of carrageenan are decreased and dispersed because of extraction [128]. The k-Carrageenan has a high viscosity and strong gel strength. While viscosity is only reliant on the extraction temperature, the gel strength of k-carrageenan depends on its monosaccharide concentration, purity, and critical gel temperature [129]. Table 2 shows different methods for biopolymer extraction from microalgae.

Table 2. Isolation techniques for biopolymer extraction from microalgae.

Microalgae Species	Isolation Method	Solvent	Isolation Conditions	Biopolymer	Yield	Reference
Alaria esculenta, *Saccharina latissima* and *Ascophyllum nodosum*	Solvent extraction	Water	0.2 M HCl and 0.1 M $NaHCO_3$	Alginate	• Alaria (10%) • Saccharina (15%)	[130]
Ulva sp.	Solvent extraction	Dimethyl Sulfoxide	• Temperature 180 °C, • Residence time 40 min.	PHA	77.88%	[131]
Nizamuddinia zanardinii	Subcritical water extraction.	Water	• Temperature 150 °C, • Residence time 29 min.	Fucoidan	25.98%	[104]
Saccharica japonica	Subcritical water extraction.	Water	• Temperature 127 °C, • Residence time 12 min.	Fucoidan	13.65%	[105]

3.3. Bio-Composite Polymers

Biopolymers are often made using techniques such as electrospinning, melt casting, etc. Because of their low cost and low risk of tissue damage, algae–polymer composites are a viable option in biomedical industries [116]. The potential of bio-composite materials (also known as "green composites") to replace traditional materials used in manufacturing industries has substantially enhanced their attractiveness recently. Many researchers have been drawn to bio-composites because of their advantages over typical synthetic materials, including their ability to be composted after their expiration date, their ease of disposal, and their ability to be sustainable and renewable. Furthermore, bio-composites can be applied to a wide range of items due to their similar mechanical qualities.

Cinar et al. [18] provided detailed descriptions of how to create bio-composite polymers in their literature, along with illustrations of how to characterize them. However, there have been improvements in the synthesis of composite algal biopolymers [18]. In another study, Kumar et al. [118] reported a new method to blend aqueous extracts of algae and alginate. Sayin et al. [116] reported that dried algae powders were combined with PLA and hot-pressed at 180 °C to create biopolymer composites, while Tran et al. [117] created lipid-extracted algae-PVA composites using the ultrasonication method. Important criteria for the manufacturing of composite materials include particle size and distribution as well as algal filler shape. Due to the intense interfacial contact, ultrasonic treatment disturbs and produces smaller algae particles that are readily reinforced. For the manufacture of algal bio-composites blends, one can employ physically assisted procedures such as microwave-assisted, supercritical-fluid-assisted, UV-assisted, etc.

3.4. Applications of Algae Biomass-Based Biopolymers

There are many applications of algae biomass-based biopolymers in the literature. The significant use of algae-based biopolymers is discussed in this section. Figure 2 shows the possible applications of algal-driven biopolymers.

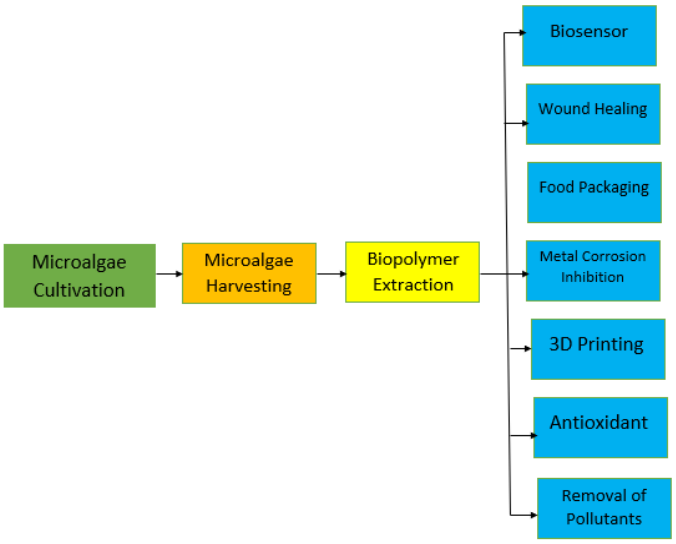

Figure 2. Applications of algal-driven biopolymers.

3.4.1. Biosensor

Recent technical developments have facilitated the development of sophisticated electrochemical biosensor structures, which are essential for healthcare monitoring [132]. Two of the most studied polysaccharides in this area are chitosan and carboxymethyl cellulose due to their high qualities, which include biocompatibility, biodegradability, non-toxicity, naturally renewable, and the capacity to create adherent thin films [133]. By using parallel reactions that can happen in enzymatic reactions with substrate or product, laccase-based biosensors can be used to determine medications in a non-direct manner [134].

3.4.2. Removal of Pollutants

Biopolymers include starch, cellulose, polysaccharides, alginate, and chitosan, which are naturally occurring biopolymers. These biopolymers adsorb polycyclic aromatic hydrocarbons, metals, sulfide-containing contaminants, benzene, and other pollutants, creating a complex hybrid while removing contaminants from wastewater [135]. The use of biopolymers for the adsorption process results in strong and efficient adsorption and may not result in secondary pollution or harmful by-products. The ability to restore and reuse it is also simple [136]. Clays and biopolymers cooperate in an adsorption process to remove dyes and remediate heavy-metal contamination. The removal of hydrophobic contaminants requires the use of biopolymers such as polysaccharides and polypeptides because natural clays are inadequate for this purpose. This results in a powerful combination that may be used for environmental cleanup [137]. When clay and biopolymer are combined as bio-composites, compared to when they are used individually, their qualities, such as resilience to low wettability, pH fluctuations, and poor specificity, are significantly improved. According to Xia et al. [138], two bacterial strains from wastewater treatment plants (WWTPs) *Klebsiella* sp. (designated as EPS-K) and *Bacillus* sp. (EPS-B) were used to remove mercury. For the elimination of organic pollutants, a biopolymer with integrated phosphate groups (PCel) has been developed. Using phosphoric acid and sodium tripolyphosphate to modify cellulose surface has been investigated to produce biopolymers. The highest levels of adsorption for investigated organic pollutants were at acidic-to-neutral pH, with a capacity of 47.58 mg/g for Rhodamine B and 45.52 mg/g for Amitriptyline [138]. Several

investigations used modified cellulose for adsorption as its surface has hydroxyl (OH) groups [139].

3.4.3. Biomedical Applications

Biopolymer possess valuable properties such as non-toxicity, biodegradability, water-holding capacity, and high tensile strength. These unique properties make biopolymers a good feedstock for the biomedical engineering sector, especially, in bone-tissue engineering and regenerative medicines. According to a recent study by Sathiyavimal et al. [140], since hydroxyapatite (HAp) is a crucial mineral for human bone, chitosan can be used to create a composite biopolymer of HAp. Bahmani et al. [141] employed soybean oil epoxidized acetate (SOEA) in combination with HAp nanoparticles, comparing the mechanical characteristics of the biopolymer after adding hydroxyethyl acrylate to one portion of the composite and removing it from another. Sayin et al. [116] investigated marine alga–PLA composites for collagen membranes. Polylactide was used in this study to improve the qualities of algal strains such *Galaxaura oblongata, Corallina elongate*, *Sargassum vulgare*, *Cystoseria compressa* and *Stypopodium schimperi*. Regarding skin-grafting applications, type IV MAP (*Sargassum vulgare*) showed the greatest qualities.

3.4.4. 3D Printing

Due to 3D printing's ability to build complicated structures quickly and accurately, it has gained popularity recently. The challenge currently is to describe the mechanical and biological characteristics of naturally existing bio-based materials [142]. Ponthier et al. [99] filled a PVA bio-composite for 3D printing with the algae *Nanochloropsis salina*. Because of their adaptability, biopolymers can be used for a variety of purposes that require different material characteristics. 3D-printed biopolymers are employed in adsorption for environmental remediation and medicinal applications. To manufacture fillers for the methyl orange degradation, Sangiorgi et al. [143] used polylactic acid that had been treated with TiO_2. Because the composite contains 30% TiO_2, 100% of the methyl orange may be completely degraded in 24 h. The stem cell activity of 3D-printed scaffolds coated with nanoscale ceramics was investigated [144].

3.4.5. Antioxidant

In the food business, biopolymers are mostly used as antioxidants. Compared to other antioxidants, biopolymers are preferable since they are non-toxic. Biopolymers do not show the negative health impacts that manufactured antioxidants do [140]. For example, biopolymers prevent the oxidation of unsaturated lipids at the oil–water interface that keeps food fresh [145]. Pérez Córdoba and Sobral [146] investigated the antioxidant characteristics of three different gelatin bio-composites: gelatin–sodium caseinate (G-C), pure gelatin (G), and gelatin–chitosan (G-Ch). The results showed that G–C compounds combined with actives showed high antioxidant properties. By utilizing active enzymes such as *Aspergillus oryzae* and *Aspergillus flavipes*, Zanutto-Elgui et al. [147] used goat and cow milk to create bioactive peptides. Studies have shown that this process has a potent antioxidation ability of up to 92.5% DPPH equivalent, making it valuable in the food and pharmaceutical industries. Gopu and Selvam [148] extracted *Amphiroa rigida*, an algae strain, using ultrasound to produce a powerful antioxidant. Given that the developed ARPS can scavenge DPPH and ABTS, it was determined that it also has strong antioxidant effects.

3.5. Degradation of Bioplastics

Prior to now, the biodegradability of polymers was assessed using tests for microbial development, tensile strength changes, and the loss of other physical characteristics that fall within qualitative evaluation. Soil burial tests were used as one of the approaches for determining how well the bio-composites were degrading, even though quantitative assessment tests also include analytical procedures for each reactant and product [149]. To reduce the quantity of CO_2 that the soil produced compared to the bio-composites, the soil

was replaced with hygroscopic aluminum silicate [150]. In contrast to a non-biodegradable polymer matrix, which is disposed of by burning or landfilling, bio-composites with a biodegradable polymer matrix are disposed of via composting, which can be used as fertilizer. Because they are constructed of different components, it is challenging to recycle more complex bio-composites [151]. Biopolymers can degrade by a variety of chemical, biological, or even a combination of processes, including the four main types of degradation: thermal degradation, photodegradation, oxidative degradation, and high-energy degradation. Temperature, humidity, and the quantity and bacteria species affect the biodegradation rate. PLA was recycled as a monomer after hydrolysis and enzymatic breakdown. PLA degraded differently depending on the environment it was exposed to [152]. PLA film's permeability to oxygen and water vapor considerably increased as the number of extrusions was increased during processing [153]. Numerous studies have been conducted to determine how successfully certain polymers may be recycled. With the aid of catalysts, the thermal breakdown process of PHAs can produce its vinyl monomers [154]. Therefore, the threat posed by plastic and new plastic pollutants, including micro- and nano-plastics as well as plastic leachates, would be reduced because of the biodegradability of biopolymers and bio-composites. However, the product and its use determine the trade-off between strength, applicability, and degradability.

4. Economic Impact of Biochar and Biopolymer

Thermochemical methods used to create biochar, primarily in rural regions, contribute to the development of that area and help small and medium-sized businesses produce enough energy, increase farmer income, and provide solutions for managing agricultural waste. This makes it possible to link small-scale production systems to bigger ones, creating closed-loop models where waste from one process may be utilized as an input for another, having favorable social, economic, and environmental effects, and promoting regenerative economic sustainability [155]. For the creation of new opportunities, similar interactions between different waste reuse and biochar synthesis methods are needed. Economic sustainability has been established, opening the door for the creation of new corporations and the development of new products and procedures by using waste from one agro-processing industry to shed light on hazardous pollutant issues in another and incorporating the by-products into soil application. Considering both technical and economic factors, heat-created strategies that balance usability, energy efficiency, and limited discharges may be included in the local network to make biochar creation possible [155]. The following economic benefits are listed: cost savings from waste disposal and lower greenhouse gas emissions. Utilizing a range of methods and procedures, this application for regenerative economic sustainability reduces waste while increasing the value of the resources used. A multiunit model would frequently be useful in breaking down strategies for increasing productivity, modernizing operations, and judiciously allocating environmental burdens to achieve environmental benefits [156].

An industry analysis based on analytical research and consulting estimates that the global polymer market was valued at $666.6 billion in 2018. The market is expected to expand quickly, with a compound annual growth rate (CAGR) of 5.1% [157]. Biopolymers' main markets include the pharmaceutical, healthcare, food, and beverage sectors. In the medical industry, biodegradable polyester is extremely useful for creating surgical implants. In the food and beverage business, biopolymers are principally used to produce cellophane films, which are widely used in food packaging. In 2018, the market for biopolymers expanded rapidly and was valued at $12 billion [157]. Between 2019 and 2025, the biopolymer market is predicted to grow quickly at a CAGR of 19% [157]. As shown by Europe's 55% market share in 2018, the European Biomass Industry Association has made several attempts to improve market acceptance of biopolymers. Biopolymers are often used in the pharmaceutical industry to heal wounds of any form, size or depth. Common biopolymers, including chitosan, gelatin, alginate, and pectin, are used to make hydrogels, which offer a moist environment for dry wounds. These biopolymers are also

employed in the creation of bandages for wounds. These factors come together to form the expected growth driver for the global biopolymer market. The initial cost related to generating a product is essential in the biopolymer sector. Key players in the sector are trying to overcome this issue by forming a joint venture with an agriculture firm to build a symbiotic link for the growth of the biopolymer [158].

5. Recommendations and Future Perspectives

Extracting certain value-added compounds, such as pigments or polyunsaturated fatty acids, before making algal biochar might increase its economic viability. Therefore, the properties and quality of algal biochar, as well as its potential uses, might differ greatly depending on the extraction technique and the algae species employed. Additionally, the use of algae that can grow effectively in wastewater is necessary to make algal biochar for wastewater treatment more economically viable. Future research efforts should focus on creating new engineering processes, improving wastewater treatment for biochar, extracting value-added products before creating algal biochar, and finding out the structure of biochar and any uses for it. It is also crucial to investigate and assess the advantages and drawbacks of algal biochar for the environment. Additionally, little attention was put into finding the unexpected environmental effects, such as the consumption of energy, materials, and chemicals linked to the emissions into the air, soil, and water, aside from pursuing exceptional applications with the ideal operational circumstances. It is feasible to screen microalgal species to find the optimal algal biomass for the manufacture of biopolymers. There are few publications, nevertheless, that cover computational screening techniques for making biopolymers from algae species. The potential for biopolymer synthesis by algae can be predicted in the future by screening algal species using artificial intelligence. Additionally, in the near future, mapping polymer synthesis from many species should be implemented, followed by integrated and creative culture tactics for greater yield with lower input costs.

6. Conclusions

In comparison to non-renewable activated carbon, biochar is more attractive as an adsorbent because of its cheaper cost of manufacturing, greater efficiency, and renewability. Torrefaction, pyrolysis, and hydrothermal carbonization are viable thermochemical conversion processes for producing microalgal-based biochar, and changes are being made to improve their yield and characteristics. Additionally, their adsorption capacity, effectiveness, and adsorptive processes are influenced by their physiochemical characteristics. The adsorption ability of various types of microalgal-based biochar under laboratory conditions has been the subject of several adsorption experiments, which provide data and analysis. Here, more analysis using actual effluents and other advancements in such renewable technologies should be explored. Algal biopolymers and bio-composites provide a greener alternative to synthetic polymers. The time is right to conduct extensive testing of algal replacements for common and one-time-use polymers. A new ray of hope is the potential synthesis of polymers and by-products in wastewater-grown algae biorefineries. To achieve net-zero carbon emissions and to produce algal polymers in sufficient quantities to meet the growing demand, sustainable cultivation and extraction methods are needed. In addition, the discovery of new algae strains and species with high polymer content is crucial. Moreover, process optimization and new screening methods are essential to increase productivity.

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References

1. Yu, K.L.; Lau, B.F.; Show, P.L.; Ong, H.C.; Ling, T.C.; Chen, W.H.; Ng, E.P.; Chang, J.S. Recent Developments on Algal Biochar Production and Characterization. *Bioresour. Technol.* **2017**, *246*, 2–11. [CrossRef]
2. Nitsos, C.; Filali, R.; Taidi, B.; Lemaire, J. Current and Novel Approaches to Downstream Processing of Microalgae: A Review. *Biotechnol. Adv.* **2020**, *45*, 107650. [CrossRef] [PubMed]
3. Alazaiza, M.Y.D.; Albahnasawi, A.; Ahmad, Z.; Bashir, M.J.K.; Al-Wahaibi, T.; Abujazar, M.S.S.; Abu Amr, S.S.; Nassani, D.E. Potential Use of Algae for the Bioremediation of Different Types of Wastewater and Contaminants: Production of Bioproducts and Biofuel for Green Circular Economy. *J. Environ. Manag.* **2022**, *324*, 116415. [CrossRef]
4. Chai, W.S.; Tan, W.G.; Halimatul Munawaroh, H.S.; Gupta, V.K.; Ho, S.H.; Show, P.L. Multifaceted Roles of Microalgae in the Application of Wastewater Biotreatment: A Review. *Environ. Pollut.* **2021**, *269*, 116236. [CrossRef] [PubMed]
5. Roy Chong, J.W.; Tan, X.; Khoo, K.S.; Ng, H.S.; Jonglertjunya, W.; Yew, G.Y.; Show, P.L. Microalgae-Based Bioplastics: Future Solution towards Mitigation of Plastic Wastes. *Environ. Res.* **2022**, *206*, 112620. [CrossRef]
6. Nguyen, M.K.; Lin, C.; Hoang, H.G.; Sanderson, P.; Dang, B.T.; Bui, X.T.; Nguyen, N.S.H.; Vo, D.V.N.; Tran, H.T. Evaluate the Role of Biochar during the Organic Waste Composting Process: A Critical Review. *Chemosphere* **2022**, *299*, 134488. [CrossRef] [PubMed]
7. Nguyen, T.B.; Nguyen, V.T.; Hoang, H.G.; Cao, N.D.T.; Nguyen, T.T.; Vo, T.D.H.; Nguyen, N.K.Q.; Pham, M.D.T.; Nghiem, D.L.; Vo, T.K.Q.; et al. Recent Development of Algal Biochar for Contaminant Remediation and Energy Application: A State-of-the Art Review. *Curr. Pollut. Rep.* **2022**, 1–17. [CrossRef]
8. Chen, Y.D.; Ho, S.H.; Wang, D.; Wei, Z.S.; Chang, J.S.; Ren, N.Q. Lead Removal by a Magnetic Biochar Derived from Persulfate-ZVI Treated Sludge Together with One-Pot Pyrolysis. *Bioresour. Technol.* **2018**, *247*, 463–470. [CrossRef]
9. Xiao, X.; Chen, B.; Chen, Z.; Zhu, L.; Schnoor, J.L. Insight into Multiple and Multilevel Structures of Biochars and Their Potential Environmental Applications: A Critical Review. *Environ. Sci. Technol.* **2018**, *52*, 5027–5047. [CrossRef]
10. Huang, Q.; Song, S.; Chen, Z.; Hu, B.; Chen, J.; Wang, X. Biochar-Based Materials and Their Applications in Removal of Organic Contaminants from Wastewater: State-of-the-Art Review. *Biochar* **2019**, *1*, 45–73. [CrossRef]
11. Kandasamy, S.; Devarayan, K.; Bhuvanendran, N.; Zhang, B.; He, Z.; Narayanan, M.; Mathimani, T.; Ravichandran, S.; Pugazhendhi, A. Accelerating the Production of Bio-Oil from Hydrothermal Liquefaction of Microalgae via Recycled Biochar-Supported Catalysts. *J. Environ. Chem. Eng.* **2021**, *9*, 105321. [CrossRef]
12. Berslin, D.; Reshmi, A.; Sivaprakash, B.; Rajamohan, N.; Kumar, P.S. Remediation of Emerging Metal Pollutants Using Environment Friendly Biochar- Review on Applications and Mechanism. *Chemosphere* **2022**, *290*, 133384. [CrossRef]
13. Li, S.; Yang, F.; Li, J.; Cheng, K. Porous Biochar-Nanoscale Zero-Valent Iron Composites: Synthesis, Characterization and Application for Lead Ion Removal. *Sci. Total Environ.* **2020**, *746*, 141037. [CrossRef] [PubMed]
14. Su, Z.; Jin, K.; Wu, J.; Huang, P.; Liu, L.; Xiao, Z.; Peng, H.; Fan, L.; Zhou, W. Phosphorus Doped Biochar as a Deoxygenation and Denitrogenation Catalyst for Ex-Situ Upgrading of Vapors from Microwave-Assisted Co-Pyrolysis of Microalgae and Waste Cooking Oil. *J. Anal. Appl. Pyrolysis* **2022**, *164*, 105538. [CrossRef]
15. Gao, R.; Hu, H.; Fu, Q.; Li, Z.; Xing, Z.; Ali, U.; Zhu, J.; Liu, Y. Remediation of Pb, Cd, and Cu Contaminated Soil by Co-Pyrolysis Biochar Derived from Rape Straw and Orthophosphate: Speciation Transformation, Risk Evaluation and Mechanism Inquiry. *Sci. Total Environ.* **2020**, *730*, 139119. [CrossRef]
16. Das, S.K.; Sathish, A.; Stanley, J. Production of Biofuel and Bioplastic from Chlorella Pyrenoidosa. *Mater. Today Proc.* **2018**, *5*, 16774–16781. [CrossRef]
17. Beckstrom, B.D.; Wilson, M.H.; Crocker, M.; Quinn, J.C. Bioplastic Feedstock Production from Microalgae with Fuel Co-Products: A Techno-Economic and Life Cycle Impact Assessment. *Algal Res.* **2020**, *46*, 101769. [CrossRef]
18. Cinar, S.O.; Chong, Z.K.; Kucuker, M.A.; Wieczorek, N.; Cengiz, U.; Kuchta, K. Bioplastic Production from Microalgae: A Review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 3842. [CrossRef]
19. Devadas, V.V.; Khoo, K.S.; Chia, W.Y.; Chew, K.W.; Munawaroh, H.S.H.; Lam, M.K.; Lim, J.W.; Ho, Y.C.; Lee, K.T.; Show, P.L. Algae Biopolymer towards Sustainable Circular Economy. *Bioresour. Technol.* **2021**, *325*, 124702. [CrossRef]
20. Bernaerts, T.M.M.; Gheysen, L.; Foubert, I.; Hendrickx, M.E.; van Loey, A.M. The Potential of Microalgae and Their Biopolymers as Structuring Ingredients in Food: A Review. *Biotechnol. Adv.* **2019**, *37*, 107419. [CrossRef]
21. Negm, N.A.; Hefni, H.H.H.; Abd-Elaal, A.A.A.; Badr, E.A.; Abou Kana, M.T.H. Advancement on Modification of Chitosan Biopolymer and Its Potential Applications. *Int. J. Biol. Macromol.* **2020**, *152*, 681–702. [CrossRef]
22. Kolan, K.; Liu, Y.; Baldridge, J.; Murphy, C.; Semon, J.; Day, D.; Leu, M. Solvent Based 3D Printing of Biopolymer/Bioactive Glass Composite and Hydrogel for Tissue Engineering Applications. *Procedia CIRP* **2017**, *65*, 38–43. [CrossRef]
23. Kartik, A.; Akhil, D.; Lakshmi, D.; Panchamoorthy Gopinath, K.; Arun, J.; Sivaramakrishnan, R.; Pugazhendhi, A. A Critical Review on Production of Biopolymers from Algae Biomass and Their Applications. *Bioresour. Technol.* **2021**, *329*, 124868. [CrossRef]
24. Lee, X.J.; Ong, H.C.; Gan, Y.Y.; Chen, W.H.; Mahlia, T.M.I. State of Art Review on Conventional and Advanced Pyrolysis of Macroalgae and Microalgae for Biochar, Bio-Oil and Bio-Syngas Production. *Energy Convers. Manag.* **2020**, *210*, 112707. [CrossRef]

25. Zhang, Z.; Zhu, Z.; Shen, B.; Liu, L. Insights into Biochar and Hydrochar Production and Applications: A Review. *Energy* **2019**, *171*, 581–598. [CrossRef]
26. Giannakoudakis, D.A.; Hosseini-Bandegharaei, A.; Tsafrakidou, P.; Triantafyllidis, K.S.; Kornaros, M.; Anastopoulos, I. Aloe Vera Waste Biomass-Based Adsorbents for the Removal of Aquatic Pollutants: A Review. *J. Environ. Manag.* **2018**, *227*, 354–364. [CrossRef]
27. Cai, Y.; Lim, H.R.; Khoo, K.S.; Ng, H.S.; Cai, Y.; Wang, J.; Tak-Yee Chan, A.; Show, P.L. An Integration Study of Microalgae Bioactive Retention: From Microalgae Biomass to Microalgae Bioactives Nanoparticle. *Food Chem. Toxicol.* **2021**, *158*, 112607. [CrossRef]
28. Bach, Q.V.; Chen, W.H.; Lin, S.C.; Sheen, H.K.; Chang, J.S. Wet Torrefaction of Microalga Chlorella Vulgaris ESP-31 with Microwave-Assisted Heating. *Energy Convers. Manag.* **2017**, *141*, 163–170. [CrossRef]
29. Gan, Y.Y.; Ong, H.C.; Show, P.L.; Ling, T.C.; Chen, W.H.; Yu, K.L.; Abdullah, R. Torrefaction of Microalgal Biochar as Potential Coal Fuel and Application as Bio-Adsorbent. *Energy Convers. Manag.* **2018**, *165*, 152–162. [CrossRef]
30. Gan, Y.Y.; Ong, H.C.; Chen, W.H.; Sheen, H.K.; Chang, J.S.; Chong, C.T.; Ling, T.C. Microwave-Assisted Wet Torrefaction of Microalgae under Various Acids for Coproduction of Biochar and Sugar. *J. Clean. Prod.* **2020**, *253*, 119944. [CrossRef]
31. Yu, K.L.; Lee, X.J.; Ong, H.C.; Chen, W.H.; Chang, J.S.; Lin, C.S.; Show, P.L.; Ling, T.C. Adsorptive Removal of Cationic Methylene Blue and Anionic Congo Red Dyes Using Wet-Torrefied Microalgal Biochar: Equilibrium, Kinetic and Mechanism Modeling. *Environ. Pollut.* **2021**, *272*, 115986. [CrossRef] [PubMed]
32. Yu, K.L.; Show, P.L.; Ong, H.C.; Ling, T.C.; Chi-Wei Lan, J.; Chen, W.H.; Chang, J.S. Microalgae from Wastewater Treatment to Biochar–Feedstock Preparation and Conversion Technologies. *Energy Convers. Manag.* **2017**, *150*, 1–13. [CrossRef]
33. Choi, Y.K.; Choi, T.R.; Gurav, R.; Bhatia, S.K.; Park, Y.L.; Kim, H.J.; Kan, E.; Yang, Y.H. Adsorption Behavior of Tetracycline onto Spirulina Sp. (Microalgae)-Derived Biochars Produced at Different Temperatures. *Sci. Total Environ.* **2020**, *710*, 136282. [CrossRef]
34. Chen, Y.C.; Chen, W.H.; Lin, B.J.; Chang, J.S.; Ong, H.C. Impact of Torrefaction on the Composition, Structure and Reactivity of a Microalga Residue. *Appl. Energy* **2016**, *181*, 110–119. [CrossRef]
35. Chen, B.; Gu, Z.; Wu, M.; Ma, Z.; Lim, H.R.; Khoo, K.S.; Show, P.L. Advancement pathway of biochar resources from macroalgae biomass: A review. *Biomass Bioenergy* **2022**, *167*, 106650. [CrossRef]
36. Sekar, M.; Mathimani, T.; Alagumalai, A.; Chi, N.T.L.; Duc, P.A.; Bhatia, S.K.; Brindhadevi, K.; Pugazhendhi, A. A Review on the Pyrolysis of Algal Biomass for Biochar and Bio-Oil–Bottlenecks and Scope. *Fuel* **2021**, *283*, 119190. [CrossRef]
37. Koçer, A.T.; Mutlu, B.; Özçimen, D. Investigation of Biochar Production Potential and Pyrolysis Kinetics Characteristics of Microalgal Biomass. *Biomass Convers. Biorefin.* **2020**, *10*, 85–94. [CrossRef]
38. Shyam, S.; Arun, J.; Gopinath, K.P.; Ribhu, G.; Ashish, M.; Ajay, S. Biomass as Source for Hydrochar and Biochar Production to Recover Phosphates from Wastewater: A Review on Challenges, Commercialization, and Future Perspectives. *Chemosphere* **2022**, *286*, 131490. [CrossRef] [PubMed]
39. Sun, J.; Norouzi, O.; Mašek, O. A state-of-the-art review on algae pyrolysis for bioenergy and biochar production. *Bioresour. Technol.* **2021**, *346*, 126258. [CrossRef]
40. Law, X.N.; Cheah, W.Y.; Chew, K.W.; Ibrahim, M.F.; Park, Y.K.; Ho, S.H.; Show, P.L. Microalgal-Based Biochar in Wastewater Remediation: Its Synthesis, Characterization and Applications. *Environ. Res.* **2022**, *204*, 111966. [CrossRef]
41. Chaiwong, K.; Kiatsiriroat, T.; Vorayos, N.; Thararax, C. Study of Bio-Oil and Bio-Char Production from Algae by Slow Pyrolysis. *Biomass Bioenergy* **2013**, *56*, 600–606. [CrossRef]
42. Grierson, S.; Strezov, V.; Shah, P. Properties of Oil and Char Derived from Slow Pyrolysis of Tetraselmis Chui. *Bioresour. Technol.* **2011**, *102*, 8232–8240. [CrossRef] [PubMed]
43. Chandel, N.; Ahuja, V.; Gurav, R.; Kumar, V.; Tyagi, V.K.; Pugazhendhi, A.; Kumar, G.; Kumar, D.; Yang, Y.-H.; Bhatia, S.K. Progress in Microalgal Mediated Bioremediation Systems for the Removal of Antibiotics and Pharmaceuticals from Wastewater. *Sci. Total Environ.* **2022**, *825*, 153895. [CrossRef] [PubMed]
44. Aysu, T.; Ola, O.; Maroto-Valer, M.M.; Sanna, A. Effects of Titania Based Catalysts on In-Situ Pyrolysis of Pavlova Microalgae. *Fuel Process. Technol.* **2017**, *166*, 291–298. [CrossRef]
45. Jia, L.; Cao, C.; Cheng, Z.; Wang, J.; Huang, J.; Yang, J.; Pan, Y.; Xu, M.; Wang, Y. Ex Situ Catalytic Pyrolysis of Algal Biomass in a Double Microfixed-Bed Reactor: Catalyst Deactivation and Its Coking Behavior. *Energy Fuels* **2020**, *34*, 1918–1928. [CrossRef]
46. Sharma, M.; Singh, J.; Baskar, C.; Kumar, A. A Comprehensive Review on Biochar Formation and Its Utilization for Wastewater Treatment. *Pollut. Res.* **2018**, *37*, S1–S18.
47. De Siqueira Castro, J.; Assemany, P.P.; de Oliveira Carneiro, A.C.; Ferreira, J.; de Jesus Júnior, M.M.; de Ávila Rodrigues, F.; Calijuri, M.L. Hydrothermal Carbonization of Microalgae Biomass Produced in Agro-Industrial Effluent: Products, Characterization and Applications. *Sci. Total Environ.* **2021**, *768*, 144480. [CrossRef] [PubMed]
48. Venkatachalam, C.D.; Ravichandran, S.R.; Sengottian, M. Lignocellulosic and Algal Biomass for Bio-Crude Production Using Hydrothermal Liquefaction: Conversion Techniques, Mechanism and Process Conditions: A Review. *Environ. Eng. Res.* **2022**, *27*, 200555. [CrossRef]
49. Khoo, C.G.; Lam, M.K.; Mohamed, A.R.; Lee, K.T. Hydrochar Production from High-Ash Low-Lipid Microalgal Biomass via Hydrothermal Carbonization: Effects of Operational Parameters and Products Characterization. *Environ. Res.* **2020**, *188*, 109828. [CrossRef]

50. Yao, C.; Wu, P.; Pan, Y.; Lu, H.; Chi, L.; Meng, Y.; Cao, X.; Xue, S.; Yang, X. Evaluation of the Integrated Hydrothermal Carbonization-Algal Cultivation Process for Enhanced Nitrogen Utilization in Arthrospira Platensis Production. *Bioresour. Technol.* **2016**, *216*, 381–390. [CrossRef]
51. Xiang, W.; Zhang, X.; Chen, J.; Zou, W.; He, F.; Hu, X.; Tsang, D.C.W.; Ok, Y.S.; Gao, B. Biochar Technology in Wastewater Treatment: A Critical Review. *Chemosphere* **2020**, *252*, 126539. [CrossRef]
52. Singh, A.; Sharma, R.; Pant, D.; Malaviya, P. Engineered Algal Biochar for Contaminant Remediation and Electrochemical Applications. *Sci. Total Environ.* **2021**, *774*, 145676. [CrossRef]
53. Wang, H.; Wang, H.; Zhao, H.; Yan, Q. Adsorption and Fenton-like Removal of Chelated Nickel from Zn-Ni Alloy Electroplating Wastewater Using Activated Biochar Composite Derived from Taihu Blue Algae. *Chem. Eng. J.* **2020**, *379*, 122372. [CrossRef]
54. Dai, Y.; Zhang, N.; Xing, C.; Cui, Q.; Sun, Q. The Adsorption, Regeneration and Engineering Applications of Biochar for Removal Organic Pollutants: A Review. *Chemosphere* **2019**, *223*, 12–27. [CrossRef] [PubMed]
55. Nizam NU, M.; Hanafiah, M.M.; Mahmoudi, E.; Halim, A.A.; Mohammad, A.W. The removal of anionic and cationic dyes from an aqueous solution using biomass-based activated carbon. *Sci. Rep.* **2021**, *11*, 8623. [CrossRef] [PubMed]
56. Bhatia, S.K.; Bhatia, R.K.; Jeon, J.M.; Pugazhendhi, A.; Awasthi, M.K.; Kumar, D.; Kumar, G.; Yoon, J.-J.; Yang, Y.H. An overview on advancements in biobased transesterification methods for biodiesel production: Oil resources, extraction, biocatalysts, and process intensification technologies. *Fuel* **2021**, *285*, 119117. [CrossRef]
57. Li, H.; Dong, X.; da Silva, E.B.; de Oliveira, L.M.; Chen, Y.; Ma, L.Q. Mechanisms of Metal Sorption by Biochars: Biochar Characteristics and Modifications. *Chemosphere* **2017**, *178*, 466–478. [CrossRef]
58. Leng, L.J.; Yuan, X.Z.; Huang, H.J.; Wang, H.; Wu, Z.B.; Fu, L.H.; Peng, X.; Chen, X.H.; Zeng, G.M. Characterization and Application of Bio-Chars from Liquefaction of Microalgae, Lignocellulosic Biomass and Sewage Sludge. *Fuel Process. Technol.* **2015**, *129*, 8–14. [CrossRef]
59. Ge, Y.; Zhu, S.; Chang, J.S.; Jin, C.; Ho, S.H. Immobilization of Hg(II) on High-Salinity Spirulina Residue-Induced Biochar from Aqueous Solutions: Sorption and Transformation Mechanisms by the Dual-Mode Isotherms. *Environ. Pollut.* **2020**, *265*, 115087. [CrossRef]
60. Amin, M.; Chetpattananondh, P. Biochar from Extracted Marine Chlorella Sp. Residue for High Efficiency Adsorption with Ultrasonication to Remove Cr(VI), Zn(II) and Ni(II). *Bioresour. Technol.* **2019**, *289*, 121578. [CrossRef]
61. Inyang, M.I.; Gao, B.; Yao, Y.; Xue, Y.; Zimmerman, A.; Mosa, A.; Pullammanappallil, P.; Ok, Y.S.; Cao, X. A Review of Biochar as a Low-Cost Adsorbent for Aqueous Heavy Metal Removal. *Crit. Rev. Environ. Sci. Technol.* **2015**, *46*, 406–433. [CrossRef]
62. Zheng, H.; Guo, W.; Li, S.; Chen, Y.; Wu, Q.; Feng, X.; Yin, R.; Ho, S.H.; Ren, N.; Chang, J.S. Adsorption of P-Nitrophenols (PNP) on Microalgal Biochar: Analysis of High Adsorption Capacity and Mechanism. *Bioresour. Technol.* **2017**, *244*, 1456–1464. [CrossRef] [PubMed]
63. Nartey, O.D.; Zhao, B. Biochar Preparation, Characterization, and Adsorptive Capacity and Its Effect on Bioavailability of Contaminants: An Overview. *Adv. Mater. Sci. Eng.* **2014**, *2014*, 715398. [CrossRef]
64. Enaime, G.; Baçaoui, A.; Yaacoubi, A.; Lübken, M. Biochar for Wastewater Treatment—Conversion Technologies and Applications. *Appl. Sci.* **2020**, *10*, 3492. [CrossRef]
65. Ronsse, F.; van Hecke, S.; Dickinson, D.; Prins, W. Production and Characterization of Slow Pyrolysis Biochar: Influence of Feedstock Type and Pyrolysis Conditions. *GCB Bioenergy* **2013**, *5*, 104–115. [CrossRef]
66. Ho, S.H.; Chen, Y.D.; Li, R.; Zhang, C.; Ge, Y.; Cao, G.; Ma, M.; Duan, X.; Wang, S.; Ren, N.Q. N-Doped Graphitic Biochars from C-Phycocyanin Extracted Spirulina Residue for Catalytic Persulfate Activation toward Nonradical Disinfection and Organic Oxidation. *Water Res.* **2019**, *159*, 77–86. [CrossRef] [PubMed]
67. Deng, Y.; Zhang, T.; Wang, Q.; Deng, Y.; Zhang, T.; Wang, Q. Biochar Adsorption Treatment for Typical Pollutants Removal in Livestock Wastewater: A Review. In *Engineering Applications of Biochar*; IntechOpen: London, UK, 2017. [CrossRef]
68. Zhang, J.; Liu, J.; Liu, R. Effects of Pyrolysis Temperature and Heating Time on Biochar Obtained from the Pyrolysis of Straw and Lignosulfonate. *Bioresour. Technol.* **2015**, *176*, 288–291. [CrossRef]
69. Tran, N.H.; Reinhard, M.; Gin, K.Y.H. Occurrence and Fate of Emerging Contaminants in Municipal Wastewater Treatment Plants from Different Geographical Regions-a Review. *Water Res.* **2018**, *133*, 182–207. [CrossRef]
70. Daneshvar, E.; Zarrinmehr, M.J.; Kousha, M.; Hashtjin, A.M.; Saratale, G.D.; Maiti, A.; Vithanage, M.; Bhatnagar, A. Hexavalent Chromium Removal from Water by Microalgal-Based Materials: Adsorption, Desorption and Recovery Studies. *Bioresour. Technol.* **2019**, *293*, 122064. [CrossRef]
71. Bordoloi, N.; Goswami, R.; Kumar, M.; Kataki, R. Biosorption of Co (II) from Aqueous Solution Using Algal Biochar: Kinetics and Isotherm Studies. *Bioresour. Technol.* **2017**, *244*, 1465–1469. [CrossRef]
72. Poo, K.M.; Son, E.B.; Chang, J.S.; Ren, X.; Choi, Y.J.; Chae, K.J. Biochars Derived from Wasted Marine Macro-Algae (Saccharina Japonica and Sargassum Fusiforme) and Their Potential for Heavy Metal Removal in Aqueous Solution. *J. Environ. Manag.* **2018**, *206*, 364–372. [CrossRef] [PubMed]
73. Barber, E.A.; Liu, Z.; Smith, S.R. Organic Contaminant Biodegradation by Oxidoreductase Enzymes in Wastewater Treatment. *Microorganisms* **2020**, *8*, 122. [CrossRef]
74. Kuo, H.C.; Lin, Y.G.; Chiang, C.L.; Liu, S.H. FeN@ N-doped graphitic biochars derived from hydrothermal-microwave pyrolysis of cellulose biomass for fuel cell catalysts. *J. Anal. Appl. Pyrolysis* **2021**, *153*, 104991. [CrossRef]

75. Kumar, M.; Sun, Y.; Rathour, R.; Pandey, A.; Thakur, I.S.; Tsang, D.C. Algae as potential feedstock for the production of biofuels and value-added products: Opportunities and challenges. *Sci. Total Environ.* **2020**, *716*, 137116. [CrossRef] [PubMed]
76. Nautiyal, P.; Subramanian, K.A.; Dastidar, M.G. Adsorptive Removal of Dye Using Biochar Derived from Residual Algae after In-Situ Transesterification: Alternate Use of Waste of Biodiesel Industry. *J. Environ. Manag.* **2016**, *182*, 187–197. [CrossRef]
77. Chen, Y.D.; Liu, F.; Ren, N.Q.; Ho, S.H. Revolutions in Algal Biochar for Different Applications: State-of-the-Art Techniques and Future Scenarios. *Chin. Chem. Lett.* **2020**, *31*, 2591–2602. [CrossRef]
78. Plaza, M.G.; Pevida, C.; Arias, B.; Fermoso, J.; Casal, M.D.; Martín, C.F.; Rubiera, F.; Pis, J.J. Development of Low-Cost Biomass-Based Adsorbents for Postcombustion CO_2 Capture. *Fuel* **2009**, *88*, 2442–2447. [CrossRef]
79. Tan, X.F.; Liu, S.B.; Liu, Y.G.; Gu, Y.L.; Zeng, G.M.; Hu, X.J.; Wang, X.; Liu, S.H.; Jiang, L.H. Biochar as Potential Sustainable Precursors for Activated Carbon Production: Multiple Applications in Environmental Protection and Energy Storage. *Bioresour. Technol.* **2017**, *227*, 359–372. [CrossRef] [PubMed]
80. Creamer, A.E.; Gao, B.; Zhang, M. Carbon Dioxide Capture Using Biochar Produced from Sugarcane Bagasse and Hickory Wood. *Chem. Eng. J.* **2014**, *249*, 174–179. [CrossRef]
81. Saha, D.; Kienbaum, M.J. Role of Oxygen, Nitrogen and Sulfur Functionalities on the Surface of Nanoporous Carbons in CO_2 Adsorption: A Critical Review. *Microporous Mesoporous Mater.* **2019**, *287*, 29–55. [CrossRef]
82. Gadipelli, S.; Guo, Z.X. Graphene-Based Materials: Synthesis and Gas Sorption, Storage and Separation. *Prog. Mater. Sci.* **2015**, *69*, 1–60. [CrossRef]
83. Plaza, M.G.; González, A.S.; Pis, J.J.; Rubiera, F.; Pevida, C. Production of Microporous Biochars by Single-Step Oxidation: Effect of Activation Conditions on CO2 Capture. *Appl. Energy* **2014**, *114*, 551–562. [CrossRef]
84. Creamer, A.E.; Gao, B. Carbon-Based Adsorbents for Postcombustion CO_2 Capture: A Critical Review. *Environ. Sci. Technol.* **2016**, *50*, 7276–7289. [CrossRef]
85. Zhang, C.; Wang, C.; Cao, G.; Chen, W.H.; Ho, S.H. Comparison and Characterization of Property Variation of Microalgal Biomass with Non-Oxidative and Oxidative Torrefaction. *Fuel* **2019**, *246*, 375–385. [CrossRef]
86. Wu, X.; Tian, Z.; Hu, L.; Huang, S.; Cai, J. Macroalgae-Derived Nitrogen-Doped Hierarchical Porous Carbons with High Performance for H2 Storage and Supercapacitors. *RSC Adv.* **2017**, *7*, 32795–32805. [CrossRef]
87. Wang, J.; Li, Z.; Yan, S.; Yu, X.; Ma, Y.; Ma, L. Modifying the Microstructure of Algae-Based Active Carbon and Modelling Supercapacitors Using Artificial Neural Networks. *RSC Adv.* **2019**, *9*, 14797–14808. [CrossRef]
88. Gümüş, F. Utilization of Algal Waste Biomass-Derived Biochar Prepared by a Microwave-Assisted Method for Aniline Green Adsorption. *Water Air Soil Pollut.* **2022**, *233*, 364. [CrossRef]
89. Gao, Y.; Sun, R.; Li, A.; Ji, G. In-Situ Self-Activation Strategy toward Highly Porous Biochar for Supercapacitors: Direct Carbonization of Marine Algae. *J. Electroanal. Chem.* **2021**, *882*, 114986. [CrossRef]
90. Hung, C.M.; Huang, C.P.; Hsieh, S.L.; Tsai, M.L.; Chen, C.W.; Dong, C.D. Biochar Derived from Red Algae for Efficient Remediation of 4-Nonylphenol from Marine Sediments. *Chemosphere* **2020**, *254*, 126916. [CrossRef]
91. de Bhowmick, G.; Sarmah, A.K.; Sen, R. Production and Characterization of a Value Added Biochar Mix Using Seaweed, Rice Husk and Pine Sawdust: A Parametric Study. *J. Clean. Prod.* **2018**, *200*, 641–656. [CrossRef]
92. Kakarla, R.; Choi, J.W.; Yun, J.H.; Kim, B.H.; Heo, J.; Lee, S.; Cho, D.H.; Ramanan, R.; Kim, H.S. Application of High-Salinity Stress for Enhancing the Lipid Productivity of Chlorella Sorokiniana HS1 in a Two-Phase Process. *J. Microbiol.* **2018**, *56*, 56–64. [CrossRef] [PubMed]
93. Ramanan, R.; Tran, Q.G.; Cho, D.H.; Jung, J.E.; Kim, B.H.; Shin, S.Y.; Choi, S.H.; Liu, K.H.; Kim, D.S.; Lee, S.J.; et al. The Ancient Phosphatidylinositol 3-Kinase Signaling System Is a Master Regulator of Energy and Carbon Metabolism in Algae. *Plant Physiol.* **2018**, *177*, 1050–1065. [CrossRef] [PubMed]
94. Venkata Mohan, S.; Hemalatha, M.; Chakraborty, D.; Chatterjee, S.; Ranadheer, P.; Kona, R. Algal Biorefinery Models with Self-Sustainable Closed Loop Approach: Trends and Prospective for Blue-Bioeconomy. *Bioresour. Technol.* **2020**, *295*, 122128. [CrossRef]
95. Roja, K.; Ruben Sudhakar, D.; Anto, S.; Mathimani, T. Extraction and Characterization of Polyhydroxyalkanoates from Marine Green Alga and Cyanobacteria. *Biocatal. Agric. Biotechnol.* **2019**, *22*, 101358. [CrossRef]
96. Faidi, A.; Lassoued, M.A.; Becheikh, M.E.H.; Touati, M.; Stumbé, J.F.; Farhat, F. Application of Sodium Alginate Extracted from a Tunisian Brown Algae Padina Pavonica for Essential Oil Encapsulation: Microspheres Preparation, Characterization and in Vitro Release Study. *Int. J. Biol. Macromol.* **2019**, *136*, 386–394. [CrossRef] [PubMed]
97. Morales-Jiménez, M.; Gouveia, L.; Yáñez-Fernández, J.; Castro-Muñoz, R.; Barragán-Huerta, B.E. Production, Preparation and Characterization of Microalgae-Based Biopolymer as a Potential Bioactive Film. *Coatings* **2020**, *10*, 120. [CrossRef]
98. Mirzadeh, M.; Arianejad, M.R.; Khedmat, L. Antioxidant, Antiradical, and Antimicrobial Activities of Polysaccharides Obtained by Microwave-Assisted Extraction Method: A Review. *Carbohydr. Polym.* **2020**, *229*, 115421. [CrossRef]
99. Ponthier, E.; Domínguez, H.; Torres, M.D. The Microwave Assisted Extraction Sway on the Features of Antioxidant Compounds and Gelling Biopolymers from Mastocarpus Stellatus. *Algal Res.* **2020**, *51*, 102081. [CrossRef]
100. Flórez-Fernández, N.; López-García, M.; González-Muñoz, M.J.; Vilariño, J.M.L.; Domínguez, H. Ultrasound-Assisted Extraction of Fucoidan from Sargassum Muticum. *J. Appl. Phycol.* **2017**, *29*, 1553–1561. [CrossRef]

101. Hmelkov, A.B.; Zvyagintseva, T.N.; Shevchenko, N.M.; Rasin, A.B.; Ermakova, S.P. Ultrasound-Assisted Extraction of Polysaccharides from Brown Alga Fucus Evanescens. Structure and Biological Activity of the New Fucoidan Fractions. *J. Appl. Phycol.* **2018**, *30*, 2039–2046. [CrossRef]
102. Flórez-Fernández, N.; Domínguez, H.; Torres, M.D. A Green Approach for Alginate Extraction from Sargassum Muticum Brown Seaweed Using Ultrasound-Assisted Technique. *Int. J. Biol. Macromol.* **2019**, *124*, 451–459. [CrossRef] [PubMed]
103. Gereniu, C.R.N.; Saravana, P.S.; Chun, B.S. Recovery of Carrageenan from Solomon Islands Red Seaweed Using Ionic Liquid-Assisted Subcritical Water Extraction. *Sep. Purif. Technol.* **2018**, *196*, 309–317. [CrossRef]
104. Alboofetileh, M.; Rezaei, M.; Tabarsa, M.; You, S.G.; Mariatti, F.; Cravotto, G. Subcritical Water Extraction as an Efficient Technique to Isolate Biologically-Active Fucoidans from Nizamuddinia Zanardinii. *Int. J. Biol. Macromol.* **2019**, *128*, 244–253. [CrossRef]
105. Saravana, P.S.; Tilahun, A.; Gerenew, C.; Tri, V.D.; Kim, N.H.; Kim, G.D.; Woo, H.C.; Chun, B.S. Subcritical Water Extraction of Fucoidan from Saccharina Japonica: Optimization, Characterization and Biological Studies. *J. Appl. Phycol.* **2018**, *30*, 579–590. [CrossRef]
106. Saravana, P.S.; Cho, Y.N.; Woo, H.C.; Chun, B.S. Green and Efficient Extraction of Polysaccharides from Brown Seaweed by Adding Deep Eutectic Solvent in Subcritical Water Hydrolysis. *J. Clean. Prod.* **2018**, *198*, 1474–1484. [CrossRef]
107. 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] [PubMed]
108. Costa, S.S.; Miranda, A.L.; Andrade, B.B.; de Jesus Assis, D.; 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] [PubMed]
109. Ramos, F.D.; Delpino, C.A.; Villar, M.A.; Diaz, M.S. Design and Optimization of Poly(Hydroxyalkanoate)s Production Plants Using Alternative Substrates. *Bioresour. Technol.* **2019**, *289*, 121699. [CrossRef]
110. Rueda, E.; García-Galán, M.J.; Ortiz, A.; Uggetti, E.; Carretero, J.; García, J.; Díez-Montero, R. Bioremediation of Agricultural Runoff and Biopolymers Production from Cyanobacteria Cultured in Demonstrative Full-Scale Photobioreactors. *Process Saf. Environ. Prot.* **2020**, *139*, 241–250. [CrossRef]
111. Sirohi, R.; Prakash Pandey, J.; Kumar Gaur, V.; Gnansounou, E.; Sindhu, R. Critical Overview of Biomass Feedstocks as Sustainable Substrates for the Production of Polyhydroxybutyrate (PHB). *Bioresour. Technol.* **2020**, *311*, 123536. [CrossRef]
112. Abdo, S.M.; Ali, G.H. Analysis of Polyhydroxybutrate and Bioplastic Production from Microalgae. *Bull. Natl. Res. Cent.* **2019**, *43*, 97. [CrossRef]
113. Kavitha, G.; Kurinjimalar, C.; Sivakumar, K.; Palani, P.; Rengasamy, R. Biosynthesis, Purification and Characterization of Polyhydroxybutyrate from Botryococcus Braunii Kütz. *Int. J. Biol. Macromol.* **2016**, *89*, 700–706. [CrossRef] [PubMed]
114. Ghosh, S.; Gnaim, R.; Greiserman, S.; Fadeev, L.; Gozin, M.; Golberg, A. Macroalgal Biomass Subcritical Hydrolysates for the Production of Polyhydroxyalkanoate (PHA) by Haloferax Mediterranei. *Bioresour. Technol.* **2019**, *271*, 166–173. [CrossRef] [PubMed]
115. Akdoğan, M.; Çelik, E. Enhanced Production of Poly(3-Hydroxybutyrate-Co-3-Hydroxyvalerate) Biopolymer by Recombinant Bacillus Megaterium in Fed-Batch Bioreactors. *Bioprocess Biosyst. Eng.* **2021**, *44*, 403–416. [CrossRef] [PubMed]
116. 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]
117. Tran, D.T.; Lee, H.R.; Jung, S.; Park, M.S.; Yang, J.W. Lipid-Extracted Algal Biomass Based Biocomposites Fabrication with Poly(Vinyl Alcohol). *Algal Res.* **2018**, *31*, 525–533. [CrossRef]
118. Kumar, L.; Brice, J.; Toberer, L.; Klein-Seetharaman, J.; Knauss, D.; Sarkar, S.K. Antimicrobial Biopolymer Formation from Sodium Alginate and Algae Extract Using Aminoglycosides. *PLoS ONE* **2019**, *14*, e0214411. [CrossRef] [PubMed]
119. Zhang, C.; Show, P.L.; Ho, S.H. Progress and Perspective on Algal Plastics—A Critical Review. *Bioresour. Technol.* **2019**, *289*, 121700. [CrossRef] [PubMed]
120. Yuan, Y.; Macquarrie, D.J. Microwave Assisted Step-by-Step Process for the Production of Fucoidan, Alginate Sodium, Sugars and Biochar from Ascophyllum Nodosum through a Biorefinery Concept. *Bioresour. Technol.* **2015**, *198*, 819–827. [CrossRef]
121. Abraham, R.E.; Su, P.; Puri, M.; Raston, C.L.; Zhang, W. Optimisation of Biorefinery Production of Alginate, Fucoidan and Laminarin from Brown Seaweed Durvillaea Potatorum. *Algal Res.* **2019**, *38*, 101389. [CrossRef]
122. Charoensiddhi, S.; Lorbeer, A.J.; Lahnstein, J.; Bulone, V.; Franco, C.M.M.; Zhang, W. Enzyme-Assisted Extraction of Carbohydrates from the Brown Alga Ecklonia Radiata: Effect of Enzyme Type, PH and Buffer on Sugar Yield and Molecular Weight Profiles. *Process Biochem.* **2016**, *51*, 1503–1510. [CrossRef]
123. Etman, S.M.; Elnaggar, Y.S.R.; Abdallah, O.Y. Fucoidan, a Natural Biopolymer in Cancer Combating: From Edible Algae to Nanocarrier Tailoring. *Int. J. Biol. Macromol.* **2020**, *147*, 799–808. [CrossRef]
124. Bittkau, K.S.; Neupane, S.; Alban, S. Initial Evaluation of Six Different Brown Algae Species as Source for Crude Bioactive Fucoidans. *Algal Res.* **2020**, *45*, 101759. [CrossRef]
125. Rajauria, G.; Ravindran, R.; Garcia-Vaquero, M.; Rai, D.K.; Sweeney, T.; O'Doherty, J. Molecular Characteristics and Antioxidant Activity of Laminarin Extracted from the Seaweed Species Laminaria Hyperborea, Using Hydrothermal-Assisted Extraction and a Multi-Step Purification Procedure. *Food Hydrocoll.* **2021**, *112*, 106332. [CrossRef]

126. Becker, S.; Scheffel, A.; Polz, M.F.; Hehemann, J.H. Accurate Quantification of Laminarin in Marine Organic Matter with Enzymes from Marine Microbes. *Appl. Environ. Microbiol.* **2017**, *83*, e03389-16. [CrossRef] [PubMed]
127. Qureshi, D.; Nayak, S.K.; Maji, S.; Kim, D.; Banerjee, I.; Pal, K. Carrageenan: A Wonder Polymer from Marine Algae for Potential Drug Delivery Applications. *Curr. Pharm. Des.* **2019**, *25*, 1172–1186. [CrossRef]
128. Bouanati, T.; Colson, E.; Moins, S.; Cabrera, J.C.; Eeckhaut, I.; Raquez, J.M.; Gerbaux, P. Microwave-Assisted Depolymerization of Carrageenans from Kappaphycus Alvarezii and Eucheuma Spinosum: Controlled and Green Production of Oligosaccharides from the Algae Biomass. *Algal Res.* **2020**, *51*, 102054. [CrossRef]
129. Bui, V.T.N.T.; Nguyen, B.T.; Renou, F.; Nicolai, T. Structure and Rheological Properties of Carrageenans Extracted from Different Red Algae Species Cultivated in Cam Ranh Bay, Vietnam. *J. Appl. Phycol.* **2019**, *31*, 1947–1953. [CrossRef]
130. Cebrián-Lloret, V.; Metz, M.; Martínez-Abad, A.; Knutsen, S.H.; Ballance, S.; López-Rubio, A.; Martínez-Sanz, M. Valorization of Alginate-Extracted Seaweed Biomass for the Development of Cellulose-Based Packaging Films. *Algal Res.* **2022**, *61*, 102576. [CrossRef]
131. Steinbruch, E.; Drabik, D.; Epstein, M.; Ghosh, S.; Prabhu, M.S.; Gozin, M.; Kribus, A.; Golberg, A. Hydrothermal Processing of a Green Seaweed Ulva Sp. for the Production of Monosaccharides, Polyhydroxyalkanoates, and Hydrochar. *Bioresour. Technol.* **2020**, *318*, 124263. [CrossRef]
132. Biswas, M.C.; Jony, B.; Nandy, P.K.; Chowdhury, R.A.; Halder, S.; Kumar, D.; Ramakrishna, S.; Hassan, M.; Ahsan, M.A.; Hoque, M.E.; et al. Recent Advancement of Biopolymers and Their Potential Biomedical Applications. *J. Polym. Environ.* **2022**, *30*, 51–74. [CrossRef]
133. Lu, Y.; Biswas, M.C.; Guo, Z.; Jeon, J.W.; Wujcik, E.K. Recent Developments in Bio-Monitoring via Advanced Polymer Nanocomposite-Based Wearable Strain Sensors. *Biosens. Bioelectron.* **2019**, *123*, 167–177. [CrossRef]
134. Chang, J.; Xiao, W.; Liu, P.; Liao, X.; Wen, Y.; Bai, L.; Li, L.; Li, M. Carboxymethyl Cellulose Assisted Preparation of Water-Processable Halloysite Nanotubular Composites with Carboxyl-Functionalized Multi-Carbon Nanotubes for Simultaneous Voltammetric Detection of Uric Acid, Guanine and Adenine in Biological Samples. *J. Electroanal. Chem.* **2016**, *780*, 103–113. [CrossRef]
135. Zhang, Q.; Hu, J.; Lee, D.J. Microbial Fuel Cells as Pollutant Treatment Units: Research Updates. *Bioresour. Technol.* **2016**, *217*, 121–128. [CrossRef]
136. Upadhyay, A.K.; Singh, R.; Vijay, D.; Singh, L.; Singh, D.P. Environmental Technology & Innovation Microalgal Consortia Technology: A Novel and Sustainable Approach of Resource Reutilization, Waste Management and Lipid Production. *Environ. Technol. Innov.* **2021**, *23*, 101600. [CrossRef]
137. Del Mar Orta, M.; Martín, J.; Santos, J.L.; Aparicio, I.; Medina-Carrasco, S.; Alonso, E. Biopolymer-Clay Nanocomposites as Novel and Ecofriendly Adsorbents for Environmental Remediation. *Appl. Clay Sci.* **2020**, *198*, 105838. [CrossRef]
138. Xia, L.; Tan, J.; Wu, P.; He, Q.; Song, S.; Li, Y. Biopolymers Extracted from Klebsiella Sp. and Bacillus Sp. in Wastewater Sludge as Superb Adsorbents for Aqueous Hg(II) Removal from Water. *Chem. Phys. Lett.* **2020**, *754*, 137689. [CrossRef]
139. Silva, M.S.; Silva, L.S.; Ferreira, F.J.L.; Bezerra, R.D.S.; Marques, T.M.F.; Meneguin, A.B.; Barud, H.S.; Osajima, J.A.; Silva Filho, E.C. Study of Interactions between Organic Contaminants and a New Phosphated Biopolymer Derived from Cellulose. *Int. J. Biol. Macromol.* **2020**, *146*, 668–677. [CrossRef]
140. Sathiyavimal, S.; Vasantharaj, S.; LewisOscar, F.; Selvaraj, R.; Brindhadevi, K.; Pugazhendhi, A. Natural Organic and Inorganic–Hydroxyapatite Biopolymer Composite for Biomedical Applications. *Prog. Org. Coat.* **2020**, *147*, 105858. [CrossRef]
141. Bahmani, A.; Comeau, P.A.; Montesano, J.; Willett, T.L. Extrudable Hydroxyapatite/Plant Oil-Based Biopolymer Nanocomposites for Biomedical Applications: Mechanical Testing and Modeling. *Mater. Des.* **2019**, *174*, 107790. [CrossRef]
142. Liu, J.; Sun, L.; Xu, W.; Wang, Q.; Yu, S.; Sun, J. Current Advances and Future Perspectives of 3D Printing Natural-Derived Biopolymers. *Carbohydr. Polym.* **2019**, *207*, 297–316. [CrossRef]
143. Sangiorgi, A.; Gonzalez, Z.; Ferrandez-Montero, A.; Yus, J.; Sanchez-Herencia, A.J.; Galassi, C.; Sanson, A.; Ferrari, B. 3D Printing of Photocatalytic Filters Using a Biopolymer to Immobilize TiO_2 Nanoparticles. *J. Electrochem. Soc.* **2019**, *166*, H3239–H3248. [CrossRef]
144. Shishkovsky, I.; Sherbakov, V.; Ibatullin, I.; Volchkov, V.; Volova, L. Nano-Size Ceramic Reinforced 3D Biopolymer Scaffolds: Tribomechanical Testing and Stem Cell Activity. *Compos. Struct.* **2018**, *202*, 651–659. [CrossRef]
145. Gu, L.; Peng, N.; Chang, C.; McClements, D.J.; Su, Y.; Yang, Y. Fabrication of Surface-Active Antioxidant Food Biopolymers: Conjugation of Catechin Polymers to Egg White Proteins. *Food Biophys.* **2017**, *12*, 198–210. [CrossRef]
146. Pérez Córdoba, L.J.; Sobral, P.J.A. Physical and Antioxidant Properties of Films Based on Gelatin, Gelatin-Chitosan or Gelatin-Sodium Caseinate Blends Loaded with Nanoemulsified Active Compounds. *J. Food Eng.* **2017**, *213*, 47–53. [CrossRef]
147. Zanutto-Elgui, M.R.; Vieira, J.C.S.; do Prado, D.Z.; Buzalaf, M.A.R.; de Magalhães Padilha, P.; Elgui de Oliveira, D.; Fleuri, L.F. Production of Milk Peptides with Antimicrobial and Antioxidant Properties through Fungal Proteases. *Food Chem.* **2019**, *278*, 823–831. [CrossRef] [PubMed]
148. Gopu, M.; Selvam, K. Polysaccharides from Marine Red Algae Amphiroa Rigida and Their Biomedical Potential: An in-Vitro Study. *Biocatal. Agric. Biotechnol.* **2020**, *29*, 101769. [CrossRef]
149. Aswathi Mohan, A.; Robert Antony, A.; Greeshma, K.; Yun, J.H.; Ramanan, R.; Kim, H.S. Algal Biopolymers as Sustainable Resources for a Net-Zero Carbon Bioeconomy. *Bioresour. Technol.* **2022**, *344*, 126397. [CrossRef] [PubMed]

150. Chiellini, E.; Cinelli, P.; Ilieva, V.I.; Martera, M. Biodegradable Thermoplastic Composites Based on Polyvinyl Alcohol and Algae. *Biomacromolecules* **2008**, *9*, 1007–1013. [CrossRef]
151. Zini, E.; Scandola, M. Green Composites: An Overview. *Polym. Compos.* **2011**, *32*, 1905–1915. [CrossRef]
152. Siracusa, V.; Blanco, I. Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(Ethylene Terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications. *Polymers* **2020**, *12*, 1641. [CrossRef] [PubMed]
153. Zenkiewicz, M.; Richert, J.; Rytlewski, P.; Moraczewski, K.; Stepczyńska, M.; Karasiewicz, T. Characterisation of Multi-Extruded Poly(Lactic Acid). *Polym. Test.* **2009**, *28*, 412–418. [CrossRef]
154. Ariffin, H.; Nishida, H.; Hassan, M.A.; Shirai, Y. Chemical Recycling of Polyhydroxyalkanoates as a Method towards Sustainable Development. *Biotechnol. J.* **2010**, *5*, 484–492. [CrossRef] [PubMed]
155. Amalina, F.; Razak, A.S.A.; Krishnan, S.; Zularisam, A.W.; Nasrullah, M. A Comprehensive Assessment of the Method for Producing Biochar, Its Characterization, Stability, and Potential Applications in Regenerative Economic Sustainability—A Review. *Clean. Mater.* **2022**, *3*, 100045. [CrossRef]
156. Chen, L.; Fang, W.; Liang, J.; Nabi, M.; Cai, Y.; Wang, Q.; Zhang, P.; Zhang, G. Biochar Application in Anaerobic Digestion: Performances, Mechanisms, Environmental Assessment and Circular Economy. *Resour. Conserv. Recycl.* **2023**, *188*, 106720. [CrossRef]
157. Baranwal, J.; Barse, B.; Fais, A.; Delogu, G.L.; Kumar, A. Biopolymer: A Sustainable Material for Food and Medical Applications. *Polymers* **2022**, *14*, 983. [CrossRef]
158. Khanra, A.; Vasistha, S.; Rai, M.P.; Cheah, W.Y.; Khoo, K.S.; Chew, K.W.; Chuah, L.F.; Show, P.L. Green Bioprocessing and Applications of Microalgae-Derived Biopolymers as a Renewable Feedstock: Circular Bioeconomy Approach. *Environ. Technol. Innov.* **2022**, *28*, 102872. [CrossRef]